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# Economic feasibility study for MF system as a pretreatment of SWRO in test bed desalination plant

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ABSTRACT

The test bed for seawater reverse osmosis (SWRO) desalination plant having a capacity of 10 million imperial gallons per day, located in the southeast of South Korea, is under construction by Doosan Heavy Industries and Construction. The feed water for first pass SWRO train will be pretreated by a microfiltration (MF) membrane system and conventional dual media filtration system. For the MF pretreatment system, it is necessary to evaluate the economic feasibility between the submerged and the pressurized membrane systems to apply the filtration mode of membrane modules. This article evaluates the economics using the life cycle cost (LCC) analysis method. Although many researchers reported that the submerged MF system has economic advantages over the pressurized system because the submerged system consumes lower energy, the result of this article presents on the contrary to this. The result shows that the total capital cost and operation cost of the pressurized system are lower than those of the submerged system, because the pressurized system can use the hydraulic pressure generated from the seawater supply pump and air consumption is much lower than that of the submerged system. In addition, the result of LCC estimation shows that the pressurized system has the lower cost compared with the submerged system, by approximately 13%. This represented that the pressurized MF pretreatment system has economic advantage over the submerged system especially in SWRO desalination plant.

*Keywords:* SWRO; Desalination; Pretreatment; Microfiltration and Ultrafiltration; Submerged; Pressurized; Economics; Life cycle cost analysis

## 1. Introduction

During the past few decades, desalination has become an important source of drinking water production, with thermal desalination processes developing over the past 60 years and membrane processes developing over the past 40 years [1]. Recently, the seawater reverse osmosis (SWRO) process is becoming increasingly popular as a competitive desalination technology, although the thermal desalination processes are still widely used in the middle east plants [2]. It is well known that the reverse

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osmosis (RO) process is currently considered as the most economical process than thermal desalination processes. However, the membrane fouling is a main obstacle to expanding RO applications. It is caused by the deposition of organic and inorganic water contaminants and can occur in cake layer on the membrane surface, while dissolved organics will interact directly with the membrane surface and with each other to cause membrane fouling [3]. To remove this membrane fouling, chemical cleaning (acid or base) is used, and operational downtime is often required [4]. Consequently, the pretreatment removing most of the potential elements responsible for desalinating membrane fouling such as particles, turbidity, bacteria, and large molecular weight organic matters is considered as most important process in RO process.

During the last decade, microfiltration (MF) and ultrafiltration (UF) membranes have become widely accepted as a viable alternative to conventional water treatment technologies such as dual media filtration (DMF). MF and UF are an ideal pretreatment method for RO, because it allows removing suspended solids and colloidal material completely [5]. In addition, membrane pretreatment reduces the general aging and destruction of RO membranes by the raw water components, decreases RO membrane replacement and the frequency of chemical cleaning. Through the continuous improvements in its performance and capital cost, membrane pretreatment system is becoming cost-competitive with conventional systems [6].

Two types of membrane filtration mode are available as a pretreatment of SWRO; the submerged (encased or immersed) and the pressurized mode. The submerged membrane systems can effectively replace the clarifiers and multimedia type filters found in conventional water treatment plants and are capable of operating effectively and continuously in high-solids environments. Additionally, the submerged membrane systems can be particularly cost-effective if an existing tank/basin can be utilized [7]. However, the fumes from the open tanks of the submerged systems often require complex and expensive ventilation systems, for both the safety of operators and the longevity of the facility housing the membrane system, as the fumes can corrode metal buildings or structures within the treatment plant. The pressurized membrane systems can operate with higher flux than the submerged systems, with minimal solids bulid-up on the membrane surface. In addition, the pressurized systems have many advantages over the submerged systems such as pressure decay test, repair of broken hollow fiber, and detection of piping leakage [8].

Some studies evaluated the economics of the submerged and the pressurized systems [7–10]. Most studies reported that the submerged systems are competitive in capital and operating costs compared with the pressurized systems [7,9,10]. Pilutti and Nemeth reported that the submerged systems are more cost-effective than the pressurized systems for systems larger than 10 million gallons per day [7]. However, they excluded costs for tanks and operating costs, because the operating costs are site specific. Sorgini reported that the submerged systems are 20–38% less in capital cost and 20–45% less in operating cost than the pressurized systems [9]. The study excluded costs for feed or filtrate pumps, interconnecting piping or housings for the analysis of capital cost. In addition, labor, chemical cost, energy consumption, and membrane replacement cost were excluded for the analysis of operating cost. Huehmer et al. estimated total water cost in the submerged and the pressurized UF systems as a pretreatment system of 140 mega liters per day SWRO in particular [10]. They estimated a total water cost using a capital expenditure (CAPEX) and operational expenditure (OPEX). The study reported that a total water cost of the submerged UF systems (\$0.079/m$^3$) is slightly lower than that of the pressurized UF systems (\$0.082/m$^3$). On the contrary, Martinez reported that the pressurized systems deliver lower total costs than the submerged systems [8]. The main reason for this explanation is that the pressurized systems typically require a much smaller footprint than the submerged systems. In addition, the larger operating pressure range that the pressurized systems offer makes it possible to design them at much higher fluxes. This translates to less membrane surface area, fewer membrane modules, and consequently, lower costs. However, the deals with only the conceptual comparison and clarification without any economic evaluation data.

