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## Method Article

# Process design of industrial-scale membrane distillation system for wastewater treatment in nano-electronics fabrication facilities

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## A B S T R A C T

The main challenge for implementing an industrial-scale membrane distillation (MD) system is its associated thermal power demand and resulting operational cost, which hinders the commercialization of the technology, even after forty years of its evolution and development. Nevertheless, an enormous amount of waste heat releasing from the nano-electronics facilities provides MD an opportunity to showcase its potential for treating industrial wastewater discharging from the facilities. In this work, a waste heat driven MD system for a plant capacity of 15 m<sup>3</sup>/h was analyzed in terms of its thermal power demand and unit wastewater treatment cost. The economic analysis was performed using the factored estimate method. The results show that the thermal power requirement of the industrial-scale MD system was 12.38 MW, and the unit water treatment cost can vary between 3–23 \$/m<sup>3</sup>, based on plant type (i.e., retrofitted facility or new wastewater treatment facility).

- Determination of various industrial waste heat sources in typical nano-electronics fabrication facilities via interviews of related professionals, and designed industrial-scale waste heat integrated MD system for nano-electronics industries
- Mass and energy balances around the industrial-scale MD system for wastewater treatment in nano-electronics industries
- Equipment design for the purpose and performed economic evaluation of the MD system by customizing factored estimate method

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**Abbreviations:** AGMD, Air Gap Membrane Distillation; CAPEX, Capital Expenditures; CEPCI, Chemical Engineering Plant Cost Index; CF, Contingency Fees; CO, Construction Overhead; I, Insurance; ISBL, Inside Battery Limits; MD, Membrane Distillation; NC, Normalized Capital Investment; NO, Normalized Operating and Maintenance Investment; OPMEX, Operating and Maintenance Expenditure; OSBL, Outside Battery Limits; STEC, Specific Thermal Energy Consumption; TCI, Total Capital Investment; TDC, Total Depreciable Capital; TPC, Total Permanent Capital; VOC, Volatile Organic Compound; WC, Working Capital.

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E-mail address: [ieno@kth.se](mailto:ieno@kth.se) (I.-e.-. Noor).<https://doi.org/10.1016/j.mex.2020.101066>2215-0161/© 2020 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)

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Method name:	System analysis of Membrane Distillation
Name and reference of the original method:	D. W. Green and R. H. Perry, Perry's Chemical Engineers' Handbook, Eighth Edition. McGraw-Hill Education, 2007.

1. Background

Nano-electronics industries have very complex and delicate processes for the fabrication of semiconductor chips, that require a large amount of ultrapure and process water. Typically, nano-electronics industries consume ~1000 m<sup>3</sup>/day of ultrapure water [1]. Consequently, the manufacturing units generate a corresponding amount of wastewater. These waste water streams include acids, spent solvents, waste oils, and metals [2]. Fig. 1 represents the waste produced in a typical nano-electronics manufacturing plant. Direct discharge of these wastewaters into a water body is strictly regulated by water quality control authorities unless they are pretreated according to international and local standards. Current emphasis is being placed on reducing the amount of waste produced. However, until a more suitable means of production is established, the waste streams must be treated.

In the present situation, there are many different technologies in use to treat wastewater involving mechanical separation to thermal separation. However, researchers are becoming attracted to employing membrane technologies due to their intrinsic environment-friendly attitude. Reverse osmosis, micro-filtration and nano-filtration are traditional membrane processes that are used for this purpose [3]. These methods are highly recognized and generally effective, but there is still a need for a cost-efficient system with enhanced water purity. Moreover, there are some technical issues involved in these technologies, especially organic and inorganic fouling, disposal of the brine solutions

