Current experience with the use of membrane bioreactor technology for the treatment of papermill effluent

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Abstract

The membrane bioreactor process (MBR) is a well developed and proven technology. The membrane materials and module systems have been developed continuously within the last years. Several installations have been built for municipal and industrial applications, but only few full scale MBR plants are in operation in pulp and paper industry.

The MBR process is an alternative for the aerobic treatment of papermill effluent. The system is able to replace the standard process high loaded stage followed by a low loaded activated sludge system with at least the same process efficiency and stability. The high loaded stage generally will be an aerobic suspended carrier reactor, or, leaving the aerobic system, an anaerobic reactor of the type EGSB (Extended Granulated Sludge Blanket).

MBR for industrial applications consists of an activated sludge bioreactor followed by an external side stream membrane stage for the separation of biomass. Essential advantages of this technology are the high process stability because of assured biomass retention, less area required due to a high volume load and no need of a secondary clarifier as well as a treated water quality almost free of suspended solids, giving best preconditions for reuse of treated waste water in the production.

However, using the MBR process for papermill effluent treatment the specific waste water characteristic such as size, type and quantity of remaining fibres, organic and inorganic compounds and typical load fluctuations in papermills have to be respected in the design of the pretreatment and the activated sludge bioreactor as well. Especially the bioreactor design and stable operation of the biostage will influence the overall process performance and reliability basically.

The available technical MBR systems using either low pressure submerged membranes or classical horizontal cross flow tubular modules or as a new development aerated vertical cross flow tubular modules are compared technically. Recommendations for planning are given. The technical and economical issues are examined in a case study. Basis of the process design is the model of a production of graphic paper according middle European practice with regard to production capacity, raw materials, stock preparation and specific waste water amount. For this model waste water, the MBR process is designed and investment and operation costs are determined.

The total specific operation costs for MBR with submerged membranes and with aerated tubular cross flow membranes amount to 0.22 €/m^3. MBR with classical tubular cross flow membranes amount to 0.33 €/m^3 mainly due to fact of the higher energy cost. However, the calculated specific total annual costs (capital + operation costs) are in a narrow range (0.56 €/m^3 to 0.59 €/m^3).

Zusammenfassung

Das Membranbioreaktor (MBR)-Verfahren ist entwickelt und erprobt. Die Membranmaterialien und Modulsysteme wurden in den letzten Jahren kontinuierlich weiterentwickelt. In der kommunalen und industriellen Abwasserreinigung sind bereits viele großtechnische MBR-Anlagen in Betrieb. In der Papierindustrie wird das Verfahren aber bisher nur in Einzelfällen angewendet.

Als Alternative zu den heute als Stand der Technik zu betrachtenden biologischen Standardverfahren zur Papierfabriksabwasserreinigung ist für den aeroben Fall das System der Membranbioreaktoren (MBR) zu sehen. MBR-Anlagen können mit gleicher Reinigungsleistung und Stabilität des Prozesses die beiden aeroben Stufen (Hochlast und Schwachlast) ersetzen. Als aerobe Hochlaststufe werden Schwebebettreaktoren mit fluidisiertem Bett aus Kunststoffträgermaterialien für die Biomasse, als anaerobe Hochlaststufe weiterentwickelte leistungsfähige Pelletreaktoren (EGSB) eingesetzt, jeweils gefolgt von einer konventionellen schwach belasteten Belebung mit Nachklärung.

Das MBR-Verfahren für industrielle Anwendungen besteht aus einem Belebtschlammreaktor mit extern angeordneter und betriebener (auch als *side stream* bezeichnet) Membranstufe zur Biomasseabtrennung. Wesentliche Vorteile des MBR-Verfahrens stellen die hohe Betriebssicherheit aufgrund eines gesicherten Schlammrückhalts, der geringe Platzbedarf durch hohe Raumbelastungen und Wegfall des Nachklärbeckens sowie ein nahezu feststofffreier Ablauf dar, womit auch beste Voraussetzungen für eine Rückführung gereinigten Abwassers in die Produktion gegeben sind.

Bei der Anwendung des MBR-Verfahrens zur Papierfabriksabwasserreinigung müssen bei der Planung der chem./mech. Vorreinigung und des Bioreaktors die Besonderheiten von produktionsabhängigen charakteristischen Abwasserinhaltsstoffen wie Art und Länge von Fasern, organische und anorganische Anteile sowie übliche produktionsbedingte Belastungsschwankungen beachtet werden. Die Ausführung und der stabile Betrieb des Bioreaktors beeinflussen die Leistung und Betriebssicherheit der Gesamtanlage erheblich.

In der Membranstufe werden großtechnisch getauchte Membransysteme oder klassische horizontale cross-flow Rohrmodule sowie als neue Entwicklung auch vertikale belüftete cross-flow Rohrmodule eingesetzt. Die Ausführung und technischen Merkmale der Systeme werden untersucht und verglichen. Allgemeine Planungshinweise werden genannt. Die Anlagenkosten werden anhand eines Fallbeispiels ermittelt. Als Grundlage der Betrachtung wird ein der mitteleuropäischen Praxis bei der Erzeugung grafischer Massenpapiere hinsichtlich Produktionsmenge, Roh- und Halbstoffeinsatz sowie spezifische Abwassermenge entsprechendes Modellabwasser festgelegt. Für dieses Modellabwasser werden die verschiedenen MBR-Systeme detailliert technisch ausgeführt und die Investitions- und Betriebskosten ermittelt.

Die spezifischen Gesamtbetriebskosten für MBR-Systeme mit getauchten Membranen sowie für belüftete cross-flow Rohrmodule liegen in dem Fallbeispiel bei 0,22 €/m^3. MBR-Systeme mit klassischen cross-flow Rohrmodulen liegen mit 0,33 €/m^3 deutlich höher, was hauptsächlich aus dem deutlich größeren Energieverbrauch resultiert. Die ermittelten spezifischen Gesamtjahreskosten (Kapital- und Betriebskosten) liegen zwischen 0,56 bis 0,59 €/m^3 in einem relativ engen Bereich.

Introduction

The MBR technique is listed as *best available techniques* (BAT) in the reference document (BREF) for waste water treatment in the chemical sector [1]. European projects for minimisation of operation and investment costs using MBR have been started end of 2005 [2]. This demonstrates that this process is a well accepted standard along a wide front. A substantial potential for further development can be expected.

MBR using ultrafiltration (UF) membranes to retain the biomass in an activated sludge tank instead of the secondary clarifier, which usually is a settling tank, has been in use already for several years in municipal sewage treatment and some special industrial fields [3], [4]. Only in the last few years it has been tested in pulp and paper industry [5]. Today only few plants are operated in paper mills [6] but some more had been under construction and have recently been started up. So this really is an emerging new technique for our industry [7].

The advantages of the MBR process – which as a single stage process has to be compared to aerobic two stage processes – are smaller bioreactor volume (due to higher biomass concentrations) and no secondary clarifier due to the membranes retaining the activated biomass. The MBR therefore needs much less area compared to a standard aerobic system. The treated effluent is virtually free of suspended solids. The MBR is predestined for internal water circuit treatment in papermills (kidney systems) and treated waste water reuse [8].

The cost of the system (invest and operation) are higher than for the standard aerobic two stage system suspended carrier reactor plus low load activated sludge treatment. So it will be used only in cases, where the above mentioned advantages justify the higher costs.