The test bed for SWRO desalination plant having the capacity of 10 million imperial gallons per day (MIGD), located in the southeast of South Korea, will be completed in August 2013 by Doosan Heavy Industries and Construction, led by the Ministry of Construction and Transportation of Korean Government and Busan City. Initial foreseen production capacity of such SWRO plant is 10 MIGD, which is equivalent to 45,460 m$^3$/day. The test bed will be constructed with two SWRO trains having the capacity of two MIGD and eight MIGD. The feed water for two MIGD SWRO train will be pretreated by MF membrane systems, whereas that for eight MIGD SWRO train will be pretreated by conventional DMF. In the MF pretreatment system, it is necessary to evaluate the economic feasibility between the submerged and the pressurized membrane systems to apply the filtration mode of membrane modules. The main purpose of this study is to evaluate and compare the economics of the pressurized and the submerged MF systems as a pretreatment of SWRO, using the life cycle cost (LCC) analysis method.

## 2. Materials and methods

### 2.1. Calculation of energy consumption

Energy consumption is one of the largest cost elements and may dominate the LCC. Energy consumption by pump, blower, and agitator is calculated by gathering data on the operation pattern of the MF system output. Output of MF system varies over time; therefore, a time-based usage pattern needs to be established. The equation for calculation of input power is as follows:

$$P = \frac{Q \times H \times \text{s.g.}}{366 \times \eta_p \times \eta_m} [\text{kW}] \quad (1)$$

where $P$ is the power, $Q$ is the flow rate ($m^3/h$), $H$ is the head (m), $\eta_p$ is the pump efficiency (%), $\eta_m$ is the motor efficiency (%), s.g. is the specific gravity.

### 2.2. Calculation of net present value

To calculate the LCC, it is required to consider the effect of inflation, interest rates, exchange rates, taxation, etc. However, due to the difficulties accurately predicting inflation and exchange rate, the cost profile may be prepared at constant prices basis. To estimate the impact of discounting, the following common equation may be applied.

$$\text{NPV} = \sum_{n=0}^{T} \frac{C_n}{(1+r)^n} \quad (2)$$

where NPV is the net present value of future cash flows, $C_n$ is the nominal cash flow in the $n$th year (USD), $n$ is the specific year in the life cycle costing period, $r$ is the discounting rate (%), $T$ is the length of the time period under consideration in years (year).

Discounting is a process for taking account of the changing value of money. Since LCC analysis considers costs that will be incurred some times in the future, it is necessary to discount all revenues and expenditures to a specific decision point.