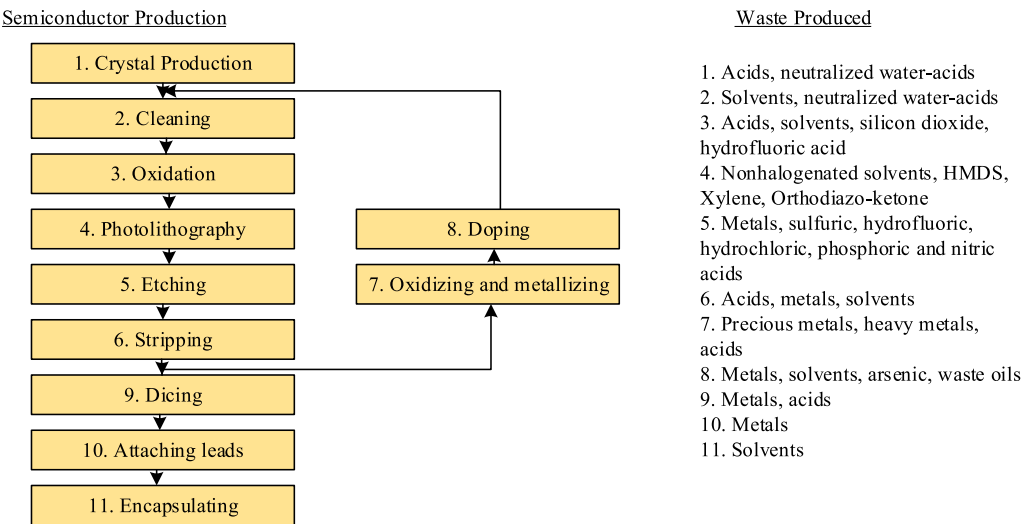
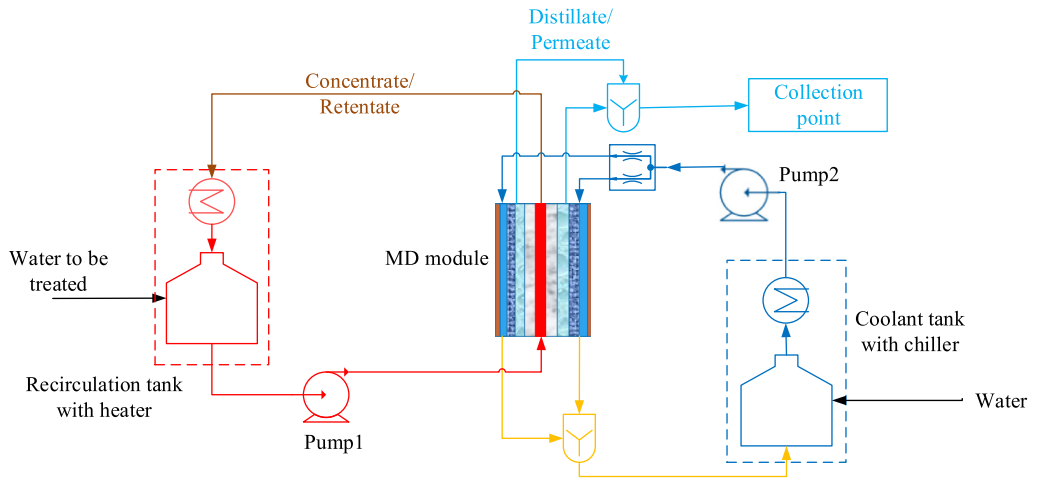


Fig. 1. Waste produced in nano-electronics fabrication facilities (adapted from [2]).



**Fig. 2.** Schematic flow diagram of AGMD separation process.

and upper pressurization limits. In this regard, “Membrane distillation” (MD) is one of the promising membrane processes which have unique characteristics for water treatment. The MD process takes place at temperatures below 100°C and at ambient pressure. As compared to other water purification methods, it is less sensitive to feed concentration, and it utilizes low-grade heat [4]. Fig. 2 presents the schematic diagram of the air gap membrane distillation (AGMD) separation process.

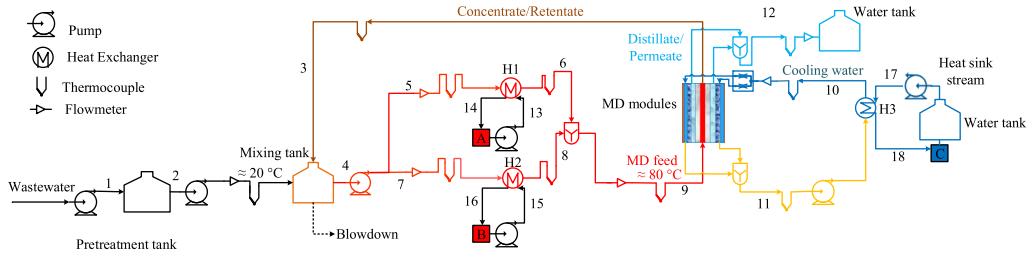
Due to the fact that the system can be operated using low-grade heat sources, including district heating [5] and industrial waste heat [6]. These integrated systems provide sustainable, cost-effective and energy-efficient approaches for wastewater treatment. Moreover, these systems can play a vital role in reducing carbon footprints and promoting the concept of a green world. In this work, industrial waste heat integrated membrane distillation process for wastewater treatment in nano-electronics fabrication facilities is investigated.

