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Techno-economic system analysis of membrane distillation process for treatment of chemical mechanical planarization wastewater in nano-electronics industries

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ABSTRACT

Membrane distillation (MD) is a promising separation technology for the treatment of chemical mechanical planarization (CMP) wastewater releasing from nano-electronics industries. In order to determine the feasibility of the process at industrial scale, the most important factors are large-scale system evaluation and related economics. Since membrane distillation is a thermally driven process, therefore, different integration possibilities between an air gap membrane distillation (AGMD) system and low-grade heat sources are identified and analyzed in this work. Global mass and energy balances are conducted around AGMD system for CMP wastewater treatment in a typical nano-electronics manufacturing facility. It is determined that around 100 GWh of thermal energy can be readily recovered via internal sources and reused to treat 120,000 m^3 CMP wastewater/year with MD feed temperature of 80 °C. Along with the technical feasibility of the system, the detailed economic evaluation has also been performed. Annual capital investment and operating cost showed that the expected CMP wastewater treatment cost can be as low as 3 $/$m^3$, which is estimated to be nearly 95% lower than the wastewater treatment cost using electro-chemical systems.

1. Introduction

In 1958 the very first patent on the principle of integrated circuits (ICs) was published by Jack Kilby of Texas Instruments labs. Since then, the concept of forming transistors on a silicon crystal wafer has been used to fabricate ICs [1]. The manufacturing process of these ICs is quite complex, as outlined in Fig. 1. The first stage is to create a high-purity silicon ingot, which is further sliced into 200–300 mm diameter silicon wafers. The second stage involves forming a silicon dioxide top layer and then, diffusing a dopant to alter its electrical characteristics; follow-on deposition of the desired insulating/conducting layers on the silicon substrate is performed, depending on the application. In the next stage, a cover layer of photoresist is employed across wafer surface and later on, the wafer is printed with an image on the specific zones of the device via photolithography. In this process, a mask is used to imprint a precise IC pattern by exposing the wafer to UV light where the exposed photoresist becomes weakened/soluble and is washed off by a developer solution. Afterwards, etching is done to eliminate the materials and chemically reactive free radicals from the pattern traces by using a plasma stream, producing nearly vertical etch profiles essential for the miniscule features in today's densely packed chip designs. After plasma etching, residual photoresist is removed using the photoresist stripper. These steps are repeated several times to build layers of transistors, with zonal interconnects created in the metallization stage via bonding pads. A finishing conductive layer is placed on the entire wafer to protect the circuit from damage and contamination, and finally the wafer surfaces are smoothened with hybrid chemical etching and free abrasive polishing [2,3].

Such a complex manufacturing process involves numerous material inputs, resulting in the management of several waste streams. For an estimate, weight per weight, the quantity of fuel and other chemicals needed is almost 630 times the chip weight, as compared to a 2:1 ratio required in car manufacturing [4]. In a typical nano-electronics fabrication facility (fab), 20–40 kg of fresh water is required per cm^2 of silicon processed [5] which equates to approximately 0.4 Mm^3 annually [6,7]. Consequently, the nano-electronics manufacturing units generate a corresponding amount of wastewater (approx. 83% of required water) from different areas including silicon growth, oxidation, doping, dicing, ion implantation, photolithography, etching, stripping, metallization, chemical mechanical planarization (CMP), washing and cleaning, etc.

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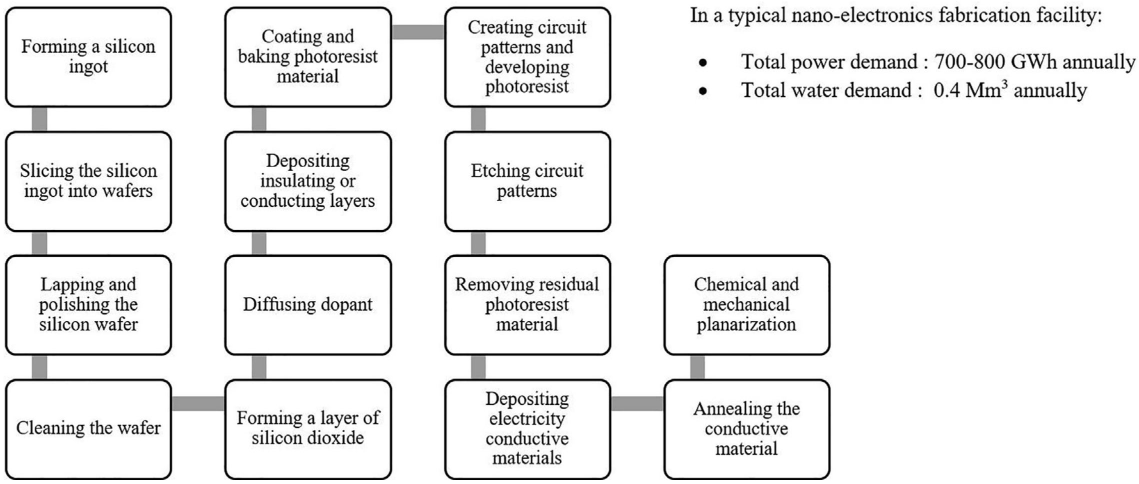

Fig. 1. Semiconductor chips manufacturing process steps with information of annual power and water demand by a typical nano-electronics fabrication facility [7,26,27].