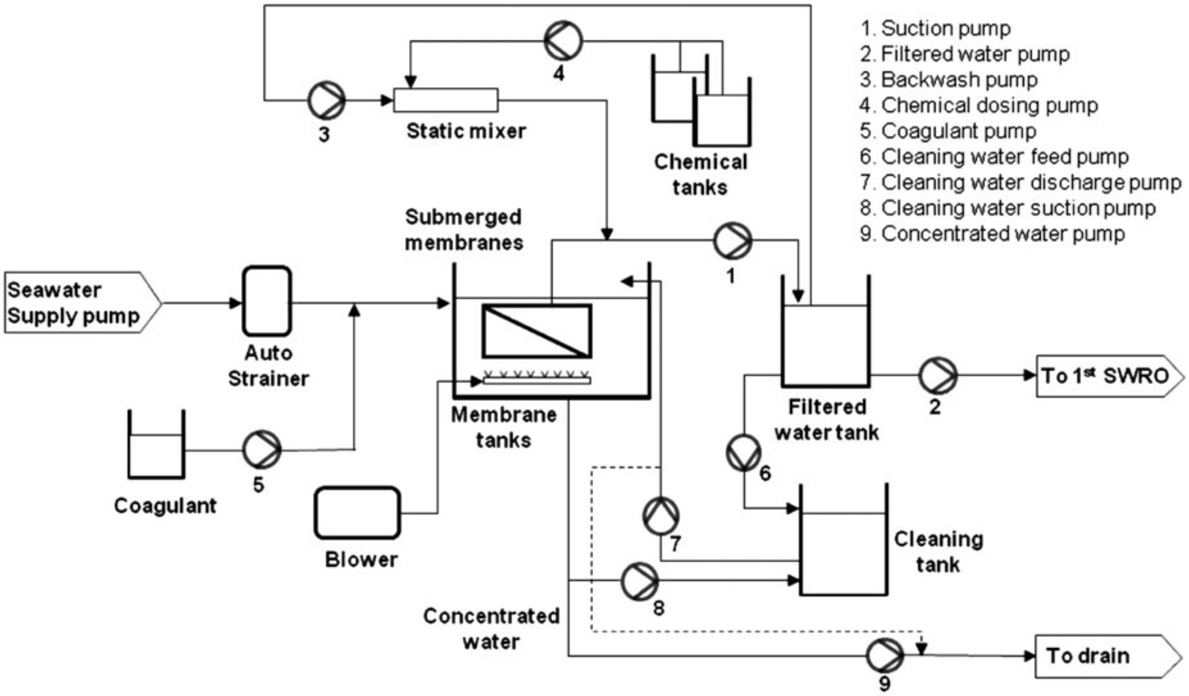
### 2.3. LCC analysis

LCC analysis is a method for assessing the total cost of facility ownership. LCC of any piece of equipment is the total lifetime cost to purchase, install, operate, maintain, and dispose of that equipment. LCC analysis is especially useful when project alternatives that fulfill the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings. In other words, LCC analysis is a management tool that can help companies minimize waste and maximize energy efficiency for many types of systems. LCC analysis should be performed early in the design process, while there is a chance to refine the design to ensure a reduction in LCC. The first and most challenging task of an LCC analysis, or any economic evaluation method, is to determine the economic effects of alternative designs of systems and to quantify these effects and express them in dollar amounts [11,12].

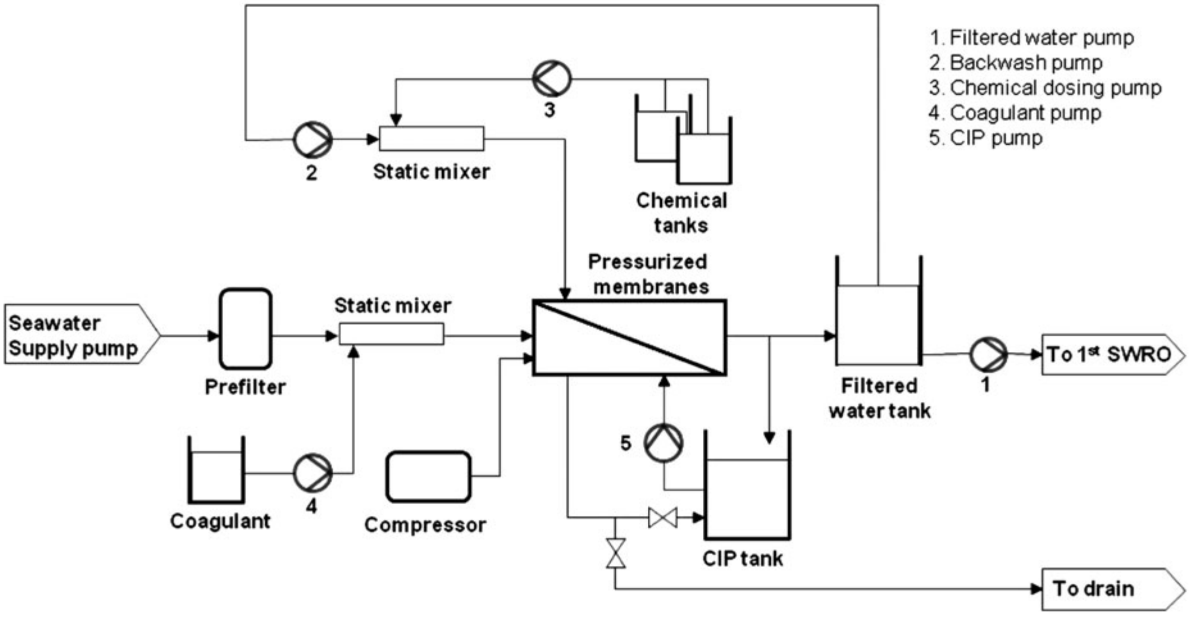
LCC analysis includes the cost of the energy consumed over the specified life cycle, inflationary and interest costs, capital and installation costs, maintenance costs, and other cost factors. The MF system with the lowest LCC has the best financial return on investment and will provide the lowest cost of product water to the plant owner. The basic LCC equation is as follows:

$$\text{LCC} = C_{ic} + C_{in} + C_{ic} + C_e + C_o + C_m + C_s + C_{env} + C_d \quad (3)$$