## 2. Method details

Previously published works [7,8] clearly indicate the successful application of MD in nano-electronics fabrication facilities for the treatment of different wastewater streams. However, the detailed mass and energy balances and economic evaluations are not provided for verification of industrial-scale MD system. Woldemariam et al. [5] presented a study on a detailed parametric analysis of a semi-commercial Xzero MD module, including temperature and flow rate dependencies on permeate yield and thermal energy demand; therefore, it is considered as a reference for performing the technical evaluations. This work is performed for a wastewater treatment plant having a capacity of 15 m<sup>3</sup>/h. (This paper is a co-submission of original research presented in [9]). Different industrial waste heat sources can be considered for operating an industrial-scale MD system in typical nano-electronics facilities. These heat sources are as follows.

1. Condenser outlet water from chiller (35-90°C).
2. Process cooling water from manufacturing tools (30-90°C).
3. Hot air from VOCs combustion abatement systems (350°C).
4. Spent etchant (phosphoric acid) from nitride etching (150-200°C).
5. Spent stripper (sulfuric acid) from photoresist stripping and cleaning (90-140°C).
6. Dissipated heat from compressors, steam generators and pumps (temperature varies significantly).

These heat sources can collectively provide 35-40 MW of thermal power. It is noteworthy that the above-mentioned information is tightly held and not publicly available by official means. In this work,



**Fig. 3.** Flow diagram of proposed industrial-scale waste heat driven MD integrated system; A-Condenser outlet water from chiller; B- Hot air from VOCs abatement system; C- Heat sink.

condenser outlet water from the chiller (8-12 MW) and hot air from VOCs combustion abatement system (0.25-0.5 MW) are chosen to provide the required thermal energy to the industrial-scale MD system. Fig. 3 shows the proposed waste heat driven MD system.

## 2.1. Mass and energy balance

Global mass and energy balances were performed in order to design process equipment for the integrated MD system. All calculations are performed considering atmospheric pressure.

*Commonly used symbols*

$m$  = mass flow rate

$T$  = temperature

$Q$  = thermal power

$c_p$  = heat capacity of the water

$c_{pa}$  = heat capacity of the air

$A$  = area

The total thermal power demand ( $Q_t$ ) was calculated using Eq. (1).

$$Q_t = m_{dT} STEC \quad (1)$$

where subscript  $dT$  depicts the desired total permeate, and specific thermal energy consumption is shown as STEC, which is taken from the reference study [5] when the operating conditions were as follows: MD feed inlet temperature = 80°C, cooling water inlet temperature = 26°C, and feed and coolant flow rates were 1200 L/h (0.333 kg/s).

$$Q_t = 15 \text{ m}^3/\text{h} \times 825 \text{ kWh/m}^3 = 12.38 \text{ MW}.$$

Since the maximum power provided by heat exchanger H1 cannot more than 12 MW due to heat source thermal power limitation, therefore:

$$Q_{H1} = 12 \text{ MW}$$

The remaining required power can be obtained considering heat exchanger H2,  $Q_{H2}$  can be calculated using Eq. (2).

$$\begin{aligned} Q_{H2} &= Q_t - Q_{H1} \\ Q_{H2} &= 12.38 \text{ MW} - 12 \text{ MW} = 0.38 \text{ MW} \end{aligned} \quad (2)$$

Heat sources inlet streams temperatures (based on the information given above) are mentioned as follows:

$$T_{13} = 85^{\circ}\text{C}$$

$$T_{15} = 350^{\circ}\text{C}$$

Feed, coolant and permeate temperature information was taken from the reference study and shown below.

$$T_6 = T_8 = T_9 = 80^{\circ}\text{C}$$

$$T_{10} = 26^{\circ}\text{C}$$

$$T_{11} = 39^{\circ}\text{C}$$

$$T_{12} = 43^{\circ}\text{C}$$

The equation used for calculating required MD feed flow rates based on the data obtained from the reference study is shown in Eq. (3).

$$\frac{m_{dT}}{m_d} = \frac{m_{fT}}{m_f} \quad (3)$$

where subscript  $fT$  shows the total required MD feed and subscripts  $d$  and  $f$  are the reference permeate and MD feed when MD feed temperature was  $80^{\circ}\text{C}$  and cooling water temperature was  $26^{\circ}\text{C}$ .