Membrane bioreactors (MBR) for industrial applications are designed as an activated sludge bioreactor with an external side stream membrane stage.

The membrane stage either can be equipped with submerged membrane modules or with cross flow tubular modules [9], [10]. The different types of membrane systems have to be examined regarding the physical characteristics and costs in the following analyses. The results shall provide as a help for preliminary decisions to prepare MBR projects in papermills for each individual case.

A new aspect might be the use of ceramic membranes, which is not new at all, but could be more compatible regarding the costs due to new development. This, however, still needs more research and experience.

1 Application of MBR technology for papermill effluent

The MBR is predestined for internal water circuit treatment in papermills (kidney systems) and treated waste water reuse because of the high quality of the filtrate.

Different possibilities for effluent treatment in papermills have to be evaluated.

The waste water in a papermill to be treated with MBR can be

- § a partial flow which is originated in the stock preparation depending on the paper produced,
- § a partial flow of the internal water circuit,
- § a partial flow of the total effluent,

or

- § the total effluent.

The target of the partial flow or partial flow treatment of the internal water circuit treatment before an existing waste water treatment plant (wwtp) with MBR is to reduce load for a downstream wwtp or in the case of the internal water circuit treatment to improve the internal water circuit quality directly by reuse of the produced permeate.

In the case of a partial flow treatment of the total effluent with MBR an existing wwtp can be operated low loaded if the system before was high loaded or overloaded. Additionally a supplementary load in the case of a capacity increase in production can be compensated without a large extension of an existing wwtp (e.g. an additional secondary clarifier) unless much space is not available.

A cost effective further aspect is the separation and use of a part from an existing aeration basin as volume for activated sludge bioreactor within the MBR. Due to the higher sludge concentration the overall load which have to be treated can then be much higher without volume increase. The technical preconditions and especially the hydraulic situation have to be checked and the additional effort has to be determined.

An important fact as already mentioned is the possibilities of the MBR permeate reuse in the production while the total effluent quality and volume can be kept more or less unchanged if the overall performance of the water circuit system including the MBR an the wwtp can be improved. This however depends on where permeate can be reused in the papermill according to the production and type of paper produced.

The requirements according to the German waste water levy for papermills and compliance to achieve (or reduce) supervision values for the final effluent discharge have to be examined for each papermill individually (see note in chapter 3.3). Additionally measures might be required (see comments below).

The total effluent can be treated if a far reaching treatment with minimal amount of area used is required and effluent discharge has to be minimised by reuse. However, if the specific waste water discharge has to be reduced far advanced treatment such as chemical / biochemical oxidation processes (AOP) or in addition nanofiltration or reverse osmosis for (partial) desalination are required [11]. Ultrafiltrated permeate from MBR plants delivers an optimal quality for such advanced treatment processes anyway.

When studying the implementation of MBR with treated effluent water reuse we point out the fact of proving the settling of the costs of investments decreasing the load of a levy parameter of at least 20% with the levy for the 3 years before start of operation of the new measure is particularly rewardingly. A calculation example will be done later on in the case study with a model effluent (see notes in chapter 3.3).

Before any kind of further biological effluent treatment can be installed neutralisation, chemical/mechanical primary treatment (usually sedimentation clarifiers or flotation units) for removal of suspended solids typically below 100 mg/l and cooling below a temperature of 37 °C are required (if temperature is higher than 37 °C, which depends on the type of production and water circuit closure).

It can be assumed for papermills in Western Europe that adequate primary effluent treatment is already installed in existing wwtp which could simplify the installation of MBR. But the effluent quality after an existing primary pretreatment has to be checked first by evaluating the existing operation data and later by pilot tests.

Going into the internal water circuit usually savealls such as disk filters or dissolved air flotation (DAF) for stock recovery are installed. For biological effluent treatment in the internal water circuit an improvement of fibre removal, neutralisation and cooling might be required in addition. If effluent temperature is around 55 °C thermophilic aerobic (or anaerobic) biological treatment [12] instead of cooling might be studied but is not examined here.

The preconditions mentioned above must be applied for MBR treatment as well. An additionally fine screening with mesh sizes typically below 3 mm or below 1 mm (or by implementing a DAF unit) depending on the membrane system has to be installed for protection of the membrane stage to avoid mechanical blocking or spinning effects in addition.

For reuse in paper production a treated effluent quality has to meet certain requirements, which are strongly depending on the type of production. High water quality requirements are needed for high grade printing or several kinds of speciality papers where the specific water consumption cannot be reduced further more without losses in paper quality or an increased quantity of additives (and costs).

For these paper grades specific water consumption above 8 – 12 m^3/t or for speciality papers even higher can be expected [13]. Due to the raw materials and flow conditions no (or only less and controllable) scaling especially coming from the precipitation as calcium carbonate ($CaCO_3$, lime) in MBR treatment is expected (the calcium concentration in waste water is assumed to be below 200 mg/l in these cases).

The application of MBR for paper production with lower quality grades and more closed water circuits with a specific water consumption below 8 m^3/t whereas a calcium concentration continuously above 400 mg/l with an increased risk of lime precipitation after the bioreactor might be expected is not examined here.

However, the risk of scaling with lime on membranes according to the remaining calcium concentration after the bioreactor respectively to the remaining lime precipitation potential due to pH displacement from carbon dioxide stripping and the requirements for counteractive measures such as acid dosing or other possibilities has to be tested carefully in pilot trials. All possibilities for a reduction of the calcium level by optimisation of the water circuits have to be evaluated.

If the implementation of an MBR in papermill effluent with a risk lime precipitation is required the technical solutions for an additional lime removal stage have to be tested within the pilot trials under representative conditions. This might lead to other technical solutions in the biostage treatment as well as in the membrane operation. The overall economics must be evaluated seriously before a decision for a large scale plant is made.

General remarks on effluent quality for reuse in papermills:

Generally the reused effluent should have a low concentration of suspended solids, BOD and – more or less, depending of the production – COD. Colour might be a quality parameter for white papers, but certainly only when a high percentage of the fresh water shall be substituted by treated effluent.

In any case the treated effluent must not contain any remarkable concentration of iron.

Microorganism contamination shall be low, but the effluent does not have to be sterile.

Regarding these requirements, treated effluent quality of the different treatment systems usually used for papermill effluent treatment can be evaluated as follows [8]:

The standard system high load first stage (either anaerobic or aerobic) plus low loaded activated sludge treatment generally delivers a treated effluent containing a concentration of suspended solids SS below about 30 mg/l (in case of bad settling in the secondary clarifier much more), a rather low BOD concentration and a COD concentration depending on the biodegradability of the wastewater (between about 100 and 500 mg/l). The colour is often brown, except for paper production using only BCP as fibre stock, generally with a higher intensity than the untreated effluent. Microbiological contamination is not a problem for recycling rates up to about 50 %.

The effluent can be improved for reuse by a sand filter (or even better tertiary biofilter) following the secondary clarifier. However, when settling is very bad (bulking sludge), the filter will be not operable and the reuse has to be stopped.

The secondary biofilter is a good option for reuse of the water. In cases when this system is operable the organic concentrations are low anyway. The suspended solids concentration after the filter is low, but some abrasive broke of the carrier material (generally expanded clay granules) will be in the treated water. The colour will be more intense than before treatment, but effluents which can be treated with biofilter have a bright colour anyway. The microbiological contamination will be in the same range than with activated sludge plant.