where $C_{ic}$ is the initial investment costs; purchase prices and capital expenses of the components and equipment being evaluated under the life cycle. These costs may include engineering and design fees, purchase order administration, and inspection. Initial costs are the upfront investment cost paid in the initial year of the project. $C_{in}$ is the installation and start-up costs. These costs include foundations, connection of piping, wiring, instrumentation, commissioning of the equipment, performance testing and evaluation at start-up, and staff training. These costs are ignored in this study because they are included in the initial investment costs. $C_e$ is the energy costs; cost of electrical energy consumption of the equipment over the life cycle. In this study, the electrical energy cost at the start of plant operation estimated at \$0.08/kWh and will increase at an average rate of 4% per year. The MF system is assumed to have a duty cycle of 95%. $C_o$ is the operating costs; cost of operating the equipment, excluding the energy costs, over the life cycle. These costs include labor required to operate and monitor the equipment. $C_m$ is the maintenance and repair costs over the life cycle. These costs are calculated per event and include replacement parts, routine maintenance labor, reinstallation, and transportation costs. $C_s$ is the downtime costs; cost of lost production and lost revenues during periods of downtime over the life cycle. $C_{env}$ is the environmental cost associated with environmental compliance of the equipment over the life cycle. These costs include environmental permits, inspection and containment disposal. $C_d$ is the decommissioning costs; cost to decommission equipment at the end of its lifetime. In this study, $C_s$, $C_{env}$, and $C_d$ values are ignored because these values are complicated and site specific.



(a) Submerged system



(b) Pressurized system

Fig. 1. Schematic process flow diagrams of the submerged and the pressurized MF systems.

The following assumptions, inclusions, and exclusions are used to analyze the LCC of MF pretreatment systems:

- System life span: 20 years.
- Discount rate = interest rate (9%) − inflation rate (4%) = 5%.
- Average operation hours of MF pretreatment system: 95%.
- Operating costs (labor costs): \$150,000/year.
- Maintenance and repair costs: \$200,000/year.
- Land costs, emergency and miscellaneous costs are ignored.
- Costs of membranes and racks are excluded.

## 3. Results and discussion

### 3.1. Configurations of MF system

A process flow diagram (PFD) for MF systems should be designed in the first place to analyze the LCC. The design of system is very important because the initial capital costs and operational costs vary with the design concept. The PFD shows the major pieces of equipment, piping, tank, etc. Fig. 1 shows PFDs for the submerged and the pressurized MF systems that were recommended and designed by a bidder (K.W.ENG Co., Ltd., Republic of Korea).

In the submerged system (Fig. 1(a)), the seawater supply pump transfers seawater to the membrane tanks, and large particulate matters are filtered out by an auto-strainer. $FeCl_3$ is used as a coagulant to enhance the membrane filterability. The filtered water through the submerged membrane is continuously withdrawn at constant flux of 40 $L/m^2 \cdot hr$ by the suction pumps and transferred into the filtered water tank. A part of the filtered water is used as backwashing and cleaning water. Chemically enhanced backwashing (CEB) is executed three times a day for all membrane units, and sodium hypochlorite is used as CEB chemical. The filtered water is transferred to the first pass SWRO train by a filtered water pump.

Meanwhile, the pressurized system (Fig. 1(b)) can use the hydraulic pressure generated from the seawater supply pump, whereas the submerged system requires the suction pumps (Fig. 1(a)). This means that the pressurized system can reduce the number of pumps and consequently lower the initial capital costs. Actually, the submerged system needed thirty-one (31) pumps, whereas it needed twelve (12) pumps in the pressurized system. $FeCl_3$ as a coagulant is dosed inside the inline static mixer. The pressurized membrane is operated with normal operation flux of 60 $L/m^2 h$ and below the normal transmembrane pressure (TMP) of 1.5 bar. A part of the filtered water is used as a backwashing and cleaning-in-place (CIP) water. CEB is executed once a day for all membrane units. Sodium hypochlorite (NaOCl) is used as a CEB chemical. The filtered water is transferred into the first pass SWRO train by a filtered water pump. Table 1 shows the main design parameters of the submerged and the pressurized systems.

Table 1
Design parameters of the submerged and the pressurized systems

| Parameters | Units | Submerged system | Pressurized system |
|---|---|---|---|
| No. of membrane skid/rack | ea | 50 | 6 |
| No. of membrane module | ea | 20 | 48 |
| Total no. of membrane module | ea | 1,000 | 288 |
| Feed flow rate | $m^3/h$ | 878 | 905 |
| Nominal filtration flux | $L/m^2 h$ | 30–40 | 40–60 |
| Max. transmembrane pressure | bar | 1.0 | 1.5 |
| Backwash flux | $L/m^2 h$ | 60 | 90 |
| Recovery rate | % | 98 | 95 |
| Coagulating chemical | – | $FeCl_3$ | $FeCl_3$ |
| CEB chemical | – | NaOCl | NaOCl |