Number of membrane modules in each reference cascade = 2

Reference membrane area for one MD cascade =  $A_m = 4.6 \text{ m}^2$

Reference MD feed flow rate for one MD cascade =  $1200 \text{ L/h} = 0.333 \text{ kg/s}$

Reference permeate flow rate for one MD cascade =  $5.85 \text{ L/m}^2 \cdot \text{h} \times 4.6 \text{ m}^2 \times 1 \text{ h}/3600 \text{ s} = 0.0075 \text{ kg/s}$

Recovery ratio per cycle =  $0.0075 \text{ kg/s} / 0.33 \text{ kg/s} = 0.0225$

Desired permeate flow rate =  $4.17 \text{ kg/s} = 15 \text{ m}^3/\text{h} = 330 \text{ m}^3/\text{day}$

Total MD feed flow rate =  $4.17 \text{ kg/s} / 0.0225 = 185 \text{ kg/s} = 666 \text{ m}^3/\text{h} = 14652 \text{ m}^3/\text{day}$

In this work, it is assumed that  $1 \text{ kg}$  of aqueous solution is equal to  $1 \text{ L}$  of aqueous solution.

Thus,

$$m_4 = m_9 = 185 \text{ kg/s}$$

$$m_1 = m_2 = m_{12} = 4.17 \text{ kg/s}$$

The equation used for global mass balance around MD is mentioned in Eq. (4).

$$m_{fT} = m_{rT} + m_{dT} \quad (4)$$

where subscript  $rT$  is for the corresponding retentate.

$$m_3 = 185 \text{ kg/s} - 4.17 \text{ kg/s} = 180.83 \text{ kg/s}$$

The retentate temperature was  $65^{\circ}\text{C}$  for the reference conditions. Based on this information, the temperature after the mixing tank was calculated as using Eq. (5)

$$\begin{aligned} T_4 &= \frac{m_2 c_p T_2 + m_3 c_p T_3}{m_2 c_p + m_3 c_p} \\ T_1 &= T_2 = 20^{\circ}\text{C} \\ T_3 &= 65^{\circ}\text{C} \\ T_4 &= (4.17 \text{ kg/s} \times 4180 \text{ J/kg} \cdot ^{\circ}\text{C} \times 20^{\circ}\text{C} + 180.83 \text{ kg/s} \times 4180 \text{ J/kg} \cdot ^{\circ}\text{C} \times 65^{\circ}\text{C}) / \\ &\quad (4.17 \text{ kg/s} \times 4180 \text{ J/kg} \cdot ^{\circ}\text{C} + 180.83 \text{ kg/s} \times 4180 \text{ J/kg} \cdot ^{\circ}\text{C}) \quad T_4 = T_5 = T_7 = 63.98^{\circ}\text{C} \end{aligned} \quad (5)$$

The flow rate of the wastewater stream passing through the heat exchanger H1 can be calculated using Eq. (6).

$$\begin{aligned} m_5 &= m_6 = \frac{Q_{H1}}{c_p (T_6 - T_5)} \\ m_5 &= m_6 = 12 \text{ MW} / (4180 \text{ J/kg} \cdot ^{\circ}\text{C} \times (80^{\circ}\text{C} - 63.98^{\circ}\text{C})) = 179.2 \text{ kg/s} \end{aligned} \quad (6)$$

The flow rate of the wastewater stream passing through the heat exchanger H2 can be calculated using Eq. (7).

$$\begin{aligned} m_7 &= m_8 = m_4 - m_5 \\ m_7 &= m_8 = 185 \text{ kg/s} - 179.32 \text{ kg/s} = 5.67 \text{ kg/s} \end{aligned} \quad (7)$$

The pinch point temperature difference around heat exchangers is considered 5°C. Therefore  $T_{14}$  and  $T_{18}$  is taken accordingly in Eqs. (8) and (9).

$$\begin{aligned} T_{14} &= T_5 + 5^\circ\text{C} \\ T_{14} &= 63.98^\circ\text{C} + 5^\circ\text{C} = 68.98^\circ\text{C} \end{aligned} \quad (8)$$

$$\begin{aligned} T_{18} &= T_{10} - 5^\circ\text{C} \\ T_{18} &= 26^\circ\text{C} - 5^\circ\text{C} = 21^\circ\text{C} \end{aligned} \quad (9)$$

Based on the dew point of VOCs exhaust, the temperature of hot air can be reduced up to 85°C.

$$T_{16} = 85^\circ\text{C}$$

Mass flow rates of condenser outlet water across heat exchanger H1 and hot air across heat exchanger H2 can be calculated using Eqs. (10) and (11).

