ELSEVIER

Desalination 222 (2008) 66–73

DESALINATION

www.elsevier.com/locate/desal

UF/MF pre-treatment to RO in seawater and wastewater reuse applications: a comparison of energy costs

G.K. Pearce

Membrane Consultancy Associates, P.O. Box 4006, Pangbourne RG8 7WB, UK
Tel. +44 118 9843106; Fax +44 118 9845957; email: gpearce@membraneconsultancy.com

Received 6 May 2007; accepted 17 May 2007

Abstract

Water resources are becoming increasingly scarce in many areas of the world due to development and increased demand. In consequence, the market for reverse osmosis (RO) is expanding to meet the increasing requirement by use of seawater and wastewater resources. Membrane filtration has gradually gained acceptance as the preferred pre-treatment to RO. However, although perceived as desirable, UF/MF is also thought to be an expensive option, and consideration of UF/MF is sometimes restricted to applications which are thought to be especially problematic.

In wastewater treatment applications, UF/MF is the pretreatment technology of choice due to the highly fouling nature of the feed. This paper provides examples of the energy cost for various water sources, comparing wastewater reuse with surface water, brackish water and seawater desalination. In the wastewater case, conventional activated sludge followed by UF/MF-RO is compared with MBR-RO. The comparison shows that wastewater reuse is a very attractive energy option, and that schemes should be considered where possible using UF/MF-RO after conventional sewage treatment, or MBR for smaller schemes, or where space is at a premium.

Conventional surface water sources have an energy cost of 0.1–0.3 kW h/m^3, with brackish water sources normally falling in the range 0.8–1.7 kW h/m^3. The energy cost of wastewater reuse from conventional treatment is in the range 0.8–1.2 kW h/m^3, whilst MBR-RO is in the range 1.2–1.5 kW h/m^3. Seawater has the most expensive energy cost, with a medium salinity feed needing an energy of 2.3–4.0 kW h/m^3. Although the non-conventional sources all use higher energy than surface or groundwater sources, the cost of transfer and distribution should also be considered. A typical power cost for distribution is 0.6 kW h/m^3, so proximity of the source and demand may be a key factor. The data can be used to provide guidance for resource development.

Keywords: Ultrafiltration; Microfiltration; Reverse osmosis; Desalination; Seawater; Pre-treatment; Wastewater; Reuse; Membrane bioreactor; Total water cost

1. Background

Water resources are becoming increasingly scarce in many areas of the world due to development, particularly in costal regions, and increased demand. In consequence, the market for reverse osmosis (RO) is expanding to meet the increasing requirement by use of seawater and wastewater resources. The relative contribution of various

Presented at the conference on Desalination and the Environment. Sponsored by the European Desalination Society and Center for Research and Technology Hellas (CERTH), Sani Resort, Halkidiki, Greece, April 22–25, 2007.

doi:10.1016/j.desal.0000.00.000

Table 1
Water source as a contribution to total water abstraction

	Flow	
	mLd	%
Surface water	6,525,000	63.2
Groundwater	3,751,000	36.3
Desalination	30,410	0.29
Water reuse	19,450	0.19
Total abstraction	10,326,000	

water sources to the total water abstracted for all uses is illustrated in Table 1 [1].

Water supply is dominated by surface water sources, which comprise more than 60% of the total. Most of the remainder is provided from groundwater supplies. Both desalination and water reuse are relatively small sources at present. However, groundwater is effectively a non renewable resource, so it is inevitable that the contribution of groundwater to the total abstraction will diminish.

On the other hand, water demand is increasing due to the following factors:

- Increasing population, and migration to drought prone regions
- Industrial development, and increasing water use per capita
- Climate change leading to changing weather patterns in populated areas

Desalination and water reuse are therefore predicted to be moving into a period of significant sustained growth to compensate diminishing supply and increased demand.

Desalination is now a mature technology that has been actively developed over the past 35 years. Though well established, it provides a relatively small fraction of total water abstraction at just under 0.3%, but growing at a significant rate of approximately 8% p.a. Its great advantage is that it often provides a water resource near where it is needed, since a high proportion of the world's population lives near the coast, especially in water stressed areas. The major disadvantage of desalination is that it is energy intensive.

Water reuse is a relatively new market, though growing rapidly, and already supplying just under 0.2% of total water abstraction. With a forecast annual growth rate of 14%, it is predicted to outstrip desalination by 2020. Standard treatment for wastewater normally comprises a biological treatment stage, known as conventional activated sludge (CAS), and clarification. This degree of treatment is known as secondary treatment. If followed by filtration, e.g. by a sand filter, the treatment is known as tertiary treatment. Historically, 70% of reused wastewater has only been treated to a secondary or tertiary standard, which would only be suitable for agricultural use in less developed parts of the world. To be considered for re-introduction to the drinking water supply chain, and for most industrial uses, wastewater normally requires a further level of treatment, i.e. a quaternary stage, e.g. by RO/NF, ion exchange or electro dialysis (EDI).