In terms of suspended solids and microbiological contamination the MBR treated effluent has the best quality for reuse in the production. Suspended solids are normally below 3 mg/l, BOD at detection limit.

Regarding colour, COD and some other parameters like complexing agents the runoff of an advanced oxidation process (ozonation plus biofilter) has the best quality for reuse. However, suspended solids and microorganisms are determined by the final step, which is the biofilter.

2 Technical MBR systems

2.1 Common remarks for design of MBR

Membrane bioreactors (MBR) for industrial applications are designed as an activated sludge bioreactor with an external side stream membrane stage.

As mentioned above an additionally fine screening with mesh sizes typically below 3 mm or below 1 mm (or by implementing a DAF unit) depending on the membrane system has to be installed for protection of the membrane stage to avoid mechanical blocking or spinning effects in addition.

Biomass is recirculated via the membrane stage and the bioreactor while permeate is separated through the membrane. Depending on the pore size and membrane material high molecular dissolved organic compounds (> 0,05 µm) are hold back and might be further biodegraded, if possible, due to the higher sludge age. Due to higher activated sludge concentration and the higher sludge age a further biodegradation of persistent organic compounds might be expected. This however has to be verified in large scale plants with papermill effluent.

The choice of the activated sludge concentration (MLSS) depends not on the design of a secondary clarifier as in a classical activated sludge system but is influenced by different parameters and should be optimised.

One impact is the increase of the viscosity with an increased MLSS concentration and the influence on aeration, mixing and mass transfer by diffusion [14], [15]. It is observed that the coefficient for oxygen mass transfer for clean water and waste water (α-value) decreases strongly with an increase of the MLSS in the aeration basin [16], [17] which leads at the same time to a higher process air demand and a higher energy consumption for aeration.

Our recommendation for MLSS design according to the available information is a moderate mixed liquor concentration of 10 – 12 g/l with a α-value of 0.6 for calculation of the oxygen requirement in the bioreactor. However, the results come from tests with municipal wastewater and have to be verified with papermill effluent.

The specific sludge loading in the activated sludge bioreactor related to biomass, also called F/M-ratio for BOD $B_{x,\ BOD}$ is recommended in the range of 0.08 – 0.12 kg/kgd which is conservative in relation to the design values usually used in conventional activated sludge systems. An optimal BOD removal efficiency (BOD effluent < 5 mg/l) is required to minimise the fouling potential on the membranes and to ensure optimal filterability of the mixed liquor.

The design of the aeration basin as a cascade or plug-flow reactor can improve the biodegradation efficiency according to the opinion of some specialists. This however has to be verified in plot tests and in large scale plants for papermill effluent. An adequate design of the aeration basin is from minor importance in terms of investment cost. It seems therefore to be reasonable to design the aeration basin accordingly.

It is important to install enough aeration capacity in the first cascade (s) to avoid an oxygen deficit and minimise the risk (of a massive growth) of filamentous microorganism (bulking sludge) which might affect the operation of the membrane stage. This has to be mentioned because of the higher sludge content and high oxygen consumption compared to classical activated sludge systems. More analyses about the influence of the sludge volume index (SVI) in the membrane stage treating papermill effluent have to be investigated.

The aeration basin (and membrane containers in the case of submerged membranes) should be fit with spray water system for foam control. However, defoamer should only be used when required to avoid costs and the risk of an accumulation of substances which might affect the membranes. In addition the possibility of installing a skim device on the aeration surface for the evacuation of foam out of the system can be proved if the effluent tends to have massive foam development and the foam control requires too much defoamer chemicals.

As previously mentioned a cooling stage before waste water treatment is expected to be existing (when required) when wwtp are already in operation. However, the energy input by pumps, aeration etc. through the intensive cross flow operation and recirculation in MBR have to be considered for cooling capacity in large scale projects. The temperature in the aeration basin shall not exceed 37 °C for mesophilic operation.

2.2 Technical MBR systems

Depending on the type of membrane system, the membrane filtration is either performed as outside-in or inside-out side-stream membrane filtration, as schematically shown in **figure 1**.

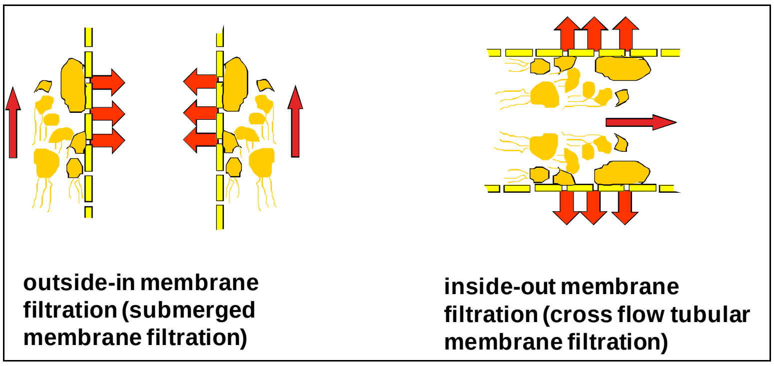

Figure 1: principles for membrane filtration

The required high turbulent flow parallel among the membrane surface for scaling and fouling control has either to be achieved by an intensive aeration using submerged modules (outside-in filtration) or by a more or less high flow velocity depending on the operation mode using cross flow tubular modules.

Different MBR systems have to be evaluated:

- MBR with submerged membrane modules with flat plate or hollow fibre membranes (type outside-in filtration), pore size < 0.1 µm (ultrafiltration UF) up to 0.4 µm (micro-filtration MF)
- MBR with classical cross flow (horizontal) tubular or aerated (vertical) cross flow tubular membrane systems (type inside-out), pore size < 0.1 µm (UF)

The technical MBR concepts are shown in the schematic flow sheets in **figure 2, 3** and **4**.