### 3.2. Initial capital costs

Table 2 shows the main items constituting the initial capital costs which include equipment, civil works, building, erection, etc. Only purchasing prices are considered and capital expenses of the components are excluded. The capital costs for the seawater intake system, membranes, racks (frame), and land costs are excluded in this study. Total initial capital cost of the pressurized system is lower than that of the submerged system (cost data not shown) because the submerged system requires many pumps and tanks. Especially, the costs for civil works of the submerged system are higher than that of the pressurized system because the submerged system requires many concrete tanks. In addition, the pressurized system does not need additional pumps for membrane operation such as suction pumps of the submerged system because the pressurized system can use the hydraulic pressure

Table 2
List of main items for the calculation of initial capital costs

| | Submerged system | | Pressurized system | |
|---|---|---|---|---|
| | Equipment | Q'ty | Equipment | Q'ty |
| Water supply and membrane operation | Auto strainer | 5 | Prefilter | 1 |
| | Seawater supply pump | 2 | Seawater supply pump | 2 |
| | Suction pump | 8 | – | – |
| Aeration | Air blower | 2 | Compressor | 1 |
| | – | – | Air receiver tank | 1 |
| Pumps (filtered water, backwash, CIP) | Filtered water pump | 2 | Filtered water pump | 2 |
| | Backwash pump | 2 | Backwash pump | 2 |
| | Concentrated water pump | 8 | CIP pump | 2 |
| | Cleaning water feed pump | 1 | – | – |
| | Cleaning water discharge pump | 2 | – | – |
| | Cleaning water suction pump | 1 | – | – |
| | Vacuum pump | 2 | – | – |
| Chemical dosing system | Static mixer | 1 | Static mixer | 2 |
| | $FeCl_3$ feed pump | 2 | $FeCl_3$ feed pump | 2 |
| | NaOCl feed pump | 3 | NaOCl feed pump | 2 |
| | Agitator | 2 | Agitator | 2 |
| Tanks | Membrane tank | 5 | – | – |
| | Permeate tank | 1 | Filtered water tank | 1 |
| | Cleaning tank | 2 | CIP tank and assy | 2 |
| | Concentrated water tank | 1 | – | – |
| | Air separation tank | 5 | – | – |
| | Vacuum tank | 1 | – | – |
| | $FeCl_3$ storage tank | 1 | $FeCl_3$ storage tank | 1 |
| | NaOCl storage tank | 1 | NaOCl storage tank | 1 |
| Instrument and electricity | Pressure gauge | 24 | Pressure gauge | 24 |
| | Magnetic flow meter | 5 | Flow transmitter | 10 |
| | Turbidity analyzer | 1 | Turbidity analyzer | 1 |
| | Paddlewheel flow meter | 1 | Pressure transmitter | 17 |
| | Pressure transmitter | 5 | pH analyzer | 3 |
| | Level switch | 4 | Level transmitter | 3 |
| | Flow indicator | 1 | Temperature transmitter | 6 |
| | Level transmitter | 6 | – | – |
| | Motor control center | 1 | Motor control center | 1 |
| | Cable with assy | 1 | Cable with assy | 1 |
| Valve, piping, fitting | – | – | – | – |
| Civil works and building | Civil works | – | Hoist crane | – |
| | Building | – | Building | – |
| Etc. | Erection | – | Erection | – |
| | Packing and transportation | – | Packing and transportation | – |
| | Document and eng. fee | – | Document and eng. fee | – |
| | Management charge | – | Management charge | – |

generated from the seawater supply pump. The initial capital costs per unit volume of filtered water (USD/$m^3$) are presented in Table 3. They are calculated by dividing the total initial capital costs by the total water production on the basis of 1 and 20 years, respectively. Table 3 shows that it would be more economical to use the pressurized system than using the submerged system in terms of capital cost, by approximately 27%.

Table 3
Comparison of capital cost between the submerged and the pressurized systems

| | | Capital cost (USD/m$^3$) |
|---|---|---|
| Submerged system | 1 year | 0.385 |
| | 20 years | 0.019 |
| Pressurized system | 1 year | 0.280 |
| | 20 years | 0.014 |
| Cost difference | 1 year | 0.105 |
| | 20 years | 0.005 |
| Percentage | | 27% |

### 3.3. Power consumption

The main equipment described in Fig. 1 is listed in Table 4 to estimate the total power consumption of both systems. In this study, an electric light, control power, HVAC, and electricity for office equipment are ignored during the calculation of power consumption because they are site specific. Actual power consumption (kW) is calculated using Eq. (1), and the total power consumption per day (kWh/day) is calculated by multiplying the actual power by operation time. And finally, the total power consumption per product water (kWh/m$^3$) is calculated by dividing the total power consumption per day by daily water production.