With the widespread acceptance of ultrafiltration (UF) and microfiltration (MF) technology in the last 10–15 years, quaternary treatment has become by far the most rapidly growing segment of the wastewater reuse market. Indeed, when membrane filtration technology is combined with the biological reaction stage, a new unit operation has become possible, i.e. the membrane bioreactor (MBR). UF/MF may not require tertiary treatment by sand filters as a pre-treatment, so the term quaternary treatment becomes a misnomer. Indeed, MBR does not need any pre-treatment other than screening, and produces a feed suitable for RO/NF in a single treatment step. Table 2 illustrates the extent of wastewater treatment in terms of flowrate.

Prior to the introduction of membrane filtration, the application of RO/NF in wastewater reuse was restricted due to fouling problems. However, UF/MF and MBR provides an excellent feed quality for further treatment, and this technological

Table 2
Wastewater flows as a function of treatment standard

	Flow (mLd)
WW collected	1,011,000
WW treated	438,000
WW reuse	19,450
WW treated to 4ry std	5500
WW treated by RO/NF	4000

advance, combined with the market requirements, has led to the rapid rise in wastewater reuse schemes.

Table 3 shows the segmentation of the wastewater treatment market by end use [1,2].

RO has emerged as the most suitable technology for addressing water needs in most areas, since it is a flexible cost effective technology with a mainly good track record.

Two important trends have emerged in the last 15 years of RO development. Firstly, RO membrane performance has improved markedly, and secondly, prices have reduced sharply as markets have expanded and projects have become larger. Prior to this, new resource development was normally several times cheaper than recovering a saline source with RO; now, the RO option is often cost competitive, and provides an independent flexible option to a project developer. Recently significant improvements have been made in system design and energy recovery, enhancing the RO option even further.

Table 3
Wastewater reuse market segmentation by end user category

	%
Industry and power	65.5
Municipal	11
Agriculture	23
Other	0.5

However, the RO industry has been surprisingly slow to focus attention on the issue of pre-treatment, and, with the exception of China, often relies on conventional technology developed for different requirements. To get the most out of the latest membrane and system design developments, pre-treatment needs to provide a better product quality for the RO feed, and made more consistent and reliable.

Pre-treatment is the bugbear of the RO industry. Whilst conventional pre-treatment technology can be effective, it needs to be carefully designed, and diligently operated. Upsets, due to feed variability or contamination, will be transferred to the RO, sometimes with dire consequences. Most examples of RO system failure can be put down to pre-treatment failings, either in design or operation. The cost to rectify these shortcomings, and the lost production which results, threatens to give RO a bad name in some cases.

This paper reviews the case for ultrafiltration (UF) and microfiltration (MF) pre-treatment to RO. For brackish water and wastewater feeds, the case for UF/MF pre-treatment is normally accepted. The world's largest industrial market for RO is in China, and there, UF/MF is specified for a significant proportion of RO projects irrespective of feed type. Wastewater projects also normally use UF/MF, since the fouling nature of the feed is recognized, and UF/MF significantly improves the pre-treatment. In both cases, UF/MF ensures that significantly higher fluxes are obtained from the RO, with much less fouling, reduced chemical usage, and better on-stream time.

However, the case for seawater feeds is much less clear cut, especially for high salinity feeds, since fluxes cannot be increased much due to osmotic pressure limitations. Also, the additional expense of UF/MF is assumed to be too high, making the project unattractive. The paper will review the case for UF/MF pre-treatment, and compare the energy costs of seawater desalination with surface and brackish water sources, and with wastewater reuse. For the reuse case, membrane treatment after conventional activated sludge will be compared to MBR. The comparison will provide guidelines for resource development.

2. Advantages of membrane pre-treatment to RO

The objective of pretreatment to an RO or NF system is to remove particles, reduce organics, and provide a feed that will not cause biofouling in the RO/NF elements. Conventional pre-treatment technology relies on a combination of chemical treatment and media filtration to achieve conditioning of the feed to make it acceptable as an RO/NF feed by removing a proportion of the feed challenge. In contrast, UF/MF uses a sieving mechanism, which provides an absolute barrier to particles above the size of the UF/MF membrane pores, and thus can provide a much better RO feed.