[2,8–10]. These processes involve more than 200 types of various organic and inorganic substances (proprietary and generic) hence; the wastewaters mainly include metallic, alcoholic and acidic compounds, and nano-particles. Typically the wastewater streams linked to metallization steps contain copper (Cu^{+2}), chromium ($Cr^{+2,+3}$), lead (Pb^{+2}), nickel (Ni^{+2}), iron ($Fe^{+2,+3}$), magnesium (Mg^{+2}), calcium (Ca^{+2}), sodium (Na^{+1}) and zinc (Zn^{+2}) [11–13]. Stripping processes release the majority of VOCs including isopropyl alcohol (C_3H_8O), dimethyl sulfoxide (C_2H_6OS), dimethyl sulfide (C_2H_6S), dimethyl disulfide ($C_2H_6S_2$), N-methyl-2-pyrrolidinone (C_5H_9NO), and trace amounts of toluene (C_7H_8) and acetone (C_3H_6O) [14,15]. The etching process mainly releases waste acids which are dependent on the reaction conditions, normally contained nitric acid (HNO_3), hydrofluoric acid (HF), acetic acid (CH_3COOH) and phosphoric acid (H_3PO_4) [16,17]. The CMP wastewaters generally contain nano-particles including amorphous silica (SiO_2), alumina (Al_2O_3) and ceria (CeO_2), and copper (Cu) along with various chemical additives i.e., amino acids, carboxylic acids, hydrogen peroxide (H_2O_2), ferric nitrate ($Fe(NO_3)_3$), potassium permanganate ($KMnO_4$), benzotriazole ($C_6H_5N_3$), aminotriazole ($C_2H_4N_4$), hydrochloric acid (HCl), potassium hydroxide (KOH), nitric acid (HNO_3), oxalic acid ($C_2H_2O_4$), ammonium hydroxide (NH_4OH), polyacrylic acid ($(C_3H_4O_2)_n$), polyethylene glycol ($C_{2n}H_{4n+2}O_{n+1}$) and biocides. The CMP wastewater contains approximately 3–12% solids by weight and pH levels range from 6.8 to 10 [18,20–25]. Most of the nano-electronics industries' wastewaters are pretreated before release, according to the applicable standards [28–32].

Nevertheless, while handling different nano-electronics industries' wastewaters, treatment of CMP wastewater attains considerable attention due to ever-growing application of CMP technology in nano-electronics industries. Typically, CMP processes are responsible for 30–40% of the total fresh water consumption by a nano-electronics fab, which leads to generation of large amount of the CMP wastewater. Moreover, owing to its high solid content and complex composition, CMP wastewater is noticeably different from most of the nano-electronics industries' wastewaters. In the present situation, there are many different technologies in practice to treat CMP wastewater including coagulation/flocculation [28], electro-chemical separation (electro-filtration/dialysis/coagulation) [6,29–32], membrane separation (reverse osmosis, micro-filtration, ultra-filtration, nano-filtration and pervaporation) [33–36], and magnetic seeding aggregation [37,38]. These technologies are generally effective, yet there are some limitations or drawbacks involved. Traditional chemical coagulation/flocculation treatment processes are associated with low separation efficiency, high chemical demand and high sludge disposal costs. Electro-chemical processes have high electrical energy demand and problem of electrode blockage. Aforementioned membrane separation techniques have issues especially concerning organic and inorganic fouling/scaling, and handling and disposal of the resulting concentrated solutions whereas; magnetic seeding aggregation is cost-inefficient due to expensive magnetic seeds. Therefore, there is a clear need to introduce new approaches for the cost-efficient and environmentally friendly handling of CMP wastewater in nano-electronics industries.

In this setting, membrane distillation (MD) is a promising membrane process for wastewater treatment. Membrane distillation, a thermally driven process, provides a double barrier during purification: separation due to differentiation in contaminant boiling point, and membrane hydrophobicity that delivers high recovery ratios with pure distillate production. The main driving force is temperature difference between the feed and cold side of the MD module. This results in water evaporation from the feed side, which forms a liquid/vapor interface at the membrane surface, with subsequent condensation on the cooled side of the membrane. The process normally takes place at temperatures below 100 °C and at ambient pressure [39,40]. As compared to other water purification methods, MD technology can theoretically achieve 100% rejection at relatively mild operating temperature and pressure; it is mostly insensitive to feed concentration and pH; it utilizes low-grade heat; it needs less pretreatment procedures as compared to pressure-based membrane processes; and it requires less mechanical properties of membrane and lower capital costs than reverse osmosis and distillation [41,42].

Our previous study [43] clearly indicates that MD has potential to be successfully employed in the nano-electronics industries for treating the chemical mechanical planarization wastewater. A key factor in the technology's advancement relates to handling the relatively high thermal energy demand as compared to other water purification processes [44], which is especially critical at full scale. Still, due to the fact that the system can be operated using low grade heat sources, there are many opportunities available as heat sources including solar energy [45–51], geothermal energy [52], district heating [53,54] and industrial waste heat [55–61] to facilitate the thermal energy requirement of MD system.

The objective of the present work is to introduce the concept of an integrated MD wastewater treatment system for nano-electronics industries. By considering energy efficiency as the key parameter, this paper is focused on the techno-economic system evaluation of industrial waste heat and/or district heating driven MD systems for the treatment of CMP effluent in nano-electronics industries. This study specifically aims at finding out the optimal integration option in the view of unit water treatment cost, as an important economic criterion.

2. Methodology

The applied method involves a system analysis based on energy and mass balances with input obtained from the nano-electronics industries, coupled with results from Xzero AGMD experiments performed for treating CMP wastewater from imec, Belgium [43]. In order to determine the techno-economic feasibility of the industrial scale system for CMP wastewater treatment, previously published performance of a semi-commercial Xzero MD module was considered as a reference [54].

2.1. Integrated MD wastewater treatment system

Typically, 15 m^3/h (4.17 kg/s) of CMP wastewater is released from a generic nano-electronics industry (5000 m^2 fab) having ten CMP tools [18]. Therefore, the MD wastewater treatment system considered in this study is designed for continuous CMP wastewater flow rates matching this amount. There are various waste heat sources available in a typical nano-electronics industries for driving the MD process, including condenser outlet water from chiller, process cooling water exhaust from manufacturing tools, hot air from VOCs combustion abatement systems, used etchant (phosphoric acid) from nitride etching, used stripper (sulfuric acid) from photo-resistant stripping and cleaning, and dissipated heat from compressors, steam generators and pumps. Usually, the total amount of waste heat released from the nano-electronics industries is in the range of 35–40 MW [48]. In this study, condenser outlet water from chillers (temperature: 85–90 °C; capacity: 8–12 MW) and hot air from VOCs combustion abatement systems (temperature: 350–400 °C; capacity: 0.25–0.5 MW) are considered to provide thermal power to the MD feed water in order to achieve a target temperature of 80 °C. Using the chosen heat sources, the industrial scale waste heat driven MD setup was designed and analyzed in order to fulfil energy requirement of MD system for treatment of CMP wastewater of flow rate 15 m^3/h (corresponding to 120,000 m^3/year) releasing from a generic nano-electronics manufacturing facility. Besides, in a condition when industrial waste heat is not sufficient for the purpose, district heating (supply line temperature: 85 °C and return line temperature: 45 °C) is included as an external heat source for satisfying the thermal energy demand of MD system. The number of MD modules and required membrane area were calculated based on the CMP wastewater flow rate and previously reported specific thermal energy consumption (STEC) to heat the MD feed [54]. Moreover, it was assumed that the STEC is not a function of CMP wastewater concentration under values of 10% (w/v %). The total thermal power requirement (Q_t) for operating the MD system can be calculated using Eq. (1).

$$Q_t = \sum \dot{m} c_p \Delta T = \dot{m}_{dT} STEC \tag{1}$$

where $\dot{m}$ represents the mass flowrate of CMP wastewater streams passing through heat recovery exchangers, c_p shows the heat capacity of water (4180 J/kg·C), ΔT is temperature difference of CMP wastewater streams across heat recovery exchangers and $\dot{m}_{dT}$ depicts the total MD permeate flowrate.