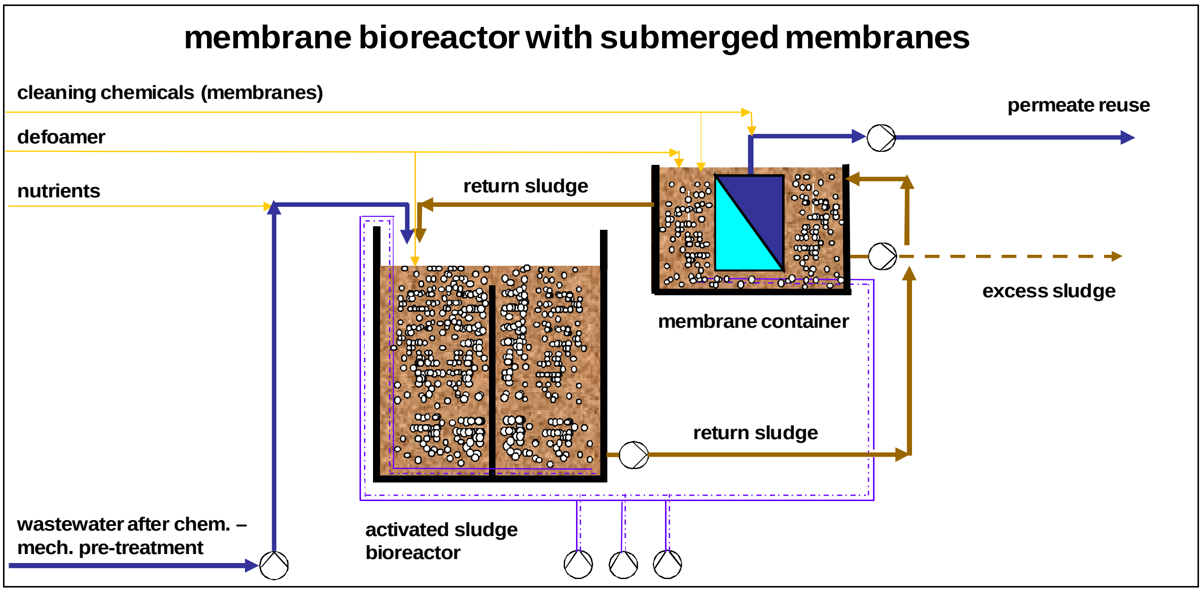

Figure 2: schematic flow sheet MBR with submerged membranes

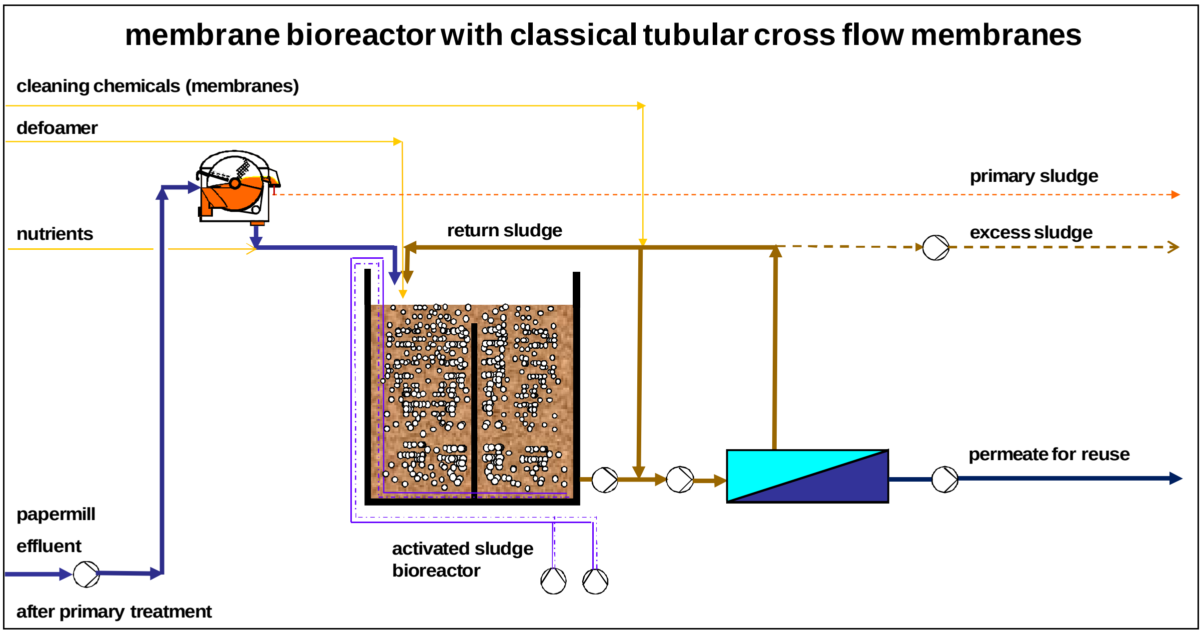

Figure 3: schematic flow sheet MBR with cross flow tubular membranes

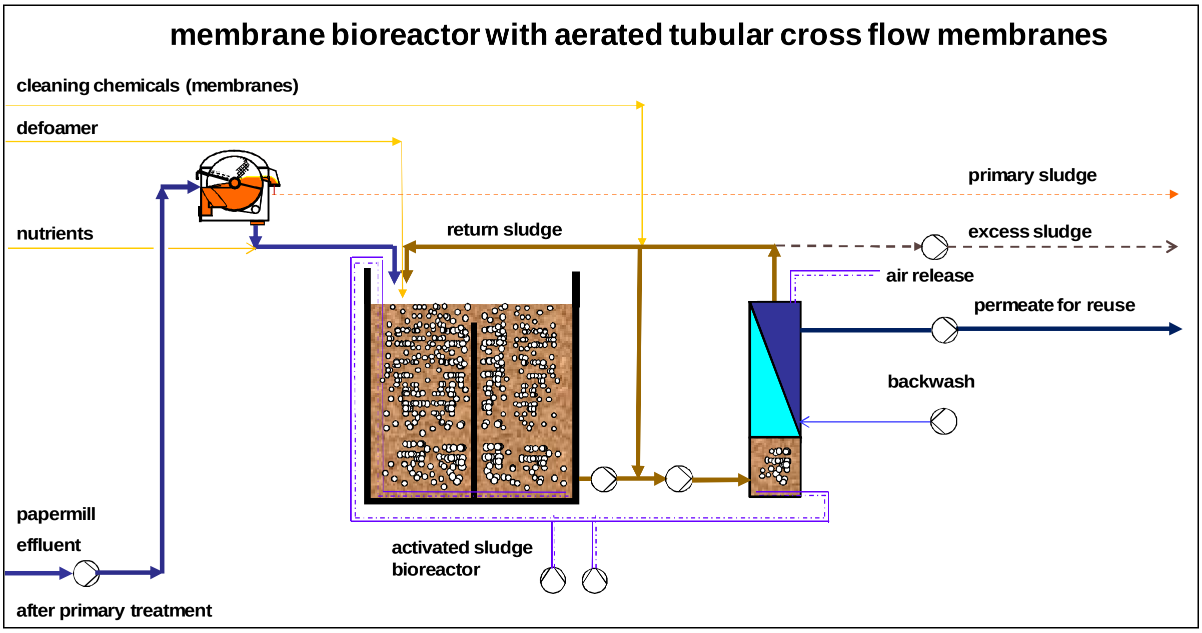

Figure 4: schematic flow sheet MBR with aerated cross flow tubular membranes

An excerpt of basic figures for the different MBR systems is shown in **table 1**.