Dissolved species such as salts and organic solutes, pass through the UF/MF membrane. Organics may be a problem to the RO/NF, since they can cause fouling due to surface adsorption, or they may provide a food source to micro-organisms. It is therefore necessary that the effect of these organics on the RO is investigated, and that methods are investigated to remove them, or to mitigate their effect.

Since membranes provide a barrier to particulates, they provide significant benefits to the RO/NF, and to the overall system design. These benefits fall into two broad categories, namely reduced cost of the overall system, and improved on-stream time and security of supply. The benefits can be summarized as follows:

- Significantly higher RO design flux and recovery is normally possible
- Low space – >33% saving with UF/MF
- RO membrane replacement rate reduced significantly
- Can treat surface water, with poor and/or variable quality
- Reduced requirement for RO disinfection and cleaning

Membrane filtration is accepted as the best pre-treatment alternative for some feed sources and in some markets, whereas it is considered expensive or unnecessary in other cases. For example, membranes are accepted in all markets for wastewater pre-treatment, whilst for surface water, acceptance varies with location. For seawater, membrane pre-treatment is considered expensive, and is only just beginning to gain acceptance.

The status of membrane filtration for RO pre-treatment for various source waters is summarized below:

Surface water – membrane filtration accepted; uptake greater in new markets

– UF/MF provides clear RO performance improvement
– Improves stability and reliability
– Reduces total water cost
– Often specified for the industrial expansion in China

Wastewater – membrane filtration accepted

– UF/MF provides much better RO feed quality than conventional
– Removes particles and organics due to use of coagulant
– Used as standard design for new systems
– Significant potential for MBR-RO

Seawater – membrane filtration case emerging

– Considered expensive
– Important advantages for open intake
– Improves opex, total water cost, and plant on-stream time

As shown above, membranes are used in wastewater pre-treatment primarily for technical reasons, whereas for other sources, both membrane and conventional pre-treatment can perform the duty and the design is decided commercially on a case by case basis.

Table 4
Energy costs of treatment for surface and groundwater sources

	Power (kW h/m^3)
Surface water – conventional treatment	0.15–0.30
Surface water – conventional + UF/MF	0.25–0.35
Groundwater infl. by surface – UF/MF	0.1

3. Energy costs from conventional sources

Typical energy costs of producing potable water from surface and groundwater sources are shown in Table 4. The tabulated costs cover the power cost of the treatment works itself, and are dependent upon the extent of treatment requirements. If UF or MF polishing is used after conventional treatment, the additional power cost is low at about 0.1 kW h/m^3, which is similar to the requirement for groundwater schemes. If UF/MF is used in place of conventional processes for treating raw surface water, power costs will be higher than for polishing and will depend on pre-treatment requirements, but are likely to be around 0.2 kW h/m^3. A separate entry has not been included in the table for this type of treatment since in many cases, such treatment may not meet all of the treated water quality parameters, and therefore is not strictly comparable with conventional treatment.

In some parts of the world, coastal aquifers are brackish due to saline intrusion. Table 5 summarizes the costs of treating brackish sources from three typical cases. The groundwater example is a relatively high salinity aquifer based on a case study in Florida, in which pre-treatment requirements are low, whilst the surface water is a low salinity river water with greater pre-treatment requirements. These two cases are taken from the large element consortium study [3]. The estuary case is typical of many schemes currently being considered in which there is a significant tidal influence on feed salinity, partially abated by management of abstraction timing.

The power costs of brackish water treatment are significantly greater than from conventional sources due to the power requirements of the RO in overcoming osmotic pressure. However, the impact of the RO is not as great as may have been expected.

An important factor to consider is the cost of distribution. A typical figure for distribution costs in the UK is 0.6 kW h/m^3, which is significant in comparison to the costs of the actual treatment, and indeed exceeds treatment costs for the conventional sources considered in Table 4. It is therefore evident that it is important to secure water sources and provide treatment as close as possible to where it is needed to control transfer costs.

4. Energy cost for wastewater reuse

Treatment of wastewater by a biological process followed by clarification is typically known as the conventional activated sludge process (CAS), and produces a secondary treated effluent. This is not suitable as an RO feed, and requires

Table 5
Brackish water power costs from three case studies

Feed	Salinity TDS (ppm)	Pre-treatment (kW h/m^3)	RO system (kW h/m^3)	Total treatment (kW h/m^3)	Distribution (kW h/m^3)
Brackish surface water	930	0.2	0.63	0.83	
Brackish groundwater	2200	0.1	0.88	0.98	
Estuary case study	3000–11,000	0.29	1.38	1.67	2.27

Table 6
2ry/3ry wastewater treatment; the O&M cost of pre-treatment to an RO feed standard (MWH, West Basin, based on a 19 mLd facility)

	Conv.	MF
Utilities (kW h/m^3)		
Power	0.2	0.2
O&M costs (US cents/m^3)		
Power	2	1.8
Other	14	3.2
Total	13	5

further treatment. Prior to the introduction of UF/MF and MBR, conventional treatment stages of lime clarification and sand filtration were used. However conventional pre-treatment has very high chemical costs, and so is unattractive for RO pre-treatment. Table 6 shows the comparison of conventional and membrane filtration in treating secondary or tertiary wastewater to an RO feed standard [4].

