

## Ten persistent myths and the realities of membrane bioreactor technology for municipal applications

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### ABSTRACT

Twelve years after the first full scale municipal application in Europe of membrane bioreactor (MBR) technology, the process is now accepted as a technology of choice for wastewater treatment, and the market is showing sustained growth. However early misconceptions about the technology are persistent and false statements are commonly encountered in articles and conferences, generating unnecessary research efforts or even fuelling either fascination or scepticism with regards to the technology, which is ultimately detrimental to the perception of the process by water professionals. We try to provide some factual and rational clarifications on ten issues which are often wrongly reported about MBR technology.

**Key words** | Europe, market, membrane bioreactor technology, municipal wastewater treatment

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### INTRODUCTION

In 2009, the MBR community celebrated the 20<sup>th</sup> anniversary of the invention of Prof. Yamamoto (the concept of “low pressure / submerged filtration systems”), which has accelerated the implementation of the membrane activated sludge process to treat municipal or industrial wastewater. The technology is now mature and widely applied in different regions of the world. In Europe, more than 800 commercial MBR units were in operation by the end of 2008, among which 37 MBR plants had a capacity greater than 5,000 m<sup>3</sup>/d (Lesjean *et al.* 2008 & Huisjes *et al.* 2009). Within a decade, the constructed systems increased in size from only few thousands of people equivalent (p.e.) up to large plants serving more than 100,000 p.e., demonstrating that MBR has become a technology of choice also in large wastewater treatment schemes.

The high pace of the development and implementation of this technology was unfortunately accompanied by misconceptions, initially generated false hopes about the potential of the technology, and very often fuelled by slow or contradictory results of basic R&D and by commercial arguments from the

system vendors. This article, based on the findings of the coalition of European projects “MBR-Network” ([www.mbr-network.eu](http://www.mbr-network.eu)), and backed up with information available in public literature together with our experience on the design and operation of MBR systems, intends to review some key aspects of the MBR technology and to present and discuss the facts in order to highlight the most obvious myths about the technology and to better address the realities. In order to avoid specific discussions of industrial applications, we decided to focus our analysis on the municipal market.

### TEN PERSISTENT MYTHS AND REALITIES

Table 1 presents ten common myths or misconceptions that are still encountered in publications and discussions. For each issue, the usual statement is provided as well as the key facts according to the state of knowledge. Each subject is then further discussed in details in the following sections.

**Table 1** | Synthesis of the ten persistent myths and corresponding reality

Subject	The usual statement	The facts
<b>Market and economics</b>		
1. MBR market	The MBR market is an industrial duopoly.	The two pioneering companies Kubota and GE-Zenon are leaders but other commercial systems are available and increased competition is expected in coming years.
2. Filtration flux	The technology has become more competitive following increasing design and operation flux.	In the last decade, the design and operation filtration flux has increased only moderately. MBR technology has become more competitive due to reduced module price with longer warranty, increased energy efficiency and improved design and operation practices.
3. Energy demand	Specific energy demand of an MBR system is < 1 kWh/m <sup>3</sup> .	True for larger plants operated under nominal design with optimised operation. Not yet true for smaller plants, particularly when operated under low hydraulic load.
4. Competitiveness	The MBR technology will extensively replace conventional activated sludge plants.	Extensive switch unlikely unless further significant technological breakthroughs. For municipal applications, the core market segment will remain medium-size plants (5,000 to 100,000 p.e.) when advanced treatment (disinfection), reuse or reduced footprint is required, with retrofitting of existing plant.
5. Decentralised systems	The MBR technology is a viable solution for decentralised sanitation.	With current commercial solutions, MBR systems are not cost-effective for most decentralised or semi-central applications (< 5,000 p.e.), with the exception of a market niche for household applications (< 50 p.e.) and water reuse.
<b>Treatment performance</b>		
6. Membrane impact on treatment	The membrane contributes to the treatment performance.	Direct contribution is insignificant except for the disinfection and turbidity removal. The biological step and related design and operation conditions have strongest impact on treatment performances. However, indirectly, the use of membranes offers greater operating flexibility and allows a constant quality of the treated water during flow/load variations.
7. Disinfection	UF membranes guarantee better disinfection performance than MF membranes.	Not true for bacteria: both MF and UF achieve 6 LRU (log removal unit). Minor superiority of UF membranes for virus removal (both achieve 4 LRU). The overall physical integrity of the membrane module has more relevance for the disinfection performance.
8. Trace organics	MBR plants are better for removing organic micropollutants.	Wrong statement. Under similar operation conditions for the biology (T°, load, process), regular MBRs shows very similar performances to conventional activated sludge. Contrary to frequent reports, this is not an argument in favour of MBR.