The total power consumption of the pressurized system (0.3932 kWh/m$^3$) is lower than that of the submerged system (0.4735 kWh/m$^3$), by approximately 17% (Table 4). Many researchers reported that the submerged MF systems have advantage over the pressurized system in terms of energy consumption because it is operated at lower operating pressure than the pressurized system. However, if the pressurized system can use the hydraulic pressure generated from the seawater supply pump, the energy consumption of the pressurized system is similar to that of the submerged system especially in SWRO desalination process. As shown in Table 4, the power consumption of seawater supply pump and suction pump in the submerged system is 0.2818 kWh/m$^3$ while that of seawater supply pump in the pressurized system is 0.2714 kWh/m$^3$. Meanwhile, the submerged system requires more energy for air blowing compared with the pressurized system because the submerged MF systems should continuously aerate the membrane tanks to mitigate the membrane fouling. Aeration for the pressurized system is only used at air backwashing step, and it is normally performed for 30–45 s at half-hour intervals. Therefore, the power consumption for aeration of the submerged system (0.0651 kWh/m$^3$) is much larger than that of the pressurized system (0.0016 kWh/m$^3$).

The fumes including seawater and cleaning chemicals from open tanks of the submerged systems often require complex and expensive ventilation systems, for both the operators' safety and the longevity of the facility housing the membrane system, as the fumes can corrode metal buildings or structures within the treatment plant. However, the fumes are not generated in the closed loop system of the pressurized membrane modules. Because of the high flux as well as the above advantage, the pressurized MF systems are more preferred in commercial SWRO desalination plants than the submerged systems. Table 5 shows the references of commercial MF systems as a pretreatment of SWRO. Most of commercial SWRO plants have used the pressurized MF system. In addition, most of the membrane manufacturers provide the pressurized MF membranes for pretreatment of SWRO (references are not shown in this article).

### 3.4. Chemical consumption

$FeCl_3$ and NaOCl are considered as a coagulating and chemical backwashing agent. The chemical consumption rates are predicted from pilot test located near the test bed site. In case of the submerged system, the filtration is performed at feed flow rate of 878 m$^3$/h, and $FeCl_3$ is dosed at the concentration of 4.0 mg/L. CEB is performed at flow rate of 312 m$^3$/h, and NaOCl is dosed at the concentration of 60 mg/L. The frequency of CEB is once every 8 h, and duration is 90 s. Filtration flow rate of the pressurized system is 905 m$^3$/h, and $FeCl_3$ is dosed at the concentration of 4.0 mg/L. CEB is performed at flow rate of 324 m$^3$/h, and NaOCl is dosed at the concentration of 200 mg/L. The frequency of CEB is once a day and duration is 60 s. As shown in Table 6, the chemical consumption rates are similar in both systems.

### 3.5. LCC analysis

Table 7 shows the calculation sheet for LCC analysis used in this study. When calculating the LCC of equipment, there are financial considerations that must be factored into the equation. The considerations include expected useful life of the equipment, interest expense, inflation, discounting, interest rates, and energy rates. The useful life of the equipment is set for 20 years in this study. Inflation is an increase in prices, resulting in a decline in the purchasing power of money. Since the LCC evaluates future expenses, inflation must be factored into the equation, which is

