Membrane Distillation (MD) as a desalination component in hybrid desalination process combinations for small Island Applications

Sanju Thomas (sanju.thomas@yahoo.co.in)
Cochin University of Science and Technology https://orcid.org/0000-0001-9528-2749
Ravi Kumar Kandaswamy
IIT Delhi: Indian Institute of Technology Delhi
Sendhil Kumar Natarajan
NIT Puducherry: National Institute of Technology Puducherry
Sheffy Thomas
Federal Institute of Science and Technology
Sudhansu Sahoo
College of Engineering and Technology Department of Mechanical Engineering
Ajith Kumar
Cochin University of Science and Technology

Research Article

Keywords: Seawater Desalination, Brackish Desalination, Membrane Distillation, Hybrid Desalination Applications

Posted Date: June 2nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1523322/v1

Abstract

The brine volume and environmental damage are key factors to consider desalination as a water source for small islands. Membrane distillation (MD) is still evolving to be used as a single source for desalination with constraints in pre-treatment and pore wetting. However reverse osmosis (RO) is optimised and thermal desalination is heat intensive. A combination of various desalination technologies with MD for seawater and brackish water at 35000ppm and 15000ppm is evaluated with low thermal renewable energy source. It is identified that while RO-MD combination for brackish and seawater desalination may have the least capital and operation cost, there isn't much difference in levelised production cost considering increased recovery with combinations of RO-MD with Forward Osmosis (FO), Pressure Assisted Forward Osmosis (PAFO), Multi Effective Distillation (MED) and Counter Flow Reverse Osmosis (CFRO). The brine reduction rates are found to be halved with an increase in capital and operational cost of 50% and more. The unit cost of production for RO-MD is found to be INR 0.06 for brackish and INR 0.23 for seawater desalination. The addition of components will reduce the brine production, while increased capital and operational expanses stabilise unit cost of production.

Introduction

The energy consumption and brine management remains a concern in RO systems, especially for small islands. Andaman & Nicobar Islands are ocean locked with gradual diminishing water resource with water levels at 2-5m at 66% sources (Swarnam, 2014). The ground water conditions are neutral to alkaline with high bicarbonate content at 43 to 427 ppm and chloride content between 7 and 390 ppm (Gayen, 2014). Seawater / brackish water desalination is the solution to get potable water and meet dying ground water recharge. Energy intensity, cost and the environmental effects of desalination plants are the main concerns world over in adopting and embracing this technology (Future directions). Analysis of thermal and membrane desalination processes shows that thermal energy is better with availability of waste heat, while membrane technology is optimized due to wide scale acceptance. A typical reverse osmosis plant 5 kWh electricity to produce one kiloliter of freshwater, of which 3 kWh is for the process and other for pre-treatment (Shahtat, Saffa and Rifft, 2014). The thermal systems are reliable and can have a better production volume compared to RO systems, while having limitation with higher brine temperature and lesser conversion ratios (Future directions). Renewable energy based desalination with potential as a heat or mechanical or electricity energy is studied by many (Rodriguez, 1996; Edward, 2006; ADU; Voivontas, 1999; Fath,1997). Solar PV and thermal energy are the most explored energy sources, with water produced with RO-PV combination found as approximately 850 INR/m3 while MED-solar thermal (Concentrating solar thermal) found as 172 INR/m3 (PRODES, 2010).

Canary Islands (PV-RO, seawater, 1–5 m^3/d), Riyadh, Saudi Arabia (PV-RO, brackish water, 5 m^3/d), and Ohshima Island, Japan (PV-ED, seawater, 10 m^3/d) are few examples (Kalogirou, 2010). Experiments with different renewable energy and advanced desalination technologies (Masdar, 2017) have shown that Membrane Distillation (MD) can effectively treat brine to recover fresh water, while they are affected by fouling due to salt or other compounds deposits affecting the water recovery rates. The pretreatment of brine and energy intensity consumption should be focused to effectively use MD as a component in the desalination system (Drioli, 2015).