Table 1 | (Continued)

Subject	The usual statement	The facts
9. Sludge production	MBR produces less sludge than conventional activated sludge plants.	Wrong statement. The sludge yield is slightly higher due to complete retention by the membrane of particles and colloids. Lower sludge production achieved with greater sludge retention time is associated with greater capital and operation costs.
<b>Fouling</b>		
10. Fouling indicator	Polysaccharides, proteins, CST, TTF, etc. are relevant indicators of membrane fouling.	No recent studies could identify universal single indicators. These parameters are only indirect indicators as they all reflect the state of flocculation of the biomass. In-situ or off-line filtration tests provide more relevant information.

### Myth 1: the MBR market is an industrial duopoly

The development of highly reliable and robust membranes (hydraulic performance, membrane integrity, life span) adapted to the filtration of activated sludge under strong mechanical stress due to air scouring was a prerequisite for the success of this technology. The two pioneering companies Kubota (Japan) and GE-Zenon (Canada) have paved the way with their proprietary systems of flat-sheet and hollow-fibre membranes, respectively. In recent years, they have supplied about 75% of all municipal and industrial constructed MBR plants in Europe, but 99% of the installed membrane surface (Figure 1, from Huisjes *et al.* (2009)). This might seem to be an industrial duopoly. However, the result is biased by the very large plants equipped exclusively by these suppliers up to the end of 2008 (Lesjean *et al.* 2009). In smaller industrial applications, where the costs associated with the biological treatment outcompete the price of the membrane filtration systems, the competition is fierce and increasing with the entrance in the European market of newcomers sometimes with novel concepts (e.g. Siemens-Memcor, KMS-Puron, Toray, Norit, etc.) These newcomers are slowly penetrating

into the municipal market, also for large scale schemes. Increased competition can therefore be expected in the coming years, with a further decrease in the membrane costs. This should relativize the apparent duopoly. In addition, beyond the supply of the membrane technology, the competition is fierce throughout the MBR sector and the rest of the value chain (engineers and contractors), which represent a significant share of the total market.

### Myth 2: the technology has become more competitive following increasing design and operation flux

The increased competitiveness of the MBR technology is often accounted for by the quest for higher specific filtration fluxes, fuelling the perception that higher fluxes lead to competitive systems. However, when looking at design and operation filtration fluxes of the largest MBR units commissioned in Europe in the last decade (Lesjean *et al.* 2009), it is striking that mean fluxes have only increased very moderately – by  $3 \text{ L.h}^{-1} \text{ m}^{-2}$  over 6 years. The technology has actually become competitive as a result of decreasing specific

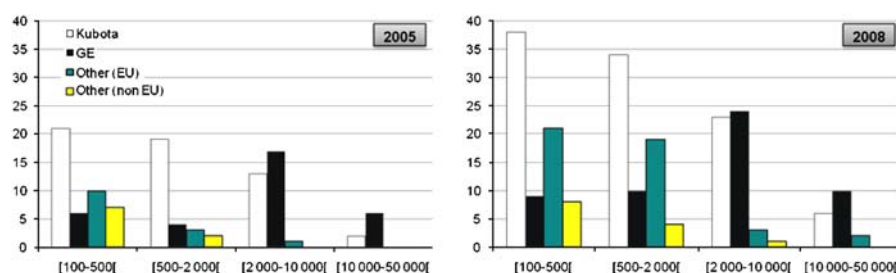


Figure 1 | Distribution of MBR plants in Europe per capacity ( $\text{m}^3/\text{d}$ ) and supplier (installed number), Huisjes *et al.* (2009). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from <http://www.iwaponline.com/wst>.