Table 4
Total power consumption of the submerged and the pressurized systems

| System/equipment name | | Pump nor. flow ($m^3$/h) | Pump nor. head (m) | Pump eff. (%) | Motor eff. (%) | Density (ton/$m^3$) | Actual power (kW) | Quantity (kind of operation) | | Operation time (h/day) | Total power consumption (kWh/$m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | CON. | STB | | |
| Submerged system | Seawater supply pump | 878 | 50 | 0.80 | 0.95 | 1.0277 | 161.6 | 1 | 1 | 24 | 0.1879 |
| | Suction pump | 176 | 25 | 0.80 | 0.95 | 1.0277 | 16.2 | 5 | 3 | 24 | 0.0939 |
| | Filtered water pump | 860 | 30 | 0.80 | 0.95 | 1.0277 | 95.0 | 1 | 1 | 24 | 0.1105 |
| | Air blower | 2,160 | 5 | 0.80 | 0.95 | 0.0013 | 56.0 | 1 | 1 | 24 | 0.0651 |
| | Backwash pump | 312 | 25 | 0.80 | 0.95 | 1.0277 | 28.7 | 1 | 1 | 0.8 | 0.0011 |
| | Concentrated water pump | 15 | 20 | 0.75 | 0.95 | 1.0277 | 1.2 | 5 | 3 | 24 | 0.0069 |
| | Cleaning water feed pump | 60 | 15 | 0.75 | 0.95 | 1.0277 | 3.5 | 1 | 0 | 12 | 0.0021 |
| | Cleaning water discharge pump | 60 | 15 | 0.75 | 0.95 | 1.0277 | 3.5 | 1 | 1 | 2 | 0.0003 |
| | Cleaning water suction pump | 60 | 15 | 0.75 | 0.95 | 1.0277 | 3.5 | 1 | 1 | 12 | 0.0021 |
| | Vacuum pump | 24 | 0.74 | 0.75 | 0.95 | 0.0013 | 0.0 | 1 | 1 | 0.5 | 0.0000 |
| | $FeCl_3$ feed pump | 1 | | 0.75 | 0.95 | 1.0277 | 1.0 | 1 | 1 | 24 | 0.0012 |
| | NaOCl feed pump | 0.48 | 50 | 0.75 | 0.95 | 1.0277 | 0.1 | 2 | 1 | 24 | 0.0002 |
| | Agitator | 1 | | 0.75 | 0.95 | | 1.0 | 2 | 0 | 24 | 0.0023 |
| | Total power consumption | | | | | | | | | | 0.4735 |
| Pressurized system | Seawater supply pump | 905 | 70 | 0.80 | 0.95 | 1.0277 | 233.4 | 1 | 1 | 24 | 0.2714 |
| | Filtered water pump | 860 | 30 | 0.80 | 0.95 | 1.0277 | 95.0 | 1 | 1 | 24 | 0.1105 |
| | Compressor | 2,160 | 5 | 0.80 | 0.95 | 0.0013 | 56.0 | 1 | 1 | 0.6 | 0.0016 |
| | Backwash pump | 324 | 35 | 0.80 | 0.95 | 1.0277 | 41.8 | 1 | 1 | 1 | 0.0020 |
| | CIP pump | 60 | 15 | 0.75 | 0.95 | 1.0277 | 3.5 | 1 | 1 | 24 | 0.0041 |
| | $FeCl_3$ feed pump | 1 | | 0.75 | 0.95 | 1.0277 | 1.0 | 1 | 1 | 24 | 0.0012 |
| | NaOCl feed pump | 0.48 | 50 | 0.75 | 0.95 | 1.0277 | 0.1 | 1 | 1 | 24 | 0.0001 |
| | Agitator | 1 | | 0.75 | 0.95 | | 1.0 | 2 | 0 | 24 | 0.0023 |
| | Total power consumption | | | | | | | | | | 0.3932 |

Table 5
References of commercial MF or UF systems as a pretreatment of SWRO

| Location | Country | RO capacity (MIGD) | Membrane manufacturer | Membrane filtration mode |
|---|---|---|---|---|
| Changi | Singapore | 55 | Siemens | Pressurized |
| Fountain Valley | USA | 49 | Siemens | Submerged |
| Shuwaikh | Kuwait | 33 | Norit | Pressurized |
| Ulu Pandan | Singapore | 32 | Asahi Kasei | Pressurized |
| Abu Dhabi | UAE | 18 | INGE | Pressurized |
| West Basin | USA | 17 | Siemens | Pressurized |
| Luggage Point | Australia | 15 | Pall | Pressurized |
| Palm Jumeirah | UAE | 14 | Norit | Pressurized |
| Kranji | Singapore | 12 | Siemens | Pressurized |
| Jeddah Port | Saudi Arabia | 9 | Hydranautics | Pressurized |
| Bedok | Singapore | 7 | Zenon | Submerged |
| Tianjin | China | 7 | Siemens | Pressurized |
| Seletar | Singapore | 5 | Hyflux | Pressurized |
| Makung | Taiwan | 4 | DOW | Pressurized |
| Qingdao | China | 2 | Norit | Pressurized |
| Kalba | UAE | 3 | Norit | Pressurized |
| Hebei | China | 2 | DOW | Pressurized |
| Colakoglu | Turkey | 1 | Norit | Pressurized |

Table 6
Chemical consumption rates for coagulation and chemical backwashing

|  | Chemicals | Concentration (mg/L) | Volume (L/day) |
|---|---|---|---|
| Submerged system | $FeCl_3$ (40%) | 4 | 210.7 |
|  | NaOCl (12%) | 60 | 50.0 |
| Pressurized system | $FeCl_3$ (40%) | 4 | 217.2 |
|  | NaOCl (12%) | 200 | 46.2 |

set to 4% a year in this study. In order to be able to add and compare cash flows that are incurred at different times during the life cycle analysis, they have to be made time equivalent. To do so, the LCC method converts them to present values by discounting. The discount rate used in calculating the LCC, may be calculated by the interest rate of 9% minus the inflation rate of 4%, yielding a net discount rate of 5%. Initial investment costs were calculated using Table 2 (cost data not shown), and installation and start-up costs were included in initial investment costs. Energy costs per year were calculated using Table 4 described in Section 3.3. In this study, the permeate water production is 860 $m^3/h$, and electricity price is estimated to be 0.08 USD/kWh. Chemical costs per year were calculated using Table 6 described in Section 3.4. The operating and maintenance costs are assumed to be 150,000 and 200,000 dollars per year, respectively. Downtime costs and other yearly costs are not considered in both systems. The present values were calculated using Eq. (2).