Table 1: Basic figures of MBR systems

Basic figures (typical) of different MBR systems for industrial waste water treatment								
MBR systems, side stream external		**submerged membranes**				**cross flow tubular membranes**		
		flat plate		**hollow fibre**		**cross flow**	**low energy**	**aerated**
Examples of engineering and manufactures companies		A	B	C	D	E	F	G
pretreatment								
risk of blocking	-	lower	lower	higher	higher	higher	higher	higher
additional pretreatment (drum screen, DAF)	mm	**< 3**	**< 3**	**< 1**	**< 1**	**< 1**	**< 1**	**< 1**
activated sludge system								
sludge conc. MLSS	g/l	**10 - 15**	**12 - 18**	**10 - 15**	**10 - 15**	**10 - 25**	**10 - 15**	**10 - 15**
sludge load Bx	kg/kgd	**0.08 - 0.12**						
membrane system								
pore size	µm	**< 0.1 (UF)**	**0.4 (MF)**	**< 0.1 (UF)**	**0.4 (MF)**	**< 0.1 (UF)**	**< 0.1 (UF)**	**< 0.1 (UF)**
membrane material	-	PES	CPE	PVDF	PE, PVDF	PES, PVDF	PES, PVDF	PES, PVDF
membrane structure	-	asym./comp.	asym./comp.	asymmetric	symmetric	asymmetric	asymmetric	asymmetric
pH resistance	-	1 - 14	1 - 14	2 - 11	2 - 11	2 - 10	2 - 10	2 - 10
temperature resistance	°C	94	no info	no info	0 - 40	60	60	60
installation	-	vertical	vertical	vertical	horizontal	horizontal	horizontal	vertical
plate diameter/plate distance/diameter	mm	6 / 6 / -	6 / ? / -	-	-	-/-/5 or 8	-/-/5 or 8	-/-/8 or 10
largest module size	m^2	720	580	2,618.000	500	53	53	53
module dimension l*b*h (or diameter*l)	m	3.3*0.75*3.0	3.1*0.65*4.3	1.9*1.8*2.3	1.6*1.4*3.1	(0.25*4)	(0.25*4)	(0.25*4)
packing density	m^2/m^3	**97**	**67**	**333**	**72**	**270**	**270**	**270**
membrane per footprint required	m^2/m^2	**206**	no info	**197**	no info	**92**	**107**	**135**
footprint membrane stage (absolute net) A,C = 100 %	%	**100**	no info	**100**	no info	**40**		**60**
typ. transmembrane pressure (max)	bar	**<0.05 (0.3)**	**0.05 (0.3)**	**0.15 (0.55)**	**0.4**	**2 - 6**	**0.1 - 1.0**	**0.1 - 0.5**
cross flow velocity	m/s	air	air	air	air	3.5-4.5	1.0-2.0	0.5-1.0 + air
flux (net)	l/m^2h	**10 - 30**	**10 - 30**	**5 - 20**	**5 - 20**	**60 - 120**	**45 - 60**	**30 - 55**
spec. air circulation quantity	Nm^3/m^2h	**0.29 - 0.5**	**0.5 - 0.75**	**0.21 - 0.42**	**0.25**	**-**	**-**	**0.01**
type of aeration for membranes	.	planar, middle bubb.	planar, coarse bubb.	line, coarse bubb.	line, coarse bubb.	-	-	no info
spec. energy consumption	kWh/m^3	**0.35 - 0.60**		**0.45 - 0.65**		**2.2 - 7.0**	**0.4 - 1.7**	**0,4 - 1,0**
backwash frequency	min	-	-	-	no info	no info	5 - 60	5 - 60
backwash time	sec	-	-	-	no info	no info	5 - 15	10 - 45
maintenance cleaning (cip)	no./a	-	-	52	52	on demand	on demand	6 - 24
recovery cleaning (in situ)	no./a	**1 - 3**	**1 - 3**	**2 - 4**	**2 - 4**			
membrane lifetime	a	**7 - 10**		**5 - 7**		**5 - 7**	**5 - 7**	**5 - 7**
PES = Polyehtersulfon	CPE = Chlorinated Polyethylene			PA = Polyamide				
PVDF = Polyvinylidenfluorid	PS = Polysulfon			PVC = Polyvinylchloride				
A, B: Hager + Elsässer GmbH, MARTIN Systems AG; MICRODYN-NADIR GmbH; Eimco Water Technologies Oy, Kubota Membrane Europe;								
C, D: Aquantis GmbH, Zenon GmbH, PURON AG; Siemens AG, Memcor; Mitsubishi Rayon								
E, F, G: WEHRLE Umwelt GmbH; Berghof Filtrations- und Anlagentechnik GmbH & Co KG; Norit X-Flow BV; Triqua BV								

As shown in table 1 the hard factors for the different membrane systems such as flux, spec. energy consumption, membrane cleaning and lifetime etc. given from suppliers are varying in quite big range not suitable for a technical/economical comparison.

Soft factors such as risk of blocking, ongoing maintenance or operational interruptions etc. have to be evaluated carefully considering the results of pilot tests and experiences from reference plants.

Before starting a project a concept comparison including proposals with well defined pre-conditions for cost evaluations is recommended.

The results of a risk analyses which we recommend for each individual case will provide the decision basis for the concept of the first choice to be tested in pilot trials [18]. A pilot test program with well defined test periods is the basis to achieve representative results for a secure design of a large scale plant.

A case study for a model papermill effluent is shown in chapter 3.

2.3 Execution examples for MBR

The following execution samples for MBR systems with submerged membranes or classical cross flow tubular membranes shown in **figure 5 – 8** are from engineering companies and manufacturers with actual MBR references from large scale applications or pilot tests with papermill effluent or applications with industrial waste water. The example in **figure 9** shows a large scale MBR with aerated tubular cross flow membranes applied for municipal waste water treatment which are not yet tested for pulp and paper effluent yet as far as we know.

The sample collection of the different membrane systems is for information only and doesn't claim to be complete.

Figure 5: MBR with flat plate submerged modules (origin: Hager + Elsässer GmbH, MARTIN Systems AG)

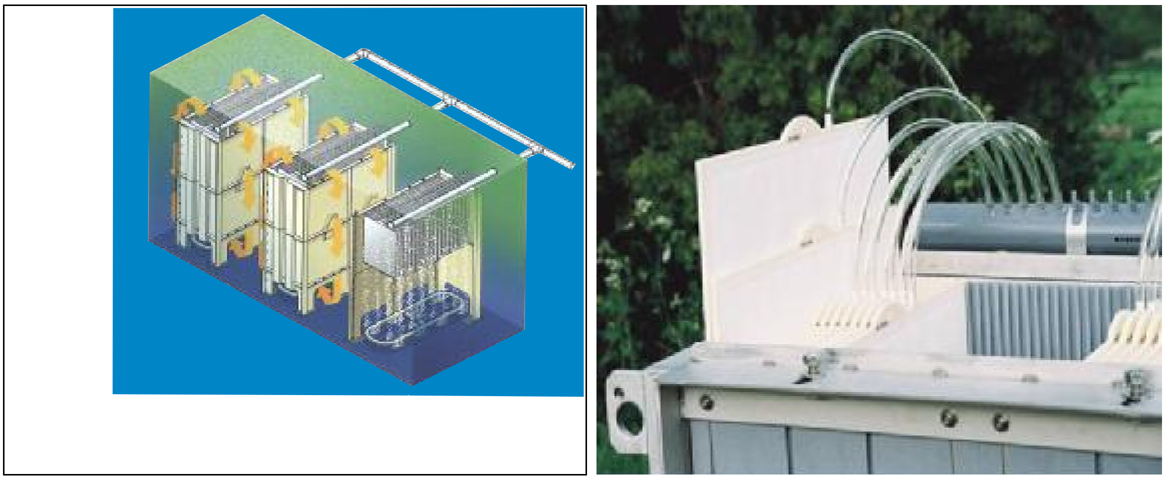

Figure 6: MBR with flat plate submerged modules (origin: Eimco Water Technologies Oy, Kubota Membrane Europe)

Figure 7: MBR with hollow fibre submerged modules (origin: Aquantis GmbH, Zenon GmbH, PURON AG)

Figure 8: MBR with horizontal cross flow tubular membranes (origin: Berghof Filtrations- und Anlagentechnik GmbH & Co KG)

Figure 9: vertical aerated cross flow tubular membranes (origin: Norit X-Flow BV, WEHRLE Umwelt GmbH)

3 Case study

In order to determine a cost comparison for the different MBR systems and to evaluate the differences of some main hard and soft factors for the concepts as previously mentioned, we designed a partial flow treatment separated from the total papermill effluent after primary treatment.