$$\begin{aligned} m_{13} &= m_{14} = \frac{Q_{H1}}{c_p (T_{13} - T_{14})} \\ m_{13} &= m_{14} = 12 \text{ MW} / (4180 \text{ J/kg} \cdot ^\circ\text{C} \times (85^\circ\text{C} - 68.98^\circ\text{C})) = 179.2 \text{ kg/s} \end{aligned} \quad (10)$$

$$\begin{aligned} m_{15} &= m_{16} = \frac{Q_{H2}}{c_{pa} (T_{15} - T_{16})} \\ m_{15} &= m_{16} = 0.38 \text{ MW} / (1000 \text{ J/kg} \cdot ^\circ\text{C} \times (350^\circ\text{C} - 85^\circ\text{C})) = 1.43 \text{ kg/s} \end{aligned} \quad (11)$$

The coolant flow rates and heat sink stream flow rates are assumed to be the same as the MD feed flowrate.

$$\begin{aligned} m_{10} &= m_{11} = 185 \text{ kg/s} \\ m_{17} &= m_{18} = 185 \text{ kg/s} \end{aligned}$$

Thermal power dissipation ( $Q_c$ ) from the system by cooling water can be calculated using Eq. (12).

$$\begin{aligned} Q_c &= Q_{H3} = m_{10} c_p (T_{11} - T_{10}) \\ Q_c &= Q_{H3} = 185 \text{ kg/s} \times 4180 \text{ J/kg} \cdot ^\circ\text{C} \times (39^\circ\text{C} - 26^\circ\text{C}) = 10 \text{ MW} \end{aligned} \quad (12)$$

Heat sink stream inlet temperature can be calculated using Eq. (13).

$$\begin{aligned} T_{17} &= T_{18} - \frac{Q_{H3}}{m_{18} c_p} \\ T_{17} &= 21^\circ\text{C} - (10 \text{ MW} / (185 \text{ kg/s} \times 4180 \text{ J/kg} \cdot ^\circ\text{C})) = 8^\circ\text{C} \end{aligned} \quad (13)$$

Thermal power loss ( $Q_l$ ) can be calculated using Eq. (14)

$$\begin{aligned} Q_l &= Q_f - Q_c \\ Q_l &= 12.38 \text{ MW} - 10 \text{ MW} = 2.38 \text{ MW} \end{aligned} \quad (14)$$

Mass flow rates and temperature of streams results for the integrated system are summarized in Table 1.

## 2.2. Equipment design

The major equipment are MD modules and heat exchangers.

### 1. Membrane modules and membrane area

Total membrane area ( $A_T$ ) can be calculated using Eq. (15).

**Table 1**  
Mass flowrates and temperatures of all main streams involved in the system.

Streams (#)	Mass flowrate, m (kg/s)	Temperature, T (°C)
Makeup wastewater (1)	4.17	20
Wastewater after pre-treatment (2)	4.17	20
Wastewater after mixing tank (4)	185	63.98
Wastewater inlet for heat exchanger H1 Inlet (5)	179.2	63.98
(associated with heat source A) Outlet (6)	179.2	80
Wastewater inlet for heat exchanger H2 Inlet (7)	5.67	63.98
(associated with heat source B) Outlet (8)	5.67	80
MD feed (9)	185	80
Concentrate/Retentate (3)	180.83	65
Distillate/permeate (12)	4.17	43
Cooling water Inlet (10)	185	26
Outlet (11)	185	39
Condenser outlet water Inlet (13)	179.2	85
Outlet (14)	179.2	68.98
Hot air Inlet (15)	1.43	350
Outlet (16)	1.43	85
Heat sink stream Inlet (17)	185	8
Outlet (18)	185	21

$$A_T = m_{dT} \frac{A_m}{m_d}$$
$$A_T = 4.17 \text{ kg/s} \times (4.6 \text{ m}^2 / 0.0075 \text{ kg/s}) = 2553 \text{ m}^2 \tag{15}$$

Total number of MD cascades =  $2557 \text{ m}^2 / 4.6 \text{ m}^2 = 555$   
Total number of MD modules required =  $555 \times 2 = 1110$

2. Heat Exchangers

The required heat exchangers area ( $A_{HX}$ ) can be calculated using Eq. (16).

$$A_{HX} = \frac{Q_{HX}}{U \Delta T} \tag{16}$$

where subscript X =1,2 and 3, U is overall heat transfer coefficient (for water:  $250 \text{ W/m}^2\text{.C}$  and for air:  $10 \text{ W/m}^2\text{.C}$ ), and  $\Delta T$  represents the temperature difference between inlet and outlet streams.