2.2. Economic model

Apart from technical assessment in terms of system size and thermal energy requirements, the economic feasibility for a plant capacity of 15 m^3/h (4.17 kg/s) was also considered. In this study, plant capacity is referred to both wastewater flow rate and distillate capacity. This economic model has been established using previously published performance of semi-commercial AGMD system considering the waste heat/district heating integration (as mentioned above) along with recent economic data from literature and manufacturers.

2.2.1. Capital investment

Total capital expenditure (CAPEX, C_{TCI}) of the plant includes different costs which are distributed among total depreciable capital (C_{TDC}), total permanent capital (C_{TPC}) and working capital (C_{WC}), as expressed in Eq. (2). Total depreciable capital includes the direct permanent capital, insurance, contingencies fees and contractor fees while total permanent capital comprises of site preparation and development costs, land cost and plant startup cost.

$$C_{TCI} = C_{TDC} + C_{TPC} + C_{WC} \tag{2}$$

Eq. (3) shows that direct permanent capital (C_{DPC}) can be calculated as the sum of inside battery limits (ISBL) and outside battery limits (OSBL). ISBL contains all the processing/manufacturing equipment cost which includes MD modules, heat exchangers, pumps/compressors, sensors, security control systems and electrical subsystems, and process construction cost while OSBL includes the cost of support facilities such as storage cost, administrative cost etc. OSBL is considered as 40% of ISBL. Moreover, working capital can be calculated as 8.33% of the cost of OSBL.

$$C_{DPC} = ISBL + OSBL = 1.4(ISBL) \tag{3}$$

On the basis of the design stage, CAPEX was estimated with the Study (factored) Estimate Method [62]. In this method, equipment cost is determined and factored up using the Lang Factor technique. (The Lang factor is defined as ratio of the total installation charges of a process to the cost of its major technical components.) The time effect is negated using the Chemical Engineering Plant Cost Index (CEPCI). The system size correction for complementing economics of scale has also been used which has related the total capital cost and total capacity of the plant. Eq. (4) presents the used approach to calculate ISBL considering Lang factor, time effect and system size correction.

$$ISBL = I_{CEPCI} f_L \left[\sum \left(\frac{C_N}{C_R} \right)^m C_{Pi} \right] L_E \tag{4}$$

where C_{Pi} represents the reference cost of equipment, C_N & C_R denotes new (desired) and reference capacity of the equipment, I_{CEPCI} is used for value of CEPCI cost index, f_L is the Lang factor taken as 5.7 for the fluid processing plant and L_E = 1.20 as location index for Europe. 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 [63].

2.2.1.1. Membrane distillation modules and membranes cost. The total required area of the membranes was determined using capacity of the MD system. The total membrane area was calculated for the new system while considering the reference membrane area and corresponding permeate flow rate in Eq. (5), where A_T and A_m are new total membrane area and reference membrane area while $\dot{m}_{dT}$ and $\dot{m}_d$ define the total and reference MD permeate flow rates, respectively. The cost of polytetrafluoroethylene (PTFE) membrane typically varies between 60 and 200 $/$m^2$ depending on the chosen application and membrane type. In this study the assumed membrane cost was taken as 90 $/$m^2$ for plate and frame modules [64]. Depending on the membrane area, number of modules were calculated considering 2.3 m^2 active membrane area of each module. The cost of each module was set to $ 6100 [54,76]. This cost is accountable for hardware (membrane frames, gaskets, spacers, cooling plates and housing/outer frame), design and fabrication of MD modules.

$$A_T = \dot{m}_{dT} \frac{A_m}{\dot{m}_d} \tag{5}$$

2.2.1.2. Heat exchangers and pumps cost. Heat exchangers cost was calculated based on the heat transfer area as described in Eq. (6), where A_{HX} is the heat exchanger area, Q_t is the thermal power provided, U is overall heat transfer coefficient, and ΔT represents the temperature difference between inlet and outlet streams across heat exchanger. (The pinch point temperature difference is considered 5 °C). Based on the required area, cost of plate and frame heat exchangers have been

Table 1
Some Constituents of total capital investment.

Constituents	Specific costs
Construction overhead	15% of purchased equipment and labor cost [64,68]
Contingency fee	10% of purchased equipment cost [64]
Insurance	5% of purchased equipment cost [63,64]
Retrofitting cost	4% of purchased equipment cost [69]
Land cost and site development cost	2% of C_{TDC} [68]
Plant startup	10% of C_{TDC} [70]
Controls, sensors and sub electrical system	140 $/m^3/day [67]

calculated from the literature [65].

$$A_{HX} = \frac{Q_t}{U\Delta T} \quad (6)$$

The cost of the centrifugal pumps/compressor is estimated based on the flow rates of the respective streams obtained from simulations. The cost curves published by National Energy Technology Laboratory (NETL) has been used for the purpose [66].

2.2.1.3. Water tank and other capital costs. The cost of feed, distillate, coolant and pretreatment tanks was calculated based on the plant capacity, recovery ratios, operating conditions and integration cases [54]. The cost of these tanks was considered as 130 $/m^3/day [67]. Table 1 contains other capital costs that have been considered in this study.