The basic design data for the MBR concepts are shown below.

3.1 Production model and design data

The model is a papermill effluent from a production of wood containing printing paper according to the data in **table 2**.

Table 2: Production model

Model: production of wood containing printing paper		
		capacity
production t/d		1,200
pulp (parts in %)		
	DIP	30
	SGW	60
	BCP	10
COD specif.	kg/t	18
Q specif.	m^3/t	16
BOD/COD		0.44

Abbreviations: DIP = deinked pulp, SGW = stone ground wood, BCP = bleached chemical pulp, mv = arithmetical mean value, max = maximum (expected), mv+s = 80^{th} percentile.

The basic effluent design data for the partial flow treatment of the total flow are shown in **table 3**.

Table 3: Basic design data partial flow treatment

Case study: basic design data partial flow treatment			
		total flow	**design MBR *)**
total flow	%	100	
partial flow for treatment	%		**25**
c_{COD} mv.	mg/l	1,100	**1,100**
c_{BOD} mv.	mg/l	480	**480**
Q_d, mv	m^3/d	19,200	**4800**
Q_h, max.	m^3h	1,040	**200**
$B_{d,COD}$ mv+s	kg/d	28,080	**7,020**
$B_{d,BOD}$ mv+s	kg/d	12,355	**3,089**
sS mv.	mg/l	150	**150**
Ca mv.	mg/l	100	**100**
SO_4 mv.	mg/l	250	**250**
temperature	°C	35	**35**
pH		6 - 9	**6 - 9**
*) production of wood containing printing paper (for instance SC-A)			
design data after primary treatment and cooling based on Qh, max buffered; loads as mv+s = 80th percentile			

The partial flow from the stock production (DIP+SGW) which could be treated directly as well usually includes most of the total load but also amounts up to 80 – 90 % of the total flow. A separation and a partial flow treatment of this part would therefore bring no big advantages if the flow is high and an additional pretreatment would be required in this model case. This might be different if a Greenfield papermill when an optimised water circuit system and a new effluent treatment concept can be considered.

The partial flow of the total effluent after primary treatment to be treated with MBR amounts to 25 % of the total effluent flow in the case study. We have assumed that permeate of the MBR will be totally reused.

The specific waste water consumption in this case study with this model paper production will be reduced from **16 m^3/t** down to **12 m^3/t**.

The expected treated effluent quality of permeate is shown in **table 4**.

Table 4: permeate quality MBR

Case study: treated effluent quality after MBR		
(expected average values)		
η COD	%	88 *
η BOD	%	99
c_{COD}	mg/l	130 *
c_{BOD}	mg/l	< 5
sS	mg/l	< 5
turbidity	NTU	< 1 **
η AOX	%	**
bacteria, viruses	%	**
* calculation according to: C.H. MÖBIUS, waste water of pulp and paper industry, Version 3.08; origin: http://www.cm-consult.de		
** removal effieciency and remaining concentrations have to be determined in pilot tests		

3.2 Waste water discharge tax for model effluent

The German wastewater levy for papermills offers the opportunity to minimize the charge when the effluent load is lower than the regulation requires [19]. The settling of the costs of investments decreasing the load of a levy parameter of at least 20% with the levy for the 3 years before start of operation of the new measure is possible.

The proof of the reduction to be reached can be provided either in a partial flow or in the total flow. However, the demands to the method for proof are different in the federal states and have to be determined for each case.

The possibilities of use of settling investment costs by implementing MBR technology with permeate reuse should be evaluated.

The opportunities for indirect dischargers using MBR technology as biological pretreatment for reduction of waste water load (and therefore costs) before discharge into a municipal waste water treatment plant are mentioned here only briefly.

The exemplary calculation of the yearly discharge tax and the reduced discharge tax if the supervision value for COD is declared lower is shown in **table 5** (see also note below table 5).

Table 5: calculation of discharge tax

Exemplary calculation of the expected discharge tax for the respectation of minimum standards (German law) according to the case study		
relevant parameters after treatment	annual discharge tax	annual discharge tax reduced
yearly flow Q_y m^3/y	6,912,000	6,912,000
c COD mg/l, ÜW	190	152
c AOX mg/l, ÜW	0.625	0.625
c P mg/l, ÜW	1	1
c N mg/l, ÜW	7	7
discharge tax € / year	**584,547**	**490,541**
discharge tax for € / 3 years [1)]	**1,740,000**	
difference for the reduced annual discharge tax to the regular discharge tax [1)]		**90,000**

note [1)]: we strongly recommend to consider the different demands to the method for proof depending on the individual federal state in Germany. If possible a reduction of existing legal supervision value for COD should be avoided if another levy parameter is taken for method of proof. The use of a partial flow treatment for proof of the required reduction might be helpful. The calculation assuming the settlement of the discharge tax by COD and by declaring a reduced COD supervision value of 20 % is only exemplary and valid for certain German federal states. The levy parameter to be reduced has not to be COD. However, if another levy parameter is taken for method of proof, the supervision value for COD reduced by 20 % (or more or less) can be declared for a reduced waste water discharge tax.

3.3 Technical Data

The following MBR systems according table 1 are examined (all membrane systems UF pore size < 0.1 µm):

§ MBR with flat plate membrane modules

§ MBR with hollow fibre membrane modules

§ MBR with classical cross flow tubular modules

§ MBR with aerated cross flow tubular modules

MBR with cross flow tubular modules which can be operated in a low energy mode are in terms of membrane surface, operation and investment costs between classical cross flow tubular and aerated cross flow tubular systems and are therefore not examined here [9]. For project studies this system can be considered as well.

The main design data for the examined different MBR systems are shown in **table 6**.

Table 6: design data

Case study - main design data of different MBR systems for treatment of papermill effluent					
		submerged membrane		tubular membrane module	
		flat plate	hollow fibre	tubular cross flow	tubular aerated
	(design data based on $Q_{h,\ max}$ buffered, loads as mv+s = 80th				
activated sludge system					
MLSS	g/l	10.5	10.5	10.5	10.5
$B_{x,\ BOD}$	kg/kgd	0.12	0.12	0.12	0.12
fine screening	mm	-	< 1	< 1	< 1
V aeration basin (h 8m)	m^3	2,303	2,231	2,451	2,451
V membrane container external	m^3	148	221	-	-
flux	l/m^2h	15	11	80	40
A membrane (all UF pore size)	m^2	12,960	18,000	2,500	5,000
spec. excess sludge related to BOD el.	kg/kg	0.5	0.5	0.5	0.5
excess sludge	kg/d	1,544	1,544	1,544	1,544

note: The limit for design is from pumping station to the bioreactor to outlet after permeate pump is used. We have assumed that the biological excess sludge of the MBR will be dewatered together with the primary sludge in existing installations. Sludge dewatering equipment is not considered in this case study.

Additional fine screening (drum screen or adequate) for MBR with hollow fibre membranes and tubular cross flow membranes is foreseen for protection of the membrane modules.

The design for the activated sludge bioreactor is considered to be the same for each type of membrane system in order to have enough security capacity for typical production related fluctuations in papermill effluent (B_x 0.12 kg/kgd, MLSS 10.5 g/).

The flux of the membrane stage is according to our experience and in coordination with engineering companies and manufacturers which haven been involved for design and cost calculation for the MBR system in this case study.