membrane module prices and longer membrane warranty, as well as decreasing specific aeration demand following novel aeration concepts such as cyclic aeration or new configuration like the double deck, but also the optimisation of the module design such as fibre arrangements, single header design, etc. Today, the benchmark of commercial MBR systems exhibit a specific aeration demand of about  $10 \text{ Nm}^3/\text{m}^3$  permeate, although many MBR plants are still operated much beyond this value (Judd 2007). In addition, the cost related to the purchase and operation of the membrane filtration systems of MBR units is only a portion of the total Life Cycle Cost (LCC). For municipal applications, the cost of the membrane modules is typically 10 to 30% of the total investment cost (for small to large plants). More efficient design and operation of the systems were achieved with regards to for example mixed liquor suspended solids (MLSS) concentration and solid retention time (impact on aeration demand of the biology), improved procedures of membrane cleaning, but also management of peak flux. We can therefore conclude that the technology has not become more competitive because of increased design flux (the design and operation filtration fluxes have only moderately increased in the past decade), but due to other factors such as greater energy efficiency and lower membrane prices with longer warranty.

### Myth 3: specific energy demand of MBR system is lower than $1 \text{ kWh}/\text{m}^3$

In the recent years, total optimised specific energy demands of below  $1 \text{ kWh}/\text{m}^3$  were often reported for full-scale operating MBR systems. It is important to note that such values are comparable when the calculation methodology and the scope are also taken into consideration, for example:

- Is the energy consumption effectively measured, or estimated from the specifications of the installed equipment?
- Does the energy demand relate to the total plant (including sludge treatment and peripheries), or to the -water only- biological treatment step (from feeding pump up to permeate pump), or to the filtration system only?
- Does the energy demand relate to operation under nominal flux, or other hydraulic loadings? (peak hourly design flux, annual average design flux or annual average operation flux ?)

The energy efficiency also depends on the size of the plant (scale-up effect), water temperature (impacting nominal filtration flux), filtration regime (constant nominal flux versus

daily or seasonal flux variation), and biological process design and operating conditions (wastewater concentration, temperature and organic load impacting the aeration requirements). Many smaller MBR plants have a specific energy demand above  $1 \text{ kWh}/\text{m}^3$  when operated much under nominal filtration flux and/or when the operation conditions of the biology and the filtration system are not optimised.

In contrast, many large plants show annual average total energy demand below  $1 \text{ kWh}/\text{m}^3$  after optimisation of the process conditions and under nominal filtration flux. In particular, a good fine-tuning of the process control system and the peak flow management may significantly improve the energy efficiency of the filtration step. Although not practiced today, a recent study has demonstrated that for larger plants the addition of primary sedimentation together with a digester may further reduce the specific energy demand of the MBR plant (Jimenez *et al.* 2010).

### Myth 4: the MBR technology will extensively replace conventional activated sludge plants

Recent investigations show that due to its compactness, the investment cost of MBR systems can now be comparable to activated sludge systems (Côté *et al.* 2005). Some studies have also demonstrated competitive Life Cycle Costs (LCC) to other technologies with equivalent degree of treatment for medium-size plants (Brepols *et al.* 2010). Looking at the rapid progress of the technology, it was tempting to predict that the MBR technology would soon become the technology of reference for wastewater treatment. But despite the annual revenue growth of the MBR market of more than 10% in the past 10 years, only about 2 million people in Europe (i.e. 0.5% of the population) are currently served by MBR plants for wastewater treatment (Huisjes *et al.* 2009).

Despite the recent improvements, greater cost competitiveness and increased acceptance of the technology, with extensive demonstration projects and improved reliability, the process is unlikely to replace all conventional activated sludge plants over the short and medium term. The additional operating costs mainly related to energy requirements (typically about  $0.2 \text{ kWh}/\text{m}^3$  higher than conventional activated sludge processes), manpower for scheduled and unscheduled membrane cleaning and membrane replacement still impair the competitiveness of MBR systems. There is also the operational risk of running an MBR system arising from potential irreversible damage due to unpredictable membrane fouling, or module clogging. Also, the effluent quality greatly exceeds the required standards

for wastewater treatment. The technology therefore remains essentially viable in specific situations, when advanced treatment is required (bathing water, sensitive discharge bodies or water reuse), or possibly in case of plant retrofitting (Bixio *et al.* 2008) or when a compact system is needed such as in tourist coastal areas.