The annual capital investment (C_a) was determined using net present value method according to the annual interest rate (I = 5% [71,72]) and plant life span (L = 20 years) by following Eq. (7). Plant availability was assumed to be 8000 h/year. The normalized annual capital investment was then determined using annual plant capacity and annual capital investment.

$$C_a = \left(\frac{I(1+I)^L}{(1+I)^L - 1}\right) C_{TCI} \quad (7)$$

2.2.2. Operating and maintenance expenditure

Operating and maintenance expenditure (OPMEX) has covered expenses for utilities (thermal/electrical energy and cooling water), chemicals and disposal, operating supplies and services, labor, equipment replacement and technical assistance.

2.2.2.1. Thermal energy cost. In MD systems, typically thermal energy cost is accountable for a large portion of the operating cost. In this study, the cost of the thermal energy, which was provided by industrial waste heat sources of the nano-electronics industries, considered negligible. However, in some cases since the thermal energy requirement was partially/fully satisfied by district heating, therefore the cost of district heating was taken as 77 $/MWh [73].

2.2.2.2. Electricity cost. Based on specific electrical energy consumption (0.35 kWh/m^3 [54]), total electricity cost (C_E) can be calculated using Eq. (8), where SEEC represents the specific electrical energy consumption, $\dot{m}_{dT}$ shows total MD permeate flowrate and E_c is unit electricity cost which is taken as 0.09 $/kWh [64,74].

$$C_E = \dot{m}_{dT} E_c(\text{SEEC}) \quad (8)$$

2.2.2.3. Other operational and maintenance costs. Other operational and maintenance costs include costs of labor, chemicals, brine disposal, membrane replacement, cooling water andservice and maintenance, which are summarized in Table 2.

The PTFE membranes in MD modules typically can be used for

Table 2
Costs of different OPMEX components.

OPMEX components	Costs
Service and maintenance	0.033$/m^3 [64,71]
Labor	0.03$/m^3 [64,67,71]
Cleaning chemicals	0.0018$/m^3 [64,67]
Pretreatment chemicals (sulfuric acid)	0.02 $/m^3 [75]
Annual membrane replacement	15% of total membrane cost/year [76]
Brine disposal	0.0015 $/m^3 [77]
Cooling water	0.02 $/m^3 of total cooling water [78]

5 years without replacement, so the membrane replacement cost is considered accordingly for annual OPMEX. Chemical cost has been calculated for membrane cleaning and for pretreatment purpose based on the plant capacity. Brine disposal cost was also estimated for disposing of the concentrate. Since MD provides high water recovery ratio and resultantly the brine volume reduces up to 10% [54], therefore, brine disposal cost is very low for MD systems as compared to other water purification methods [71]. Cost of labor usually depends on the region and the plant capacity. The same plant availability as mentioned above was used for calculating the annual operational and maintenance cost (OPM_a).

2.2.3. Unit water treatment cost

Finally, unit water treatment cost (C_w) was calculated using Eq. (9) where annual capital (C_a) and annual operational (OPM_a) costs are added and then the sum is divided by annual permeate production/ plant capacity ($\dot{m}_{dT}$).

$$C_w = \frac{C_a + OPM_a}{\dot{m}_{dT}} \quad (9)$$

3. Results and discussion

3.1. Technical evaluation

3.1.1. Thermal power demand and integration options

Owing to the temperature and thermal power limitations of the mentioned industrial waste heat sources, different configurations have been designed and analyzed to fulfil the power requirement in order to achieve the target MD feed water temperature of 80 °C. These configurations were categorized based on the origin of considered heat sources for each case i.e., industrial waste heat driven MD system (referred as case 1a), district heating driven MD system (referred as case 1b), and industrial waste heat and district heating driven MD systems (referred as case 2a/2b). Each integration case has been designed for continuous CMP wastewater flow rate of 4.17 kg/s (15 m^3/h). In order to maintain the mass balance around overall system, MD feed and concentrate flow rates were adjusted. For achieving the target temperature of 80 °C from the initial wastewater temperature of 20 °C, all cases were compared on technical basis. It is noteworthy to mention here that in all configurations, the systems were considered multicycle in order to reduce the waste volume, therefore, the concentrate/retentate stream was recycled back through the MD pilot plant unit several times. The recycled retentate was mixed with the upcoming makeup water (with or without preheating) where mixed stream temperature was determined. The mixing point temperature was different in the considered cases depending on the configuration of heat sources used. Moreover, some other conditions were also considered for the analysis i.e., (a) the system has steady state flow; (b) in order to avoid the scaling and caking on the membrane surface, a purge stream has been considered and (c) cooling water has the similar flow rate as of MD feed. Using Eq. (1), it was determined that total thermal power requirement of MD system was 12.38 MW. Fig. 2 shows the industrial scale semi-batch MD system designed for treating CMP wastewater

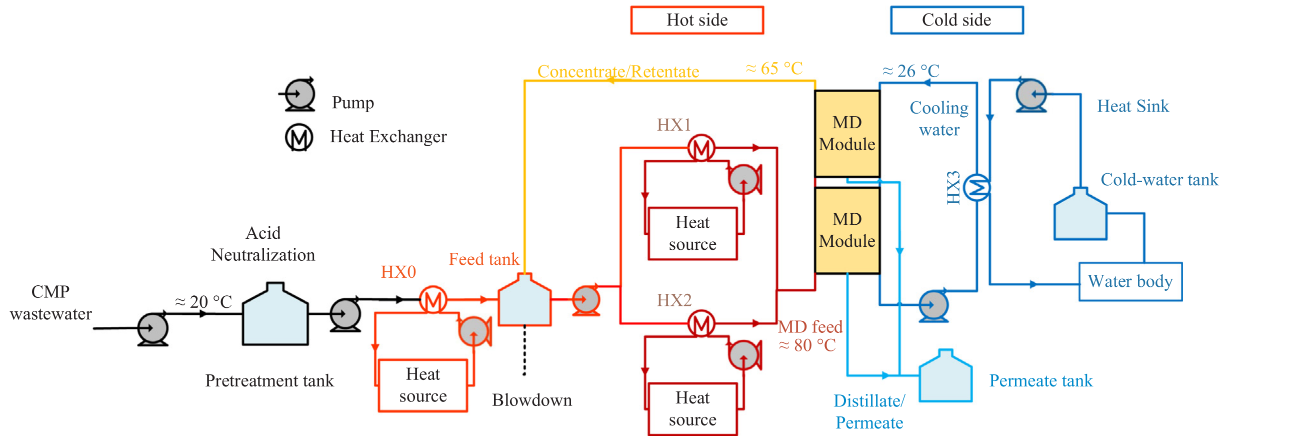

Fig. 2. Flow diagram of proposed industrial scale MD integrated system. In all cases, HX1 is considered as main heat recovery exchanger whereas; only case 1a uses the HX2 (for additional heating) and only case 2a uses the HX0 (for preheating).

while employing acid neutralization as the pretreatment technique.