In another development, IBM used concentrated photovoltaic (CPV) to drive an MD desalination supplying 90° C water to heat salty passed through a porous membranes system where to provide 30–40 liters of drinkable water per square meter of receiver area per day, generating electricity with a more than 25% yield, or two kilowatt hours per day (Osmosun). Investigations done on two pass RO with energy recovery and MD combination (Masdar, 2017) with 10% brine from first stage RO passed through low-grade, heat-driven MD, found to be operating successfully. The MD system used vacuum multi-stage with three units treating brine in parallel. using both electric and thermal energy. Innovative pilot plant of 100m3/day was done by using Ionic Liquid Membrane (ILM) technology, which has taken first pass RO brine to produce fresh water using a solvent which require low temperature heat to disintegrate pure water and polish the permeate using brackish water RO (Masdar, 2017).

Membrane distillation technology works on the hydrophobic nature of membranes to distillate water with a vapour pressure difference (Adham, 2013; Han, 2017). MD is not used for desalination alone but for other industrial and healthcare applications as well, which can be in conjunction with forward osmosis (FO) and humidification-dehumidification (HDH) process can achieve zero liquid discharge (ZLD) or minimum liquid discharge (MLD) (Adham, 2018). The MD technology readiness level (TRL) is in the range from 3 up to 8 to for a full-scale application. However, there is no conclusive analysis drawn from the outcomes of the pilot, since each pilot plant has considered a different technology and operating conditions. The common technologies used are plate& frame, hollow fibre and spiral wound configurations with objectives to increase the permeate levels and flux rates, with lesser rejects (Adham, 2018).

Research and pilot studies done by Dotremont (2010), Jansen (2013), Schwantes (2013), Minier-Mater (2014 & 2016), Duong (2016), Chafidz (2016), Mohamed (2017),Hagedorn (2017), Schwantes (2018), Andres-Manas (2020), Riz-Aguirre (2018 &2019) during the period 2010 to 2020 shows that since the MD technologies are varied and feed parameters are different, there will not be any concrete outcome that can be generated from various experiments. The mix knowledge results are beneficial to select the membrane according to TDS experiment further and co-relate. The thermal energy consumption vary from 50 kWh.m3 to 1031 kWh/m3 depending on technology, application and membranes.

Literature survey and experimental results from pilot projects conclude that while MD has its benefits in terms of additional recovery rates to be used at high TDS levels, the selection of membrane, the technology the configuration of stacking will yield cost optimisation. In this work the opportunity of MD as a desalination component for seawater and brackish water desalination is investigated for application in small islands. Various combinations of MD as a technology are discussed in combinations with Multi effective Distillation (MED), Reverse osmosis (RO), Counter Flow Reverse Osmosis (CFRO) and Forward Osmosis (FO) and Pressure Assisted Forward Osmosis (PAFO) technologies. An effort is done to analyse the capital cost, operational cost, yield and cost of production.

Methods

2.0 Desalination setup for small islands and process flow arrangements

The present study considers both brackish and seawater desalination for small islands. Better recovery rates and reduced environmental damage are key for such small island desalination. The prospect of MD as a component among RO, CFRO, MED, FO-PAFO is explored for brackish and seawater desalination prospects.

2.1 Membrane Distillation based brackish water desalination system for Andaman Island

The system is designed to operate at 15000 ppm TDS levels with the intake at aquifer designed at 20000 LPH. The permeate is expected to be at potable standard at 500 ppm or below. The brine is expected to be minimized and reduced to slats through mechanical vapor compression (MVC) or thermal vapor compression (TVC) technology. The permeate from the thermal desalination technologies are re-mineralized to potable standards.

Three options are discussed for combining MD as a component in brackish water desalination for the island namely;

i. Reverse Osmosis (RO) in combination with Membrane Distillation (MD)
ii. Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO), Pressure Assisted Forward Osmosis (PAFO) and Membrane Distillation (MD)
iii. Reverse Osmosis (RO), Pressure Assisted Forward Osmosis (PAFO), Forward Osmosis (FO) and Membrane Distillation (MD)

2.1.1 Reverse Osmosis (RO) in combination with Membrane Distillation (MD)

Figure 1 shows the process flow diagram (PFD) of a brackish water desalination system using RO and MD system. There are two streams of intake water from the same aquifer at 15000 ppm TDS levels. The first stream is passed through a RO at a flow rate of 5000 LPH, while the second one at 15000 LPH is mixed with RO reject at the mixing tank, before passing through the MD.