$$A_{H1} = \frac{Q_{H1}}{U_w(T_{13}-T_{14})} = \text{MW} / (250 \text{ W/m}^2\text{.C} \times (85^\circ\text{C} - 68.98^\circ\text{C})) = 2997 \text{ m}^2$$
$$A_{H2} = \frac{Q_{H2}}{U_a(T_{15}-T_{16})} = 0.38 \text{ MW} / (10 \text{ W/m}^2\text{.C} \times (350^\circ\text{C} - 85^\circ\text{C})) = 143 \text{ m}^2$$
$$A_{H3} = \frac{Q_{H3}}{U_w(T_{11}-T_{10})} = 10 \text{ MW} / (250 \text{ W/m}^2\text{.C} \times (39^\circ\text{C} - 26^\circ\text{C})) = 3093 \text{ m}^2$$

3. Pumps

Based on the flow rates of streams, commercial pumps/compressors, and water tanks are considered to operate industrial-scale MD system.  
Water pumps: Capacity =  $670 \text{ m}^3/\text{h}$ , Number of pumps=4  
Water pumps: Capacity =  $15 \text{ m}^3/\text{h}$ , Number of pumps=2  
Air compressor: Number of compressors=1

2.3. Cost evaluation

The detailed calculation method for capital expenditure (CAPEX) and operating and maintenance expenditure (OPMEX) for a  $15 \text{ m}^3/\text{h}$  AGMD plant is presented below.



**Table 2**  
Cost of reference equipment.

$C_{pi}$ of MD modules	6100 \$/module [5]
$C_{pi}$ of MD membranes	90 \$/m <sup>2</sup> [11]
$C_{pi}$ of heat exchangers	325 \$/m <sup>2</sup> [12]
$C_{pi}$ of pumps	5500 \$/100 m <sup>3</sup> /h [13]
$C_{pi}$ of water tanks	130 \$/m <sup>3</sup> /day [14]
$C_{pi}$ of process control	140 \$/m <sup>3</sup> /day [14]

### 2.3.1. Capital investment

Eq. (17) was used for total equipment cost ( $C_{eq}$ ) calculation considering the factored estimate method [10].

$$C_{eq} = I_{CEPCI} \left[ \sum \left( \frac{C_N}{C_R} \right)^m C_{pi} \right] \quad (17)$$

where  $C_{pi}$  represents the reference cost of equipment,  $C_N$  &  $C_R$  denote new (desired) and reference capacity of the equipment,  $I_{CEPCI}$  is used for the value of the chemical engineering plant cost index (CEPCI). However,  $m$  represents the degression constant, and its value is 0.8 for MD modules and heat exchangers, and 0.667 for pumps and water tanks. Table 2 shows the cost of reference equipment.

#### 1. Membrane Distillation modules cost

$$\text{Total cost of MD modules} = (575/550)^a \times (1110/1)^{0.8} \times \$6100 = \$1741434$$

where  $a$  is  $I_{CEPCI}$  and used to account for inflation. The MD modules were manufactured in 2010, and we used the most recent CEPCI for MD modules to convert all costs to the year 2017.

#### 2. Membranes cost

$$\text{Total cost of membranes} = (2553 \text{ m}^2 / 1 \text{ m}^2)^{0.8} \times \$90 = \$47854$$

#### 3. Heat Exchangers cost

$$\text{Total cost of heat exchanger H1} = (575/381.1)^b \times (2997 \text{ m}^2 / 1 \text{ m}^2)^{0.8} \times \$325 = \$296414$$

$$\text{Total cost of heat exchanger H2} = (575/381.1)^b \times (143 \text{ m}^2 / 1 \text{ m}^2)^{0.8} \times \$325 = \$26046$$

$$\text{Total cost of heat exchanger H3} = (575/381.1)^b \times (3093 \text{ m}^2 / 1 \text{ m}^2)^{0.8} \times \$325 = \$303960$$

$$\text{Total cost of Heat exchangers} = \$296414 + \$26046 + \$303960 = \$626420$$

where  $b$  is  $I_{CEPCI}$  and used to account for inflation. Cost curves were published in the year 1995, and we used the most recent CEPCI for heat exchangers to convert all costs to the year 2017.

#### 4. Pumps and compressor cost

$$\text{Total cost of 4 water pumps} = (575/389.5)^c \times (666 \text{ m}^3/\text{h} / 100 \text{ m}^3/\text{h})^{0.667} \times \$5500 \times 4 = \$115038$$

$$\text{Total cost of 2 water pumps} = (575/389.5)^c \times (15 \text{ m}^3/\text{h} / 100 \text{ m}^3/\text{h})^{0.667} \times \$5500 \times 2 = \$4582$$

$$\text{Total cost of 1 air compressor} = (575/389.5)^c \times \$23500 = \$34692$$

$$\text{Total cost of pumps and compressors} = \$115038 + \$4582 + \$34692 = \$154311$$

where  $c$  is  $I_{CEPCI}$  and used to account for inflation. Cost curves were published in the year 1998, and we used the most recent CEPCI for pumps to convert all costs to the year 2017.