3.4 Cost estimates

Table 7 gives the energy, chemicals consumption, membrane spare and the resulting operation costs on the evaluated average basis according to table 3 (specific chemical costs according typical German values).

Table 7: operation costs

Case study- operation costs of different MBR systems for treatment of papermill effluent					
		submerged membrane		**tubular membrane module**	
		flat plate	**hollow fibre**	**tubular cross flow**	**tubular aerated**
(consumption data based on average values (mv, v 30 %); hydraulic Q_d/24; 350 working days per year, 6 ct/kWh)					
activated sludge bioreactor (biostage)					
energy consumption biostage	kWh/h	179	179	179	179
energy consumption biostage	kWh/a	1,505,000	1,505,000	1,505,000	1,505,000
spec. energy consumption biostage	kWh/m^3	0.90	0.90	0.90	0.90
energy consumption biostage	€/a	90,300	90,300	90,300	90,300
spec. energy consumption biostage	**€/m^3**	**0.054**	**0.054**	**0.054**	**0.054**
membrane stage					
energy consumption membrane stage	kWh/h	81	100	480	140
energy consumption membrane stage	kWh/a	680,574	840,000	4,032,000	1,176,000
spec. energy consumption membrane stage	kWh/m^3	0.41	0.50	2.40	0.70
energy consumption membrane stage	€/a	40,834	50,400	241,920	70,560
spec. energy consumption membrane stage	**€/m^3**	**0.024**	**0.030**	**0.144**	**0.042**
energy consumption total	kWh/h	260	279	659	319
energy consumption total	kWh/a	2,185,574	2,345,000	5,537,000	2,681,000
energy costs MBR total	€/a	131,134	140,700	332,220	160,860
spec. energy costs MBR total	kWh/m^3	1.30	1.40	3.30	1.60
spec. energy costs MBR total	**€/m^3**	**0.078**	**0.084**	**0.198**	**0.096**
membrane replacement					
estimated membrane lifetime	a	7	7	5	7
membrane spare cost	€/a	138,858	128,573	65,000	85,714
spec. membrane spare cost	**€/m^3**	**0.083**	**0.077**	**0.039**	**0.051**
nutrients and chemicals					
nutrients total (urea 100 %, H_3PO_4 80 %)	€/a	15,148	15,148	15,148	15,148
defoamer	€/a	5,040	5,040	5,040	5,040
spec. nutrients and defoamer costs	**€/m^3**	**0.012**	**0.012**	**0.012**	**0.012**
membrane cleaning chemicals					
no of recovery cleaning (in situ)	no/a	3	3		
recovery + maintenance (cip) cleaning	€/a	4,768	17,070	50,400	36,960
spec. membrane cleaning chemicals	**€/m^3**	**0.003**	**0.010**	**0.030**	**0.022**
operation costs total	**€/a**	**294,948**	**306,530**	**467,808**	**303,722**
spec. operation costs total	**€/m^3**	**0.18**	**0.18**	**0.28**	**0.18**

note to table 7: as mentioned above the design of the activated sludge bioreactor and as a consequence the related operation costs are the assumed to be the same for each MBR system.

The differences in the relevant operation costs of each MBR system are illustrated in **diagram 1**.

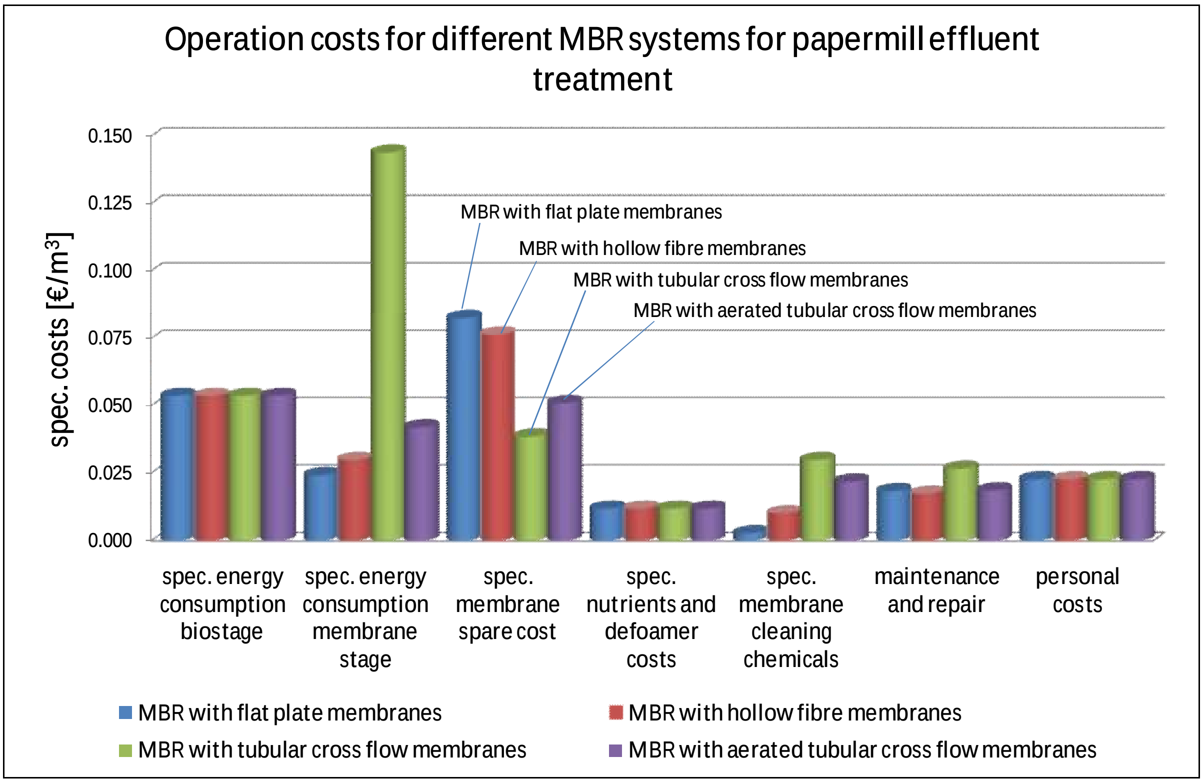

Diagram 1: operation costs of different MBR systems

The estimation of investment costs and calculation of total operation costs and annual costs is shown in **table 8**.

Table 8: total operation and yearly costs

Case study - Annual charges of the different MBR systems for treatment of papermill effluent					
		submerged membrane		tubular membrane module	
		flat plate	hollow fibre	tubular cross flow	tubular aerated
activated sludge stage (machinery equipment + electrical&pcs equipment)					
activated sludge system	€	770,000	770,000	770,000	770,000
membrane stage (machinery equipment + electrical&pcs equipment)					
membrane stage	€	2,730,000	2,530,000	1,730,000	2,530,000
civil work aeration basin, operation building	€	1,000,000	1,000,000	950,000	950,000
investment costs MBR total	**€**	**4,500,000**	**4,300,000**	**3,450,000**	**4,250,000**
annuity factor for machinery equipment + el.&pcs equipment (depreciation period 10 a)				0.14	
annuity factor for civil work (depreciation period 20 a)				0.09	
capital costs total	**€/a**	**592,714**	**564,239**	**445,617**	**559,519**
total energy, chemical, membrane spare costs	€/a	294,948	306,530	467,808	303,722
maintenance and repair	€/a	31,000	29,400	44,850	31,410
personal costs (man days p.a. 175)	€/a	38,356	38,356	38,356	38,356
operation costs total	**€/a**	**364,304**	**374,287**	**551,014**	**373,488**
yearly costs total	**€/a**	**957,019**	**938,525**	**996,631**	**933,007**
specific operation costs total per m^3	€/m^3	0.22	0.22	0.33	0.22
specific capital costs total per m^3	€/m^3	0.35	0.34	0.27	0.33
specific yearly waste water costs per m^3 total	**€/m^3**	**0.57**	**0.56**	**0.59**	**0.56**
discharge tax for 3 years	**€/3a**	**-1,740,000**	**-1,740,000**	**-1,740,000**	**-1,740,000**
part of total investment or capital costs	%	39	40	50	41
annual discharge tax reduced	**€/a**	**-90,000**	**-90,000**	**-90,000**	**-90,000**
part of total operation costs	%	25	24	16	24

note to table 8: The investment costs are set on a turn key basis including the main machinery equipment, control cabinets, PLC/PLS equipment and civil work (standard grounding). Primary treatment, cooling and sludge dewatering equipment are not considered, as mentioned already above and accordingly to the design in table 3.

As additionally shown in table 8 the discharge tax for 3 years as calculated in table 3 can compensate 39 % to 50 % of the total investment or capital costs depending on the MBR system if the use of settling investment costs by implementing MBR technology with permeate reuse is applicable.

The total operation costs are reduced by some 16 % to 25 % if a reduced COD supervision value of 20 % and a reduced discharge tax is applied (please consider the conditions mentioned in chapter 3.2).

The differences in total operation and capital costs as well as annual costs for each MBR system are illustrated in **diagram 2**.

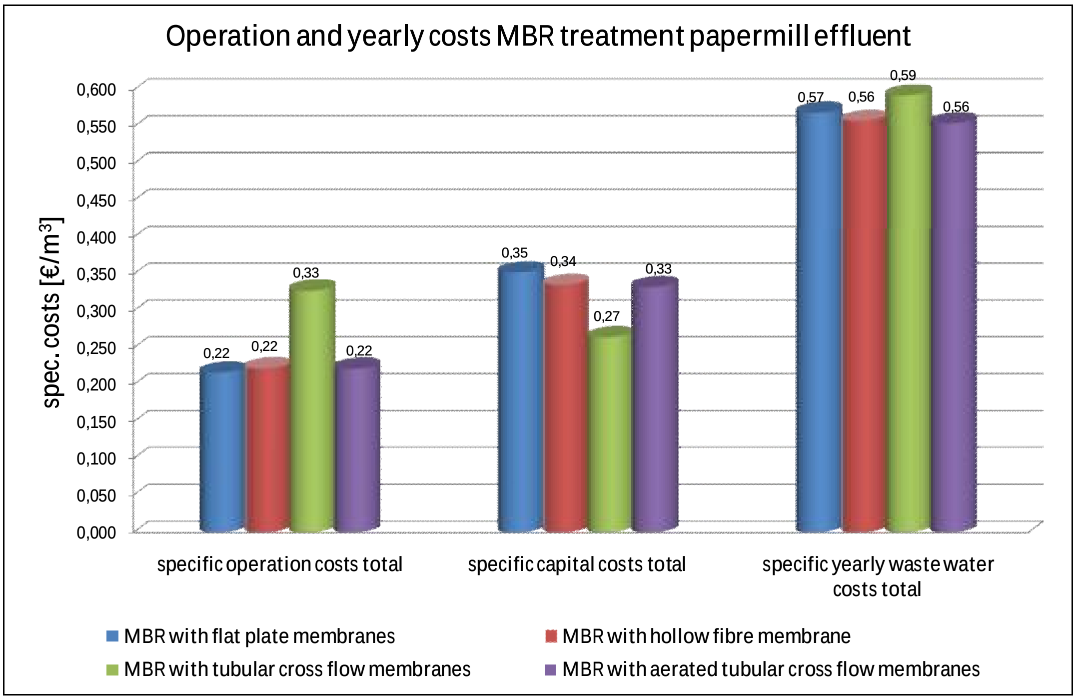

Diagram 2: annual costs of different MBR systems

Conclusions

The MBR is predestined for internal water circuit treatment in papermills (kidney systems) and treated waste water reuse.

In the case study for a papermill with a wood containing printing paper production and with a partial flow treatment of 25 % of the total flow by MBR and reuse of the permeate the specific waste water consumption will be reduced from 16 m^3/t down to 12 m^3/t accordingly.

By implementing an MBR system either an existing wwtp can be operated low loaded if the system before was higher loaded while an optimal biodegradation efficiency was not achieved or a supplementary load in the case of a capacity increase in production can be compensated without a large extension of an existing wwtp (e.g. an additional secondary clarifier) unless much space is not available. The improved performance in the wwtp and reuse of permeate will reduce the COD discharge as well.

Precondition for a reliable MBR operation is low loaded activated sludge reactor and a moderate mixed liquor concentration to ensure an optimal removal of biodegradable organic substances to minimise membrane fouling with special regard of typical fluctuations in a papermill.

The primary treatment of MBR systems has to be optimised in general to avoid high or peak loads of suspended solids especially fibre losses which might overload the primary clarification and increase the blocking risk in the membrane stage. Additional requirements to the particle size besides the concentration of suspended solids requires a fine screening for hollow fibre and tubular cross flow membrane systems used as a kind of police filter to protect the membrane stage from mechanical blocking.

The preliminary evaluation of the operation and investment costs in the case study with papermill effluent under well defined boundary conditions demonstrates the differences between the MBR concepts, respectively the membrane systems because the activated sludge bioreactor is dimensioned more or less identical in construction.

MBR systems with submerged membranes result in higher investment costs and higher costs for membrane spare, but in lower operation costs for energy and chemical cleaning compared to cross flow tubular systems.

The total specific operation costs for MBR with submerged membranes and with aerated tubular cross flow membranes amount to 0.22 €/m^3. MBR with tubular cross flow membranes amount to 0.33 €/m^3 mainly due to fact of the higher energy cost.

However, the calculated specific total annual costs (capital + operation costs) are in a narrow range (0.56 €/m^3 to 0.59 €/m^3).

The wastewater levy can help financing an MBR. In the case study approx. 39 % to 50 % of the total investment was compensated when settling of the costs of investments decreasing the load of a levy parameter of at least 20% with the levy for the 3 years before start of operation of the new measure is applicable.

But all depends on the reliability in practice which first of all has to be tested in representative pilot trials to ensure the basic design and operation costs for energy and chemical cleaning and membrane life time (as far as criteria can already be seen in the pilot tests). Soft factors such as risk of blocking, ongoing maintenance or operational interruptions etc. considering the results of pilot tests and experiences from reference plants besides cost estimations should be evaluated in a risk analyses in addition to localise the concept of choice already before starting the pilot tests.

This can only be determined case by case evaluating all technical aspects of the membrane system to be used and the characteristics of each papermill effluent.

The MBR is still more expensive than other classical biological systems. However, both the operational experience for application in papermill effluent treatment especially the life time of membranes which might be increased and the development of less expensive membrane materials will develop the application of MBR technology for treatment of papermill effluent.

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