In case 1a, the neutralized CMP wastewater with flow rate of 4.17 kg/s (15 m^3/h), and inlet temperature of 20 °C was mixed with recycled concentrate/retentate of higher temperature (~65 °C). Subsequently, the mixed CMP wastewater stream released from feed tank was divided into two parallel streams and the flow rates were selected according to the available thermal power from different available heat sources. The streams were prioritized in order to utilize the complete potential of industrial waste heat sources. The first stream having flow rate of 179.33 kg/s was heated up to 80 °C using the corresponding amount of condenser outlet water from chillers where thermal power of 12 MW was provided to reach the target level. In parallel, for the second wastewater stream (5.67 kg/s), 1.43 kg/s of hot air from VOCs abatement system, having capacity of 0.38 MW has been employed. In case 1b, district heating supply line has been used as the stand-alone source of thermal energy in order to fulfil the requirement of 12.38 MW for the MD system for treating CMP wastewater of continuous flow rate of 4.17 kg/s (15 m^3/h).

Cases 2a and 2b differ on the basis of origin and arrangement of heat sources.Case 2a has considered the preheating of the makeup water while other cases (1a,1b and 2b) have not taken this into account. In case 2a, the makeup wastewater of 20 °C was firstly preheated using district heating return line up to 40 °C with power consumption of 0.38 MW and later, it was mixed with the recycled retentate and further heated up to 80 °C using condenser outlet water from chiller. In case 2b, the retentate was mixed with the incoming make up wastewater without any preheating, then the wastewater of flow rate 185 kg/s was heated with condenser outlet water and district heating supply line to achieve the target level. Table 3 provides summary of mass flow rates and temperature levels across heat recovery exchangers, heat transfer areas required and thermal power provided.

By considering the integration cases thoroughly, they can be classified based on percentage of thermal power demand fulfilled from the industrial waste heat sources from nano-electronics industries. The outcomes show that in case 1a, 100% of the total thermal power demand has been satisfied from the industrial waste heat sources, in cases 2a &b, this share was ~95% and in case 1b the total thermal power demand was fulfilled by district heating, individually. Therefore, Case 1a can be the preferred integration case when environmental and economic impact would be considered.

3.2. Economic analysis

For determining the economic feasibility, equipment design was estimated considering 666 m^3/h of MD feed for the CMP wastewater treatment plant under consideration. The total required membrane area was calculated based on the total MD feed flow rate, while considering 2.3 m^2 of active membrane area of each module having dimensions of 730 × 630 × 165 mm^3. In the considered design, two MD modules were connected in series (one MD module set) in order to obtain improved energy efficiency through internal heat recovery. Eventually, 555 MD module sets were connected in parallel in the industrial scale CMP wastewater treatment system. In this case, obtained distillate yield was 4.17 kg/s (15 m^3/h) when the MD feed temperature was 80 °C and cooling water temperature was 26 °C. Table 4 shows the specifications of the main components and necessary amount of raw materials for the industrial scale CMP wastewater treatment system.

Fig. 3 presents the detailed cost distribution of the purchased equipment for four mentioned integration cases in full-scale wastewater treatment system of 4.17 kg/s (15 m^3/h). The findings show that MD modules and heat exchangers are two main cost-capturing components while calculating inside battery limits of the MD plant. However, the

Table 3
Summary of material flow and temperature levels across heat recovery exchangers in all integration cases.

Cases	Low grade heat sources and associated heat recovery exchangers	Mass flow rates across heat recovery exchanger, kg/s		Temperature across heat recovery exchanger, °C				Heat transfer area, m^2	Thermal power provided, MW
		Feed	Source	Feed		Source			
				Inlet	Outlet	Inlet	Outlet		
1a	Condenser outlet water (HX1)	179.33	179.33	64	80	85	69	2997	12
	Hot Air (HX2)	5.67	1.43	64	80	350	85	143	0.38
1b	District heating supply line (HX1)	185	185	64	80	85	69	3093	12.38
2a	District heating return line (HX0)	4.17	4.17	20	40	45	25	70	0.35
	Condenser outlet water (HX1)	185	187	64.5	80	85	69.5	3129	12
2b	Condenser outlet water and District heating supply line (HX1)	185	185	64	80	85	69	3093	12.38

Table 4
Design specification of industrial scale MD integrated system.

Components		Specification
MD Modules		N = 1110
Membranes		Area = 2553 m^2
Hot-side heat exchangers	Case 1a	Total heat transfer area = 3140 m^2
	Case 1b	Total heat transfer area = 3093 m^2
	Case 2a	Total heat transfer area = 3199 m^2
	Case 2b	Heat transfer area = 3093 m^2
Cold-side heat exchanger		Heat transfer area = 3093 m^2
Pumps	Case 1a	Capacity = 670 m^3/h, N = 4; Capacity = 15 m^3/h, N = 2, one air compressor
	Case 1b	Capacity = 670 m^3/h, N = 4; Capacity = 15 m^3/h, N = 2
	Case 2a	Capacity = 670 m^3/h, N = 5; Capacity = 15 m^3/h, N = 2
	Case 2b	Capacity = 670 m^3/h, N = 4; Capacity = 15 m^3/h, N = 2
Water tanks		Capacity = 100 m^3/h, N = 14 ; Capacity = 15 m^3/h, N = 1
Pretreatment tank		Capacity = 15 m^3/h, N = 1
Sulfuric acid		12 m^3/year

*N = Amount.