One global market trend pulling the MBR technology is the increasing water shortages, favouring higher quality treatment to allow water reuse. This is currently happening in many rich and water scarce regions such as the Gulf states, Australia, Spain, California, etc. However, for such water reuse applications, or also reverse osmosis pre-treatment, the MBR technology is in strong competition with tertiary filtration (membrane filtration, sand filtration or even micro-sieves). For large plants, tertiary treatments are often more competitive than MBR technology (Lesjean *et al.* 2004) due to lower total energy demand, greater membrane flux and longer membrane life span. Very large tertiary membrane treatment plants have been commissioned in the recent years (e.g. the Sulaibiya WWTP plant in Kuwait with 375,600 m<sup>3</sup>/d), and such systems can also achieve advanced phosphorus removal (<20–50 µgTP/L) with total specific energy requirement below 0.6 kWh/m<sup>3</sup> for the treatment steps activated sludge plus tertiary treatment (Gnirss & Dittrich 2001).

In addition, if we consider on one side the expected increase in energy prices (driven by supply and demand), and a stronger focus on reducing the carbon emission (due to international climate change policies), the energy consuming MBR technology will have a hard time to compete with other technical options unless there are radical technological breakthroughs. The new market opened by increasing water stress is therefore an opportunity for the MBR process, but its market share will depend on whether it can outcompete other technologies.

One crucial aspect in the decision of users will be the reliability of treatment, and the simplicity of operating MBR plants. System integrators and engineering companies will have a key role to play in optimising the overall system, not only at the filtration step, but also with regards to the pre-treatment requirements, the biological system design and proper management of flow peaks. Advanced control tools to facilitate the filtration operation while optimising the energy requirement and reducing the operational risk through the automatic detection of irreversible fouling before human operator will further increase the acceptance of the MBR technology (Manic *et al.* 2008; De la Torre *et al.* 2010b; Huyskens *et al.* 2010).

We can therefore conclude that despite a strong annual revenue growth worldwide, the MBR technology is not

expected to gradually replace conventional activated sludge plants over the medium term. The market for water reuse created by the increasing world water scarcity will represent an opportunity, but the share of the MBR technology against other processes will depend on its ability to convince the users of its reliability, low operational risks and simplicity of operation.

### **Myth 5: the MBR technology is a viable solution for decentralised sanitation**

Great expectations were also raised with regards to the application for decentralised and semi-central municipal applications (4 p.e up to 5,000 p.e.). In the “Bellagio statement” (Fane 2004), a panel of international experts predicted a strong development potential of membrane technology for sustainable decentralised sanitation. In reality, only moderate development has since been achieved. Although numerous systems are commercialised for household applications up to 50 p.e., the viability of systems for the range 50 to 5,000 p.e. is impaired by unnecessary treatment quality for this scale of application, additional staff requirements, and significant specific energy requirements due to low energy efficiency of equipment (Stüber *et al.* 2010). Current references for small-scale MBR therefore exhibit a strong increase of the specific energy demand (sometimes above 5 kWh/m<sup>3</sup>), which make those systems neither economically nor environmentally viable (Lesjean *et al.* 2008). Those systems designed for small communities (villages, city dwellings, tourist resorts or large buildings) suffer from a “scale-down” design approach of current large MBR systems, impairing the energy efficiency. The industry should rather turn to a “scale-up” design approach, adapting energy optimised household systems to small community units. This will be required to develop viable and energy efficient MBR-based solutions for semi-central applications. For such small systems, the key to success will be the simplicity and reliability of operation, which may convince investors to trust such systems.

### **Myth 6: the membrane contributes to the treatment performances**

Broad statements such as “*the membrane achieved desirable treatment performance*” are unfortunately too often encountered in reports presenting results of MBR systems. However, such statements neglect the preponderance of the biological step in the overall elimination performances of MBR systems. MBR systems are too often reduced solely to the membrane filtration step, neglecting the rest of the process. In fact they

are indeed Membrane BIO Reactors, i.e. the association of a membrane filtration step with a biological reactor, and both steps contribute to the treatment performance.