2.1.2 Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO), Pressure Assisted Forward Osmosis (PAFO) and Membrane Distillation (MD)

Figure 2 shows the process flow diagram (PFD) of a brackish water desalination system with twos terams of intake at 15000 ppm TDS levels. The forst stream at 5000 LPH is passed through a RO and counter flow reverse osmosis (CFRO), the reject of which is passed to the MD unit. A pressure assisted forward osmosis (PAFO) is used as a pre-filtration system before being passed to MD unit.

2.1.3 Reverse Osmosis (RO), Pressure Assisted Forward Osmosis (PAFO), Forward Osmosis (FO) and Membrane Distillation (MD)

Figure 3 shows the process flow diagram (PFD) of a brackish water desalination system with two streams of intake at 15000 ppm TDS levels. The first stream at 5000 LPH is passed through a RO which reject is passed to PAFO which take the second stream. The mix of RO reject is passed to PAFO, which takes the second stream as well and pass onto the FO unit.

2.2 Membrane Distillation based seawater desalination system for Andaman Island

The system is designed to operate at 35000 ppm TDS levels with the intake designed at 40000 LPH. The permeate is expected to be at potable standard at 500 ppm or below. The brine is expected to be minimized and reduced to slats through mechanical vapor compression (MVC) or thermal vapor compression (TVC) technology. The permeate from thermal desalination is re-mineralized to potable standards.

Three options are discussed for combining MD as a component in seawater desalination for the island namely;

i. Reverse Osmosis (RO) in combination with Membrane Distillation (MD)
ii. Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO) and Membrane Distillation (MD)
iii. Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO), Multi Effective Distillation (MED) and Membrane Distillation (MD)

2.2.1 Reverse Osmosis (RO) in combination with Membrane Distillation (MD)

Figure 4 shows the process flow diagram (PFD) of a seawater desalination system using RO and MD system. There are two streams of intake water from the same aquifer at 35000 ppm TDS levels. The first stream is passed through a RO at a flow rate of 20000 LPH, while the second one at 20000 LPH is mixed with RO reject at the mixing tank, before passing through the MD.

2.2.2 Reverse Osmosis (RO) and counter flow reverse osmosis (CFRO) in combination with Membrane Distillation (MD)

Figure 5 shows the process flow diagram (PFD) of a seawater desalination system using RO and CFRO and MD units. There are two streams of intake water from the same aquifer at 35000 ppm TDS levels. The first stream is passed through a combination of RO and CFRO, whose reject is given to the MD with a fresh stream of intake mixed at a convergent tank, before passing through MD unit.

2.2.3 Reverse Osmosis (RO) counter flow reverse osmosis (CFRO) combination with multi effective distillation (MED) and Membrane Distillation (MD)

Figure 6 shows the process flow diagram (PFD) of a seawater desalination system using RO and CFRO combination and another stream of MED before the rejects are passed to MD unit. The first stream is taken into RO and CFRO unit, where the reject is given to a convergent tank, which takes a second stream of intake. The mix from the convergent tank is given to MED, whose reject is given to MD unit.

Results And Discussions

3.1 Capital and operational cost of various desalination technologies.

The capital and operational cost of various desalination technologies for brackish water and seawater desalination application at 15000 ppm and 35000 ppm TDS levels are indicated in figure 8, figure 9, figure 10 and figure 11 respectively.

3.2 Performance analysis of various desalination systems with MD component considered for evaluation.

3.2.1 Brine water desalination at 15000 ppm TDS levels

The capital cost and operational cost, permeate volume, brine reject volume, TDS of Brine and levelised cost of water with of various combinations considered in section brine water desalination namely as below is shown in figure 12, figure 13, figure 14, figure 15 and figure 16 respectively.

(i)	Reverse Osmosis (RO) in combination with Membrane Distillation (MD)

(ii)	Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO), Pressure Assisted Forward Osmosis (PAFO) and Membrane Distillation (MD)

(iii)	Reverse Osmosis (RO), Pressure Assisted Forward Osmosis (PAFO), Forward Osmosis (FO) and Membrane Distillation (MD)

3.2.2 Seawater desalination at 35000 ppm TDS levels

The capital cost and operational cost, permeate volume, brine reject volume, TDS of Brine and levelised cost of water with of various combinations considered in section seawater desalination namely as below is shown in figure 17, figure 18, figure 19, figure 20 and figure 21 respectively.