It is notable that whilst power costs for conventional and membrane filtration pre-treatment are very similar, conventional pre-treatment has much higher operating costs overall, since chemical dosing costs for this type of treatment are very high.

Furthermore, Table 7 shows the effect on the RO of using membrane filtration as pre-treatment compared to conventional pre-treatment [4]. It is evident that the RO also suffers from very high operating costs if conventional pre-treatment is used since both power and cleaning costs for the RO stage are significantly greater than if membrane filtration is used.

Table 7
Energy comparison of RO system requirements including pre-treatment

	Conv. + RO	MF + RO
Utilities (kW h/m^3)		
Power	1.3	0.5
O&M costs (US cents/m^3)		
Power	13.2	5.3
Other	12.7	10.6
Total	25.9	15.9

The data are from Orange County [4,5] for a 51 mLd scale facility, and show that conventional pre-treatment has a major effect of increasing energy cost in the RO, due to fouling and high operating pressures. Since membrane filtration has lower capex and other operating costs than conventional pre-treatment, it is now widely accepted that membrane pre-treatment is mandatory for any reuse scheme. The membrane stage can either be based on UF/MF with a CAS feed, or on MBR. The energy cost of the RO stage combined with MF is 0.5 kW h/m^3, indicating that the RO energy cost alone would be just 0.4 kW h/m^3, i.e. significantly below the levels found in seawater or medium salinity brackish water applications.

Metcalfe and Eddy carried out a survey of wastewater facilities in the US [6], and found that the energy usage range was 0.32–0.66 kW h/m^3. Energy usage in wastewater treatment is somewhat lower in Europe according to Black and Veatch (B&V) [7], who have carried out extensive surveys of wastewater treatment costs. This is partly due to a greater consciousness for energy efficiency, and partly due to the fact that the average BOD loading/capita in Europe is typically 70% of that in the US (due to the use of kitchen disposal units in the US). Also, some of the facilities in the US survey were old and inefficient in energy usage, whilst those surveyed in Europe were relatively modern.

European wastewater costs can be as low as about 50% of those of the US. Long term monitoring of a wastewater treatment system in Denmark showed a usage of 0.15 kW h/m^3 for activated sludge, increasing to 0.25 kW h/m^3 if a BAF stage is included. Monitoring of a German system confirmed a usage of 0.25 kW h/m^3 for a similar comprehensive treatment system of CAS

Table 8
Typical MBR energy costs

	Municipal sewage (kW h/m^3)
Microbiology	0.3
MBR-air for fouling control	0.4

and BAF. The energy cost of membrane filtration according to B&V is 0.05–0.10 kW h/m^3, which is broadly in agreement with the data presented in the tables above. RO has an energy cost of 0.25–0.50 kW h/m^3, which is also consistent.

Assessment of MBR energy costs is somewhat higher than the early studies reported above. Table 8 shows energy costs for the MBR itself. Aeration costs for the microbiology are similar to those of conventional activated sludge. To this, aeration costs for fouling control need to be added. Currently, an efficient system uses about 0.4 kW h/m^3 for this purpose, though with system design improvements, some systems may improve on this level, and air lift systems appear to use lower energy.

However, there are other energy costs for a field system. The Singapore experience showed an average use for commercial scale MBR of 1.0 kW h/m^3. The Dutch consultancy DHV, who have done extensive piloting of several MBRs at Beverwijk in the Netherlands, are broadly in agreement with this figure, and suggest that practical experience indicates an energy use for MBR of 0.8–1.0 kW h/m^3. However recent developments are reducing air by progressively limiting wastage. Consideration is also being given to anaerobic MBRs, which would have lower energy usage.

The commercial application of both membrane filtration and RO in the treatment of wastewater feeds has shown that fouling rates can be significant at high fluxes. To minimize total water cost, relatively low fluxes should be selected, increasing capital costs whilst ensuring low operating costs [8].

5. Summary of energy costs from various sources

The cost of seawater RO (SWRO) varies according to the salinity of the feed and the system design. In this paper, energy costs have been taken for a medium salinity feed (e.g. Mediterranean Sea with a TDS of 38,000 ppm TDS) [9,10].