#### 5. Water tanks cost

$$\text{Total MD feed flow rate} = \text{Total coolant flow rate} = 14652 \text{ m}^3/\text{day}$$

$$\text{Feed and coolant tanks cost} = (14652 \text{ m}^3/\text{day} / 1 \text{ m}^3/\text{day})^{0.667} \times 2 \times \$130 = \$156180$$

$$\text{Total permeate flow rate} = \text{Total pretreated wastewater flow rate} = 330 \text{ m}^3/\text{day}$$

$$\text{Permeate and pre-treatment tanks cost} = (330 \text{ m}^3/\text{day} / 1 \text{ m}^3/\text{day})^{0.667} \times 2 \times \$130 = \$12440$$

$$\text{Total tanks cost} = \$156180 + \$12440 = \$168620$$

## 6. Process control cost

Security controls, sensors and electrical subsystems cost =  $(14652 \text{ m}^3/\text{day} / 1 \text{ m}^3 / \text{day})^{0.667} \times \$140 = \$84097$

Purchased equipment cost =  $\$1741434 + \$47854 + \$626420 + \$154311 + \$168620 + \$84097 = \$2822736$

*Scenario 1: New wastewater treatment facility*

1. Total depreciable capital (TDC) includes inside and outside battery limits, construction overhead, contingency fees and insurance.

i. Inside battery limits (ISBL) consider total equipment cost and process construction cost, can be calculated by using Eq. (18).

$$\text{ISBL} = C_{eq} f_L L_E$$

$$\text{ISBL} = \$2822736 \times 5.7^d \times 1.2^e = \$19307572 \quad (18)$$

where d is Lang factor ( $f_L$ ) for the fluid processing plant and e is Location index ( $L_E$ ) for Europe.

ii. Outside battery limits (OSBL) consider the storage and administration costs and calculated using Eq. (19).

$$\text{OSBL} = 0.4 C_{eq} f_L L_E$$

$$\text{OSBL} = \$19307572 \times 0.4 = \$7723029 \quad (19)$$

iii. Other costs include construction overhead (CO), contingency fees (CF) and insurance (I).

CO = 15% of  $C_{eq}$  and labor cost

CF = 10% of  $C_{eq}$

I = 5 % of  $C_{eq}$

CO =  $(\$2822736 + \$3600) \times 0.15 = \$423952$

CF =  $\$2822736 \times 0.1 = \$282274$

I =  $\$2822736 \times 0.05 = \$141137$

Total depreciable capital investment ( $C_{TDC}$ ) can be calculated using Eq. (20).

$$C_{TDC} = \text{ISBL} + \text{OSBL} + \text{CO} + \text{CF} + \text{I}$$

$$C_{TDC} = \$19307572 + \$7723029 + \$423952 + \$282274 + \$141137 = \$27877964 \quad (20)$$

2. Total permanent capital (TPC) includes site preparation and land costs (LC) and plant startup cost (PS).

LC = 2% of  $C_{TDC}$

PS = 10% of  $C_{TDC}$

LC =  $\$27877964 \times 0.02 = \$557559$

PS =  $\$27877964 \times 0.1 = \$2787796$

Total permanent capital investment ( $C_{TPC}$ ) can be calculated using Eq. (21).

$$C_{TPC} = \text{LC} + \text{PS}$$

$$C_{TPC} = \$557559 + \$2787796 = \$3345356 \quad (21)$$

3. Working capital (WC) can be calculated using Eq. (22).

$C_{WC} = 8.3\%$  of OSBL

$$C_{WC} = \$7723029 \times 0.0833 = \$643328 \quad (22)$$

Thus, total capital investment (TCI) for scenario 1 can be calculated using Eq. (23).

$$C_{TCI} = C_{TDC} + C_{TPC} + C_{WC}$$

$$C_{TCI} = \$27877964 + \$3345356 + \$643328 = \$31866648 \quad (23)$$

*Scenario 2: Retrofitted wastewater treatment plant*

Total capital investment (TCI) for scenario 2 can be calculated using Eq. (24)

$$C_{TCI2} = C_{eq} + I + C_R \quad (24)$$

where  $C_R$  is the retrofitting cost which is equal to 4% of  $C_{eq}$ .