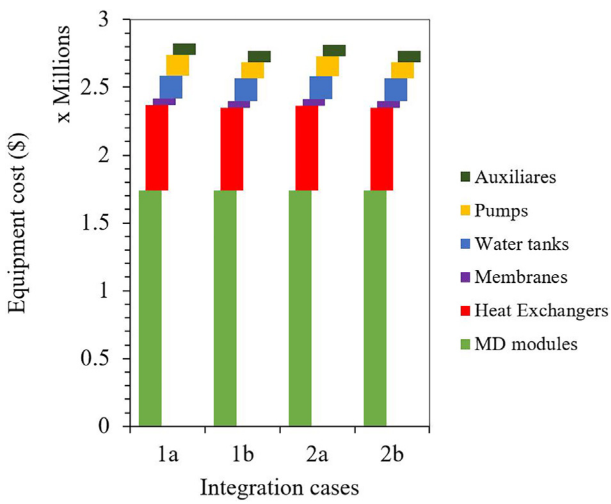

Fig. 3. Equipment cost for all the integration cases.

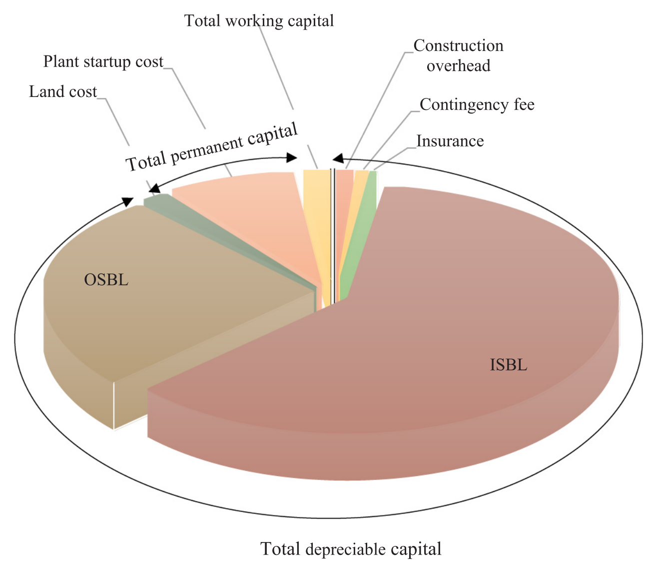

Fig. 4. Distribution of total capital investment for all the integration cases.

key cost driver is MD modules (~61–63% of total equipment cost). The contribution of heat exchangers in the total equipment cost was ~21–23%, depending on the number of heat exchangers and complexity of the process, followed by MD modules cost. Water tanks and membranes costs are ~7–8% while pumps and other auxiliaries are accountable for 7–9% of the total purchased equipment cost. It is noteworthy that the equipment specifications are quite similar therefore, the equipment cost is nearly identical in all integration cases.

Fig. 4 shows the total capital investment in terms of total depreciable capital, total permanent capital and working capital. It was found that the main contributors of the total depreciable capital investment are inside battery limits and outside battery limits. Insurance, construction overhead and contingencies fees were not more than 5 percent of the total depreciable capital investment. Since total depreciable capital investment depends mainly on the total purchased equipment cost, therefore it follows the same trend for different cases as mentioned previously and accounted for approximately 28 M$. It is noteworthy that the total capital investment in this study has also included land and plant startup cost as contrary to the most of the studies in literature. The calculated land and site development cost was 0.56 M$ and plant startup cost was 2.8 M$ for all cases, and sums up as total permanent capital investment. Moreover, total working capital of 0.65 M$ is responsible for 2% of total capital investment. The resulting annual CAPEX was ~2.5 M$/year for the mentioned cases.

Fig. 5 shows the annual OPMEX analysis considering plant capacity of 4.17 kg/s (15 m^3/h). Typically the largest part of the annual operational and maintenance cost (OPM_a) includes the thermal energy cost when the external heat sources are used to satisfy the thermal energy demand of the MD system. The similar trend has been shown by case 1b where only district heating supply line has been opted for providing the required thermal power. In case 1b, the share of thermal energy cost is 98% of OPM_a however, in cases 2a & 2b, heat supply cost is 63% of OPM_a. In case 1a, only industrial waste heat has been used for the purpose, therefore heat supply cost was considered negligible. Service and maintenance cost was 0.05–3.1% of OPM_a and labor cost was responsible for 0.05–2.8% share of OPM_a. The OPM_a also includes membranes replacement cost (~0.1–6% of OPM_a), and cleaning and pretreatment chemicals and disposal cost (0.04–2.2% of OPM_a). The cooling water contribution was 2–83% of OPM_a and electricity cost was ~0.05–3% of OPM_a. The lowest OPM_a among the mentioned cases was ~0.13 M$ for case 1a while the highest OPM_a was 7.7 M$ for case 1b due to high thermal energy cost since only district heating has been used in this case. Cases 2a and 2b (with negligible difference) have the OPM_a of 0.34 M$. The estimation shows that the Case1a can be the preferable integration option when the operating cost is prioritized.

The normalized CAPEX and OPMEX were also determined and shown in Fig. 6. For calculating the normalized CAPEX, two scenarios were considered. Scenario 1 (new wastewater treatment facility) presents the condition when the CAPEX includes ISBL, OSBL, construction overhead, contingency fee, insurance, land cost, plant startup cost and working capital, whereas scenario 2 (retrofitted plant) only includes cost of purchased equipment, insurance and retrofitting. The results

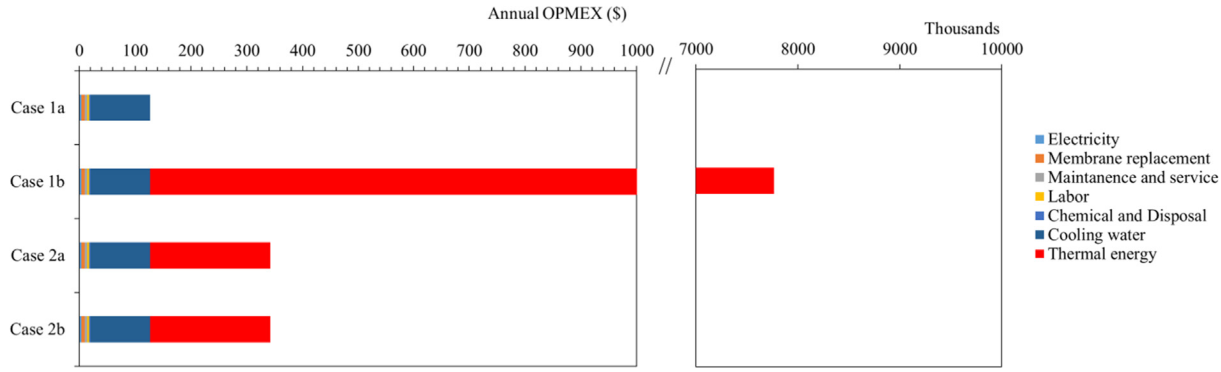

Fig. 5. Annual OPMEX for all integration cases.