The cost data are not presented in this study, however, the LCC analysis shows that the pressurized system has the lower LCC by 1,366,315 USD compared with the submerged system for entire facility over 20 years LCC term. The proportion of total costs is presented in Fig. 2. It was calculated by dividing each cost value by the LCC value of the submerged system (the largest value). As a result, the LCC of the pressurized system is less than that of the submerged system, by approximately 13%. Moreover, the total water cost of the pressurized system is calculated to be 0.062 $USD/m^3$, whereas that of the submerged system is 0.071 $USD/m^3$. Consequently, the pressurized MF pretreatment system has economic advantage over the submerged system especially in SWRO desalination plant, although many researchers reported on the contrary to this. From these results, the pressurized MF system is applied to the test bed SWRO desalination plant as a pretreatment system.

## 4. Conclusions

In this study, the economic analysis of MF system as a pretreatment of SWRO was performed using the LCC analysis method to decide and apply the filtration mode of membrane modules in the test bed

Table 7
Calculation sheet for life cycle cost analysis

| No. | Items | Unit | Submerged | Pressurized | Remarks |
|---|---|---|---|---|---|
| 1 | Number of years | | 20 | 20 | |
| 2 | Interest rate | % | 9% | 9% | Assumed |
| 3 | Inflation rate | % | 4% | 4% | Assumed |
| 4 | Initial investment costs | | – | – | CAPEX |
| 5 | Installation and start-up costs | | – | – | Not applicable |
| 6 | Energy consumption | | | | |
| | ① Specific energy consumption | kWh/m$^3$ | 0.4735 | 0.3932 | Section 3.3 |
| | ② Permeate water production | m$^3$/h | 860 | 860 | Product water |
| | ③ Total energy consumption (① × ②) | kW | 407.2 | 338.1 | |
| | ④ Average operation hours per year | h | 8,322 | 8,322 | 95% |
| | ⑤ Energy price per kWh | USD | 0.08 | 0.08 | |
| | Energy cost per year (③ × ④ × ⑤) | USD | – | – | |
| 7 | Chemical costs per year | USD | – | – | Section 3.4 |
| 8 | Operating costs per year | USD | 150,000 | 150,000 | Assumed |
| 9 | Maintenance and repair costs | USD | 200,000 | 200,000 | Assumed |
| 10 | Downtime costs per year | | – | – | Not applicable. |
| 11 | Other yearly costs | | – | – | Not applicable |
| 12 | Sum of yearly cost (6 + 7 + 8 + 9 + 10 + 11) | USD | – | – | |
| 13 | Present value of yearly costs | USD | – | – | OPEX |
| Result | | | | | |
| | Present LCC-value (4 + 5 + 13) | USD | – | – | |

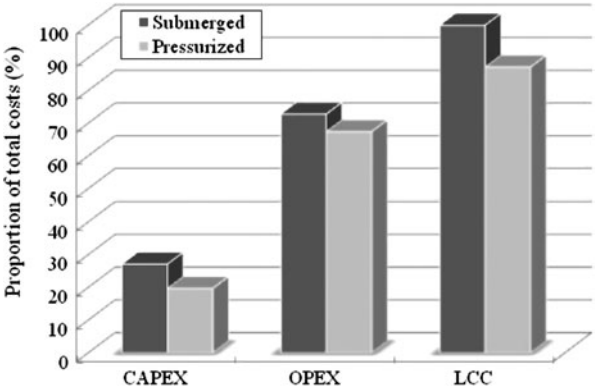


Fig. 2. The proportion of total costs for the submerged and the pressurized systems.

desalination plant. The following conclusions can be drawn:

(1) Capital cost of the pressurized system is lower than that of the submerged system because the submerged system requires many pumps for membrane operation. Moreover, the cost for civil works of the submerged system is higher than that of the pressurized system because the submerged system requires several concrete tanks.

(2) The energy consumption of the pressurized system is lower than that of the submerged system because the pressurized system can use the hydraulic pressure generated from the seawater supply pump. In addition, air consumption of the pressurized system is much lower than that of the submerged system.

(3) The LCC analysis shows that the pressurized system has the lower LCC compared with the submerged system for entire facility over 20 years LCC term. Consequently, the pressurized MF pretreatment system has economic advantage over the submerged system especially in SWRO desalination plant.

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