Retrofitting cost =  $\$2822736 \times 0.04 = \$112910$

$C_{TCI2} = \$2822736 + \$141136 + \$112910 = \$3076791$

The annual capital investment ( $C_a$ ) can be calculated using Eq. (25)

$$C_a = \left( \frac{I(1+i)^L}{(1+i)^L - 1} \right) C_{TCI} \quad (25)$$

where annual interest rate  $i=5\%$  [15,16] and plant life span =  $L = 20$  years.

$$C_{a1} = \$31866648 \times \left( \frac{(0.05 \times (1 + 0.05)^{20})}{((1 + 0.05)^{20} - 1)} \right) = \$2557062$$

$$C_{a2} = \$3076791 \times \left( \frac{(0.05 \times (1 + 0.05)^{20})}{((1 + 0.05)^{20} - 1)} \right) = \$246890$$

Normalized capital investment  $C_{NC}$  can be calculated using Eq. (26)

$$C_{NC} = \frac{C_a}{m_{dT}}$$

$$C_{NC1} = \$2557062 / 120000 \text{ m}^3 = 21.31 \text{ \$/m}^3$$

$$C_{NC2} = \$246890 / 120000 \text{ m}^3 = 2.06 \text{ \$/m}^3 \quad (26)$$

### 2.3.2. Operating and maintenance cost

Annual operating and maintenance cost ( $OPM_a$ ) is same for both scenarios and considers the following costs.

1. Thermal energy cost when industrial waste heat is used = 0  $\$/MWh$
2. Specific electrical energy demand for the considered range of MD feed flow rate is mentioned in the reference study (0.35  $kWh/m^3$ )
3. The other operational costs are taken from the literature as follows.
  - i. Service and maintenance = 0.033  $\$/m^3$  [11] [71]
  - ii. Labor = 0.03  $\$/m^3$  [11,14,15]
  - iii. Cleaning chemicals = 0.0018  $\$/m^3$  [11,14]
  - iv. Pretreatment chemicals (if required) = 0.02  $\$/m^3$  [17]
  - v. Annual membrane replacement = 15% of total membrane cost [18]
  - vi. Brine disposal = 0.0015  $\$/m^3$  [19]
  - vii. Cooling water = 0.02  $\$/m^3$  of total cooling water [20]

Thermal energy cost = \$0

Electricity cost =  $0.35 \text{ kWh/m}^3 \times 0.09 \text{ \$/kWh} \times 15 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$3780$

Maintenance and service cost =  $0.033 \text{ \$/m}^3 \times 15 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$3960$

Labor cost =  $0.03 \text{ \$/m}^3 \times 15 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$3600$

Cleaning chemicals =  $0.0018 \text{ \$/m}^3 \times 15 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$216$

Pretreatment chemical =  $0.02 \text{ \$/m}^3 \times 15 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$2400$

Membrane replacement cost =  $\$47854 \times 0.15 = \$7178$

Brine disposal cost =  $0.0015 \text{ \$/m}^3 \times 15 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$180$

Cooling water cost =  $0.02 \text{ \$/m}^3 \times 666 \text{ m}^3/\text{h} \times 8000 \text{ h} = \$106560$

$OPM_a = \$0 + \$3780 + \$7178 + \$3960 + \$3600 + \$180 + \$216 + \$2400 + \$106560 = \$127874$

Normalized operating and maintenance investment ( $C_{NO}$ ) can be calculated using Eq. (27)

$$C_{NO} = \frac{OPM_a}{m_{dT}}$$

$$C_{NO} = \$127874 / 120000 = 1.065 \text{ \$/m}^3 \quad (27)$$

## Water treatment cost

Unit water treatment cost can be calculated using Eq. (28)

$$\begin{aligned} C_w &= C_{NC} + C_{NO} \\ C_{w1} &= 21.31 \text{ \$/m}^3 + 1.06 \text{ \$/m}^3 = 22.37 \text{ \$/m}^3 \\ C_{w2} &= 2.06 \text{ \$/m}^3 + 1.06 \text{ \$/m}^3 = 3.12 \text{ \$/m}^3 \end{aligned} \quad (28)$$

## Conclusion

This paper focuses on the process design of a waste heat driven MD system for wastewater treatment in nano-electronics industries. The results show that an MD plant of capacity 15 m<sup>3</sup>/h demands 12.38 MW thermal power, which can be provided with internal waste heat sources in nano-electronics industries. The expected wastewater treatment cost ranges from 3 \\$/m<sup>3</sup> (retrofitted facility) to 23 \\$/m<sup>3</sup> (new wastewater treatment facility). The cost comparison with competitive technologies (i.e., electrochemical process (59 \\$/m<sup>3</sup>)) shows the economic superiority of waste heat driven MD system. Moreover, the proposed system has two-folds benefits in environmental aspects: water management and emission control.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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