show that the normalized annual CAPEX was ~21.3 $/m^3 of distillate for scenario 1 and it has reduced up to 2 $/m^3 of distillate for scenario 2. The normalized annual OPMEX was varied from 1 to 65 $/m^3 of distillate. Due to high cost of land, plant start up, construction, engineering and commissioning, the unit water treatment cost (C_w) in scenario 1 is almost 10 times more than scenario 2. The findings also show that Case 1a showed the least cost in both scenarios for treating per unit of the wastewater due to reasonable CAPEX and negligible thermal energy cost, which turned into less OPMEX. The C_w found in the present study is 3.1 $/m^3, ~95% less than the cost of CMP wastewater treatment while employing electro-chemical (EC) systems (59 $/m^3 of wastewater) [79]. It can also be concluded here that configuration of heat sources have negligible effect on the C_w though the selected heat sources have significant effect on the C_w. It is noteworthy to mention here that in this study the wastewater flow rate was similar to distillate/purified water flow rate, therefore, the same C_w can be associated with both i.e., wastewater treatment or distillate/clean water production.

3.3. Sensitivity analysis

As presented in the economic analysis, the two key cost drivers are MD modules and thermal energy sources. Therefore, the sensitivity analysis has been performed for the mentioned economic factors as shown in Fig. 7. In this study, the analysis was conducted for both scenarios (new water treatment facility and retrofitted facility) of Case 1a. Considering the development and cost reduction in commercial MD modules, it can be estimated that C_w can be reduced up to 15.7 $/m^3 in scenario 1 and up to 2.5 $/m^3 in scenario 2, when module cost becomes half and heat cost is considered negligible. Different heat sources may have varying cost per unit thermal energy (0–100 $/MWh), in that case, C_w can also vary from 22.3 $/m^3 to 105 $/m^3 in scenario 1 while it can be between 3.1 and 86 $/m^3 in scenario 2 when MD module unit costs 6000 $.

Along with heat cost, the analysis has also taken into account the amount of total heat recovered and waste heat used and shown C_w values for the fraction range of 0–1 for both parameters. It is found that when all the energy requirement was fulfilled by external heat sources and heat was not recovered, the C_w may reach 86 $/m^3 in scenario 1, considering thermal energy cost of 77 $/MWh. However, it can be reduced up to 75% when the industrial waste heat has been used with no heat recovery or when external heat source has been used but all the heat was recovered (quite difficult). In scenario 2, when industrial waste heat was used to fulfill the energy requirement, the C_w can be as low as 3.12 $/m^3.

Apart from cost of MD modules and thermal energy, and fraction of heat recovery, some other parameters including plant capacity and life, interest rate and membrane price also effect the C_w. In order to understand the influence of the mentioned techno-economic variables, sensitivity analysis based on these parameters was also considered in this study. With this aim, plant capacity (50,000, 120,000 and 200,000 m^3/year), plant life (12, 20 and 30 years), interest rate (1.5, 5 and 12%) and membrane price (60, 90 and 200 $/m^2) were varied under the techno-economic limitations. Fig. 8 shows the sensitivity of the C_w considering variation of mentioned techno-economic factors for the two above-mentioned scenarios for industrial waste heat driven membrane distillation system (Case 1a). Altering plant capacity can have an impact on capital investment (due to effect on number of membrane modules, membrane and heat exchanger areas) as well as on operating and maintenance costs. The outcomes of sensitivity analysis

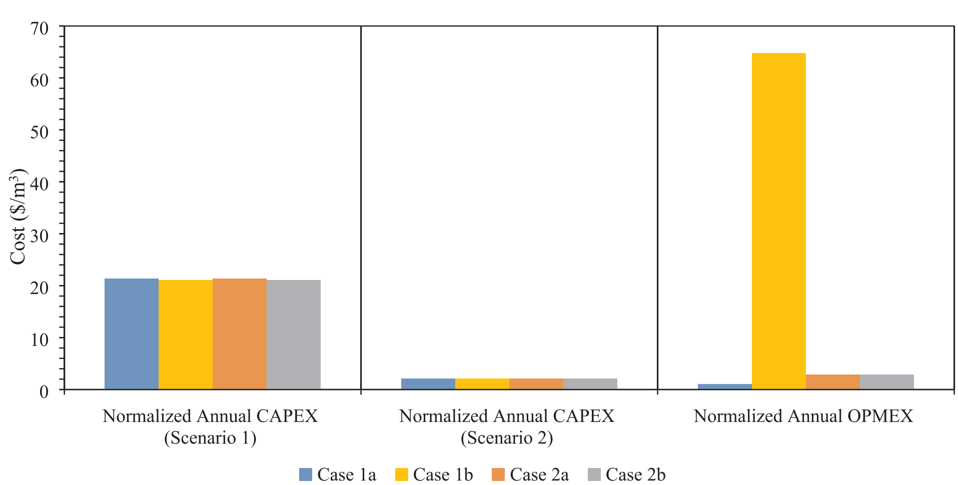

Fig. 6. Normalized annual CAPEX and OPMEX for all integration cases.