i. Reverse Osmosis (RO) in combination with Membrane Distillation (MD)
ii. Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO) and Membrane Distillation (MD)
iii. Reverse Osmosis (RO), Counter Flow Reverse Osmosis (CFRO), Multi Effective Distillation (MED) and Membrane Distillation (MD)

Conclusions

It is identified that the operation of MD as a standalone desalination unit especially for large seawater desalination units is not recommended considering the capital cost of the system. However the MD can be used with existing desalination technologies with different configurations suitable to increase the recovery while constraining the capacity. The present study has focused on MD in combination with RO, CFRO, FO, PAFO and MED combinations for brackish and seawater desalinations. It is found that brine volume in brackish water desalination with RO – MD combination can further be reduced by 50% with combination of PAFO and FO as a separate stream. The 25 years levelised cost of produced water for RO-MD and RO-PAFO-FO-MD combination is 0.06 INR and 0.07 INR respectively. Similarly in seawater desalination, the brine can be further reduced by 60% from a RO-MD combination by using a CFRO and MED-MD combination. However there is an increase of more than 50% in capital and operational expenses, while the 25 year levelised cost for RO-MD and RO-CFRO-MED-MD are almost the same at 0.24 INR and 0.25 INR considering increased recovery rates. This proves that there is a potential in brine reduction and better recovery rates by combing MD as a hybrid desalination component among existing technologies, especially in combination with RO. However the availability of low grade heat continuous heat source and optimization of MD, FO and CFRO technologies to commercial scale is important to provide reliable working desalination plants. The increase in recovery rates is ever more critical in small islands where the intake and reject are a constraint.

Thus future studies should focus on selection of right technology for the MD its placement in the desalination process flow and availability of low temperature heat source to commercialize.

Declarations

Ethical Approval: The manuscript is written as per the requirements of the journal regarding the ethical approach. The authors confirm that no part of the manuscript was written and published elsewhere.

*Consent to Particip*ate: Not applicable

Consent to Publish: The authors give the journal the authority to publish through the procedures of review and evaluation.

Authors Contributions: Sanju Thomas, Kandaswamy Ravikumar and Sendhil Kumar have conceived the project, with the latter two developed and guided the process flow diagrams. Sudhansu Sahoo have done the business perspective of various desalination combinations. Ajith Kumar have done the checking on the costing, while Sheffy Thomas has done the management and editing.

Funding: Not applicable

Competing Interests: The authors conform that there are not conflict of interest nor competing interest in the authorship and contribution.

Availability of data and materials: All and any data and materials that have led to conclusion of the results of the manuscript shall be submitted.

References

1. Adham S, Hussain A, Matar JM, Dores R, Janson A (2013) Application of membrane distillation for desalting brines from thermal desalination plants. Desalination 314:101–108. https://doi.org/10.1016/j.desal.2013.01.003
2. Adham S, Hussain A, Minier-Matar J, Janson A, Sharma R (2018) Membrane applications and opportunities for water management in the oil & gas industry. Desalination 440:2–17. https://doi.org/10.1016/j.desal.2018.01.030
3. ADU-RES Desalination Systems Powered by Renewable Energy Institutional Framework Conditions in the Mediterranean Region, Proceedings of International Seminar 19 September 2006 Le Royal Hotel, Amman, Jordan, Available at http://www.adu-res.org/pdf/CRES.pdf. Accessed on 04/04/2022
4. Andrés-Mañas AJ, Ruiz-Aguirre A, Acién FG, Zaragoza G (2020) Performance increase of membrane distillation pilot scale modules operating in vacuum-enhanced air-gap configuration. Desalination 475. https://doi.org/10.1016/j.desal.2019.. 114202
5. Chafidz A, Kerme ED, Wazeer I, Khalid Y, Ajbar A, Al Zahrani SM (2016) Design and fabrication of a portable and hybrid solar powered membrane distillation system. J Clean Prod 133:631–647. https://doi.org/10.1016/j.jclepro.2016.05.127
6. Dotremont C, Kregersman B, Sih R, Lai KC, Koh K, Seah H (2010) Seawater desalination with memstill technology - a sustainable solution for the industry. Water Pract Technol 5:1–8. https://doi.org/10.2166/wpt.2010.026 22
7. Drioli E, Ali A, Macedonio F (2015) Membrane distillation: Recent developments and perspectives. Desalination 356:56–84
8. Duong CH, Cooper P, Nelemans B, Cath TY, Nghiem LD (2016) Evaluating energy consumption of air gap membrane distillation for seawater desalination at pilot scale level. Sep Purif Technol 166:55–62. https://doi.org/10.1016/j.seppur.2016.04.014
9. Edward S (2006) The potential for wind- powered desalination in water- scarce countries, Master of Arts in Law and Diplomacy Thesis, Tufts Digital Library, USA
10. Fath HES (1997) High performance of a simple design, two effects, solar distillation unit. Energy Conv Manag 38:1895–1905
11. Future directions for global desalination industry. http://www.futuredirections.org.au/publication/research-development-global-desalinationindustry, Accessed on 03/11/2020.
12. Gayen A, Zaman A, Kar A, Ambast SK, Ravisankar N (2014) Impact Assessment of Integrated Water Resource Management through Farmers Participatory Action Research Programme (FPARP) in Andaman and Nicobar Islands. Proceedings of the workshop on Conservation Of Water Resources In Andaman & Nicobar Islands: Issues and Challenges; Ed. Indranil Roy; 27th March ; CIARI, Port Blair, A & N Islands