The main function of the membranes is to act as separation step instead of a clarifier. Except for their relevance on disinfection performance (see below) and their ability to produce a particle-free effluent, in municipal applications the quality of treatment is mainly guaranteed by the biological step, where the biodegradation, precipitation and adsorption occurs. The contribution of the membranes is therefore only one aspect of the overall treatment performance and should not shadow the combined impact of the biological process.

### Myth 7: UF membranes guarantee better disinfection performance than MF membranes

MBR plants are known to achieve complete physical disinfection and to comply with the targets of bathing water quality (as defined in the previous EG Bathing Water Directive 76/160 EEC, i.e. coliforms <500/100 ml, fecal coliforms <100/100 ml, streptococcus fecalis <100/100 ml, salmonella 0/1000 ml). Under normal operation conditions, such quality can be achieved over the lifespan of the membrane modules. For example, the Monheim MBR plant, Germany (9,700 p.e., peak flow 288 m<sup>3</sup>/h) has been undercutting this standard by an order of magnitude since it was commissioned in 2003 (Wedi *et al.* 2009).

Arguments are variously advanced for the superior disinfection performance of ultrafiltration membranes (UF, defined here for MBR in the typical range 0.02 to 0.1 µm) compared with microfiltration membranes (MF, defined here for MBR in the typical range 0.1 to 0.4 µm). However, no study has definitely shown the superiority of UF membranes over MF membranes for removing bacteria, all types of membranes implemented in commercial MBR systems showing similar elimination rates of bacteria above 6 log removal unit (LRU), although some microorganisms may have a size comparable to the MF nominal pore size such as *pseudomonas diminuta* (0.22 µm). It is considered that as long as the membrane integrity is not compromised, physical sieving occurs, thereby warranting complete retention of the bacteria.

As viruses can be smaller than MF membrane pores but are bigger than UF membrane pores (the smaller human viruses found in wastewater have a size of 20–30 nm), UF systems were often presented as the sole reliable technology to tackle viruses. In contrast, most studies performed on representative units concluded on similar elimination performances of both systems above 4 LRU (Côté *et al.* 1997), for results with MF hollow fibre membrane of 0.1–0.4 µm, and

Ueda *et al.* 1997, for results with MF flat sheet membrane of 0.2 µm). The removal mechanism was mainly attributed to the adsorption in the biomass and to the adsorption on the biofilm and gel layer attached to the membrane (Shang *et al.* 2005). Here again the retention by the membrane is not the key removal mechanism, although other studies concluded that UF membranes could account additionally for up to 1 LRU for virus removal compared with MF membranes, i.e. with moderate relative significance. Although more data is needed, the debate on MF / UF significance for virus removal seems to be exaggerated, and the impact of biosorption on the flocs and colloids in the biological step to be underestimated.

Therefore, if disinfection is targeted, the use of UF or MF membranes will not make a significant difference. The impact of the membrane and module integrity has greater relevance, highlighting the need for regular integrity control. Also the potential regrowth in the permeate side by polluted backwash water, the presence of dead volume in the system, or points of contamination risks are relevant. Therefore, when full disinfection needs to be guaranteed, an additional disinfection step is advisable. Following the “multi-barrier concept”, current projects include a UV disinfection step, much more efficient after membrane filtered effluents.

### Myth 8: MBR plants are superior to remove organic micropollutants

The MBR process was perceived as superior for removing organic micropollutants due to operational factors such as high MLSS concentration and high colloidal concentration (better adsorption), but also complete retention of slow growing specialist microorganisms (better biodegradation). This was supported by early results with industrial wastewater showing enhanced soluble COD removal with MBR compared with conventional activated sludge systems. However, all recent research investigations performed on this topic with municipal wastewater agree that for given operation conditions of organic load, solid retention time and temperature, the elimination by MBR and conventional activated sludge systems are very similar (Joss *et al.* 2006; Weiss & Reemtsma 2008; Abegglen *et al.* 2009; Bouju *et al.* 2009). The removal rate of organic micropollutants achieved with an MBR plant are very close to those delivered by a conventional plant designed for nitrification/denitrification with a similar sludge age.