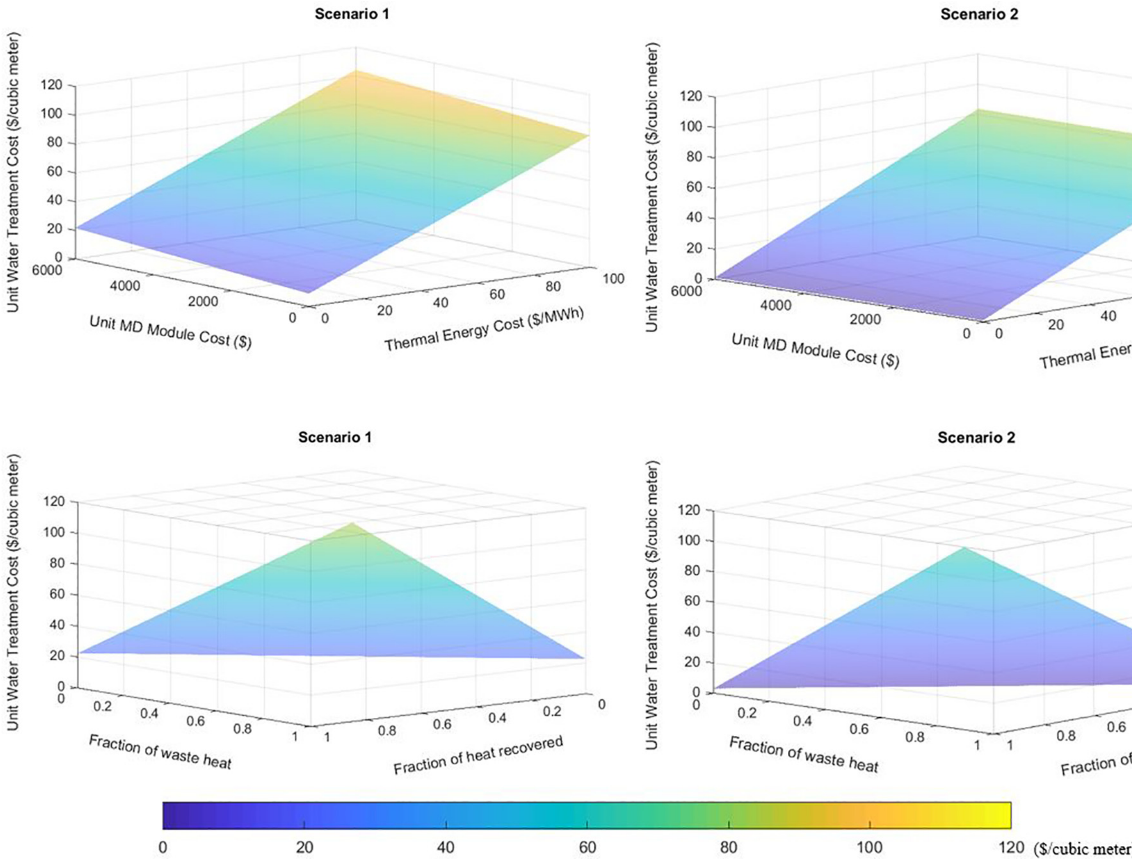

Fig. 7. Sensitivity analysis of integrated MD system.

show that decreasing plant capacity up to 50,000 m^3/year caused ~24% higher C_w in scenario 1 while the calculated increase in C_w for scenario 2 was ~18%. Plant life and interest rate were found the most critical parameters among the mentioned ones. When plant life was decreased from 20 years to 12 years, it was found that the C_w was increased by ~39% in scenario 1, and for scenario 2 the difference was ~18%. On the other hand, when plant life was increased by 10 years, the C_w was reduced by ~18% and ~12% in scenarios 1 and 2, respectively. Moreover, increase in interest rate from 5% to 12% lead to ~63% higher C_w in scenario 1 and ~44% higher C_w in scenario 2. It was found that the variation in membrane price did not present any significant effect on C_w.

4. Conclusion

This study was focused on presenting the techno-economic system analysis of low-grade heat driven MD process for treating chemical mechanical planarization wastewater in nano-electronics industries, in the view of previous studies. Since energy has been considered as the most important parameter for its techno-economic feasibility, four MD integration options with various low-grade heat sources have been investigated. The investigation considered the mass and energy balances, performance of the AGMD system, equipment design and economic evaluation of large scale MD system for treatment of CMP wastewater. Calculated annual energy consumption in the integrated MD treatment

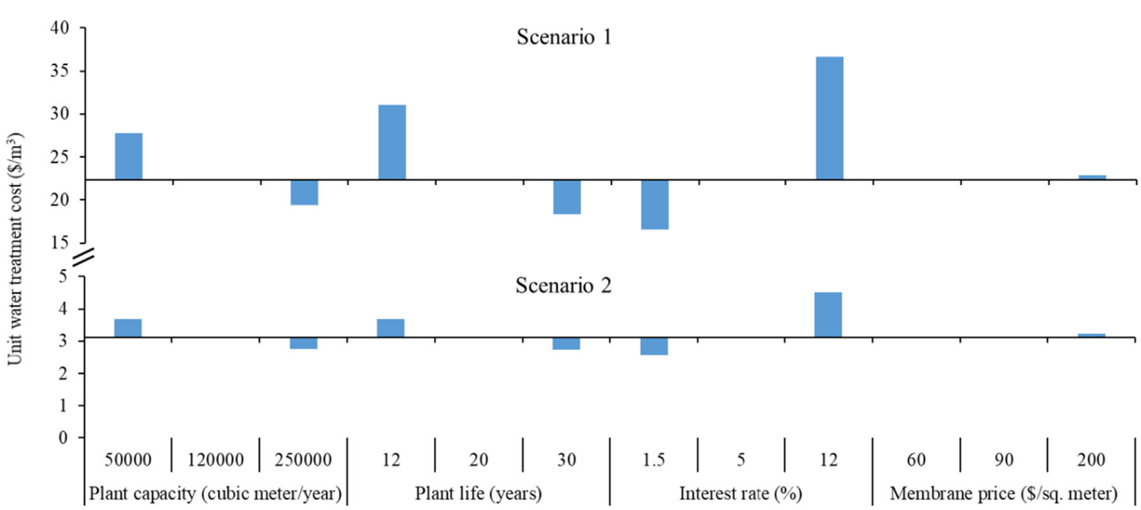

Fig. 8. Sensitivity analysis of CMP wastewater treatment cost for different techno-economic parameters.

system was 100 GWh with permeate production of 120,000 m^3/year. Industrial waste heat driven membrane distillation system was found as the most optimized among the mentioned integrated systems, which accounts for reasonable annual CAPEX (~0.25 M$) and OPMEX (~0.13 M$), with the unit water treatment cost of 3 $/$m^3$. Sensitivity analysis verifies that thermal energy cost and fraction of industrial waste heat utilization are the two most important parameters, which can vary the unit water treatment cost up to 80%.

CRediT authorship contribution statement

Imtisal-e- Noor: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Andrew Martin:** Supervision, Project administration. **Olli Dahl:** Supervision, Project administration.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seppur.2020.117013.

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