13. Hagedorn A, Fieg G, Winter D, Koschikowski J, Mann T (2017) Methodical design and operation of membrane distillation plants for desalination. Chem Eng Res Des 125:265–281. https://doi.org/10.1016/j.cherd.2017.07.024
14. Han L, Tan YZ, Netke T, Fane AG, Chew JW (2017) Understanding oily wastewater treatment via membrane distilla tion. J Membr Sci 539:284–294. https://doi.org/10. 1016/j.memsci.2017.06.012
15. Jansen EA, Assink JW, Hanemaaijer JH, van Medevoort J, van Sonsbeek E (2013) Development and pilot testing of full-scale mem brane distillation modules for deployment of waste heat. Desalination 323:55–65. https://doi.org/10.1016/j.desal. 2012.11.030
16. Kalogirou SA (2005) Seawater desalination using renewable energy sources. Energy & Combustion Science 31:242–281
17. Minier-Matar J, Hussain A, Janson A, Benyahia F, Adham S (2014) Field evaluation of membrane distillation technologies for desali nation of highly saline brines. Desalination 351:101–108. https://doi.org/10.1016/j.desal.2014.07.027
18. Minier-Matar J, Sharma R, Hussain A, Janson A, Adham S (2016) Field evaluation of membrane distillation followed by humidification/dehumidification crystallizer for inland desalina tion of saline groundwater. Desalination 398:12–21. https://doi.org/10.1016/j.desal.2016.07.006
19. Mohamed SE, Boutikos P, Mathioulakis E, Belessiotis V (2017) Experimental evaluation of the performance and energy efficiency of a Vacuum Multi-Effect Membrane Distillation system. Desalination 408:70–80. https://doi.org/10.1016/j.desal. 2016.12.020
20. Osmosun http://mascara-nt.fr/en/project/osmosun80-bora-bora-french-polynesia/ (Accessed on 01/04/2022)
21. “Global Renewable Energy Desalination by Energy Source,” PRODES (PROmotion of Renewable Energy for Water Production through Desalination), ProDes (2010) http://www.prodes-project.org. Accessed November 20, 2021
22. Renewable energy water desalination programme (2017)The New Frontier of Sustainable Water Desalination, Masdar
23. Rodriguez G, Rodriguez M, Perez J, Veza J (1996) A systematic approach to desalination powered by solar, wind and geothermal energy sources. Proceedings of the Mediterranean conference on renewable energy sources for water production 10: 20–25
24. Ruiz-Aguirre A, Andrés-Mañas JA, Zaragoza G (2019) Evaluation of permeate quality in pilot scale membrane distillation systems. Membranes 9:1–14. https://doi.org/10.3390/ membranes9060069
25. Ruiz-Aguirre A, Andrés-Mañas JA, Fernández-Sevilla JM, Zaragoza G (2018) Experimental characterization and optimization of multi-channel spiral wound air gap membrane distillation modules for seawater desalination. Sep Purif Technol 205:212–222. https://doi.org/10.1016/j.seppur.2018.05.044
26. Schwantes R, Cipollina A, Gross F, Koschikowski J, Pfeifle D, Rolletschek M, Subiela V (2013) Membrane distillation: Solar and waste heat driven demonstration plants for desalination. Desalination 323:93–106. https://doi.org/10.1016/j. desal.2013.04.011

27. Schwantes R, Bauer L, Chavan K, Dücker D, Felsmann C, Pfafferott J (2018) Air gap membrane distillation for hypersaline brine concentration: Operational analysis of a full-scale module–New strategies for wetting mitigation. Desalination 444:13–12. https://doi.org/10.1016/j.desal.2018.06.012
28. Shatat M, Saffa B Riffat, Water desalination technologies utilizing conventional and renewable energy sources, *International Journal of Low-Carbon Technologies*, Volume 9, Issue 1, March 2014, Pages 1–19, https://doi.org/10.1093/ijlct/cts025
29. Swarnam PT, Velmurugan A, Sai TP, Srivastava P, Rachel, Dam Roy S (2014) Quality of Surface water in Nicobar Islands, India, Proceedings of the Workshop on Conservation of Water Resources in Andaman & Nicobar Islands: Issues and Challenges; Organised by Central Ground Water Board at Port Blair, A & N Islands, March 27,
30. Voivontas D, Yannopoulos K, Rados K, Zervos A, Assimacopoulos D (1999) Market potential of renewable energy powered desalination systems in Greece, vol 121. Desalination, pp 159–172

Figures

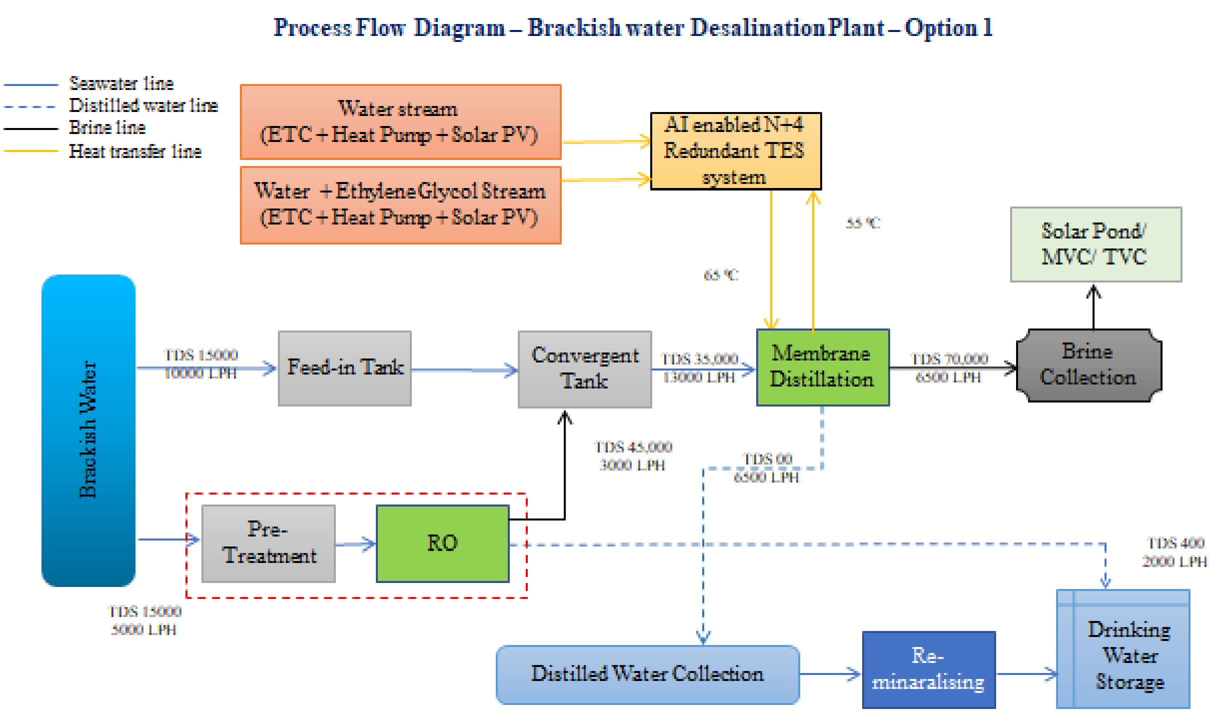

Figure 1

Brackish water desalination system in combination with RO and MD units