The summary of energy usage for the various water and wastewater sources is summarized in Table 9. For wastewater schemes, the conventional activated sludge (CAS) process is required for river discharge. In most cases, this level of treatment is suitable for direct supply to an MF-RO system without further biological treatment. Therefore, the energy cost of CAS does not necessarily need to be added to the treatment costs,

Table 9
Energy usage for various water and wastewater sources

Feed	Conv. act sludge (kW h/m^3)	Pre-treatment (kW h/m^3)	RO system (kW h/m^3)	Total treatment (kW h/m^3)
Surface water				0.15–0.3
Wastewater	0.3–0.6	0.1–0.2	0.4–0.5	0.8–1.0 (1.3)
Wastewater MBR		0.8–1.0	0.4–0.5	1.2–1.5
Brackish (930–2200 ppm)		0.1–0.3	0.6–0.9	0.8–1.0
Brackish – Tidal Estuary		0.29	1.38	1.67
Seawater (medium salinity)		0.3–1.0	2.0–3.0	2.3–4.0

depending on whether CAS treatment has to be provided anyway.

The data for MBR has been based on practical field experience. The wastewater figure assumes CAS has to be provided also, but this level of treatment is normally required irrespective of the reuse scheme as noted above. Membrane filtration and RO is added to the CAS to provide reuse quality product. The figures for brackish are from the large element consortium study in the US for a 930 ppm surface water and a 2200 ppm groundwater [3], with different pre-treatment requirements. Finally, the seawater scheme is based on a medium salinity challenge. Pre-treatment costs can become relatively high, depending on recovery.

It should be noted that membrane filtration and RO energy costs are relatively low in wastewater reuse applications since it has been found that these applications need to be operated at low fluxes to avoid fouling. This creates low energy cost, but the capex of the membrane system cost, and opex of the membrane replacement costs are higher than for similar salinity brackish water treatment.

6. Conclusions

- Wastewater reuse is a well established application and a rapidly growing market
- It is mandatory for a potable reuse scheme that RO is used to provide the final treated water quality, and that pre-treatment is provided by membrane filtration
- The total energy cost of wastewater reuse including the conventional activated sludge stage followed by MF(or UF)-RO is 0.8–1.2 kW h/m^3
- This compares with conventional surface water treatment at 0.15–0.3 kW h/m^3, brackish water at 0.8–1.7 kW h/m^3, and desalination at 2.3–4.0 kW h/m^3, thus reuse is relatively attractive compared to other non-conventional options
- MBR-RO schemes have an energy use similar to brackish water at 1.2–1.5 kW h/m^3, and could be attractive for retrofit and Greenfield site opportunities where space is at a premium
- Reuse schemes require mild operating conditions and low membrane filtration and RO fluxes to minimize power and chemical costs, and avoid fouling problems

References

[1] J. Kolodziejski and C. Gasson, Water Reuse Markets 2005–2015: A Global Assessment and Forecast Global Water Intelligence, June 2005.
[2] 19th IDA Worldwide Desalting Plant Inventory: Global Water Intelligence and Water Desalination Report, June 2006.
[3] Industry Consortium Analysis of Large Element RO/NF, Desalination & Water Purification Dev Report 03-FC-81-0916, September 2004.
[4] R.D. Reardon, S.V. Paranjape, X.J. Foussereau, F.A. DiGiano, M.D. Aitken, J.H. Kim, S.-Y. Chong and R. Cramer, Water for Reuse: Membrane Treatment of 2ry Effluent for Subsequent Use WERF Final Report, North Carolina University, 2005.
[5] S. Adham, M. Kumar and W.H. Pearce, Model developed for brackish and reclaimed water, Desal. Water Reuse, 15 (3) (2005) 38.
[6] Energy Efficiency in Wastewater Treatment Wastewater Engineering – Treatment and Reuse, 4th edn., Metcalfe and Eddy, 2003, pp. 1703–1707.
[7] F. Rogalla, The Power to Cool Water & Wastewater Treatment, 2006, pp. 41–43.
[8] Membrane Fouling Guidelines for Water and Wastewater Treatment by UF/MF, in: Proceedings of the IWA Conference, Harrogate, UK, May 2007.
[9] M. Wilf, The Guidebook to Membrane Desalination Technology, Balaban Desalination Publications (ISBN 0-86689-065-3), 2007.
[10] G.K. Pearce, C. Bartels and M. Wilf, Improving total water cost of desalination by membrane pre-treatment, in: Proceedings of the IDA Conference, Gran Canaria, October 2007 (in preparation).