Therefore the regular MBR technology is not a solution for the removal of trace organics from municipal effluent, and other combined or additional processes should be implemented. Due to the effluent quality and the particle-free effluent,

MBR systems could however possibly represent a good pre-treatment before dedicated treatment steps such as oxidation, adsorption, or high pressure filtration.

### **Myth 9: an MBR produces less sludge than conventional activated sludge plants**

This idea is very widespread and results from the fact that the first MBR plants were operated under “stabilisation mode” with a sludge retention time above 50 days. Here again, when strictly considering the mass balance under given operation conditions of organic load, solid retention time and temperature, the MBR process *must* produce more sludge than the conventional activated sludge process as it produces particle-free effluent whereas the conventional system will continuously discharge 10 to 20 mgSS/L. If, like conventional activated sludge plants, MBRs can be designed indeed with high sludge retention times under “stabilisation mode” to reduce the sludge production, there is an economic trade-off to consider. For a given MLSS concentration (i.e. a given oxygen transfer rate), high sludge retention times will also result in less compact biological reactors and greater biological oxygen demand, largely offsetting the economic advantage of less sludge production.

It is therefore obvious that for given operation conditions, MBR systems will produce slightly more sludge than activated sludge plants. It is possible to design and operate systems with high sludge retention times, and thus with lower sludge production, but this is associated with higher capital and operation costs.

### **Myth 10: polysaccharides, proteins, CST, TTF, etc. are relevant indicators of membrane fouling**

It is estimated that one third of research investigations and publications related to MBR are dedicated to understanding and controlling the membrane fouling mechanism. Although knowledge on fouling has progressed in the recent years, we should observe that many results are contradictory and the practical outcomes are limited compared with the level of investment in research. Many factors, such as polysaccharides, proteins, but also capillary suction time (CST) or time to filter (TTF), were claimed to be directly correlated to irreversible fouling. If this was true under specific circumstances of the reported studies, recent systematic surveys show that none of these compounds are universal indicators of fouling propensity of the mixed liquor, but that they actually provide indirect indication of the suspension filterability while informing on the state of flocculation of the biomass (de la

Torre *et al.* 2010a). These are therefore neither specific nor exclusive indicators of the fouling propensity. Better indicators could be the “bound to soluble” ratio of compounds such as polysaccharides or proteins. Recent developments on indicators based on filtration tests under normalised conditions showed that such systems are much more relevant and provide more reliable information on reversible or irreversible fouling propensity of the mixed liquor (Geilvoet *et al.* 2008; Huyskens *et al.* 2008; Van der Marel *et al.* 2009; de la Torre *et al.* 2009b).

We can conclude that usual parameters used to monitor irreversible membrane fouling such as polysaccharides, proteins, CST, TTF etc ... are actually all indirect indicators of the mixed liquor filterability as they are related to the state of flocculation of the biomass. However, they are not systematically correlated with the fouling propensity of the mixed liquor, and cannot be used as a universal indicator of membrane fouling. Similarly, care should be taken when using model solutions containing polysaccharides or proteins to simulate membrane fouling and/or cleaning. Many studies have shown that fouling and/or cleaning mechanisms in real biological mixed liquors cannot be reduced easily to one monosolution (de la Torre *et al.* 2009a). It should also be noted that other parameters such as Sludge Volume Index (SVI), Suspended Solids (SS), Volatile Suspended Solids (VSS), viscosity, etc., which are often reported as indicative of fouling propensity, have also been demonstrated in municipal applications to be not relevant to filtration performances (de la Torre *et al.* 2010a).

## **CONCLUSION**

The MBR technology is now a “best available” technology for industrial but also municipal wastewater treatment, especially when advanced treatment is required or a compact system is desired. With the spectacular and sustained annual growth of the market since the introduction of the submerged membrane technology, it has demonstrated its potential to be one of the key available technologies for future wastewater treatment. The global trend of water scarcity will open the new market of water reuse with promising potential.

However, the success of the technology will essentially depend on further improvement to make it competitive with other technological options. In particular, advances are required with regards to reducing the specific energy demand and improving the operation simplicity and reliability of the plants. Also, some early misconceptions on the MBR technology persist and are still debated within the water commu-

nity. This article clarifies some of these in the attempt to foster the professionalism of the MBR industry and to improve the perception of the users, based on solid data and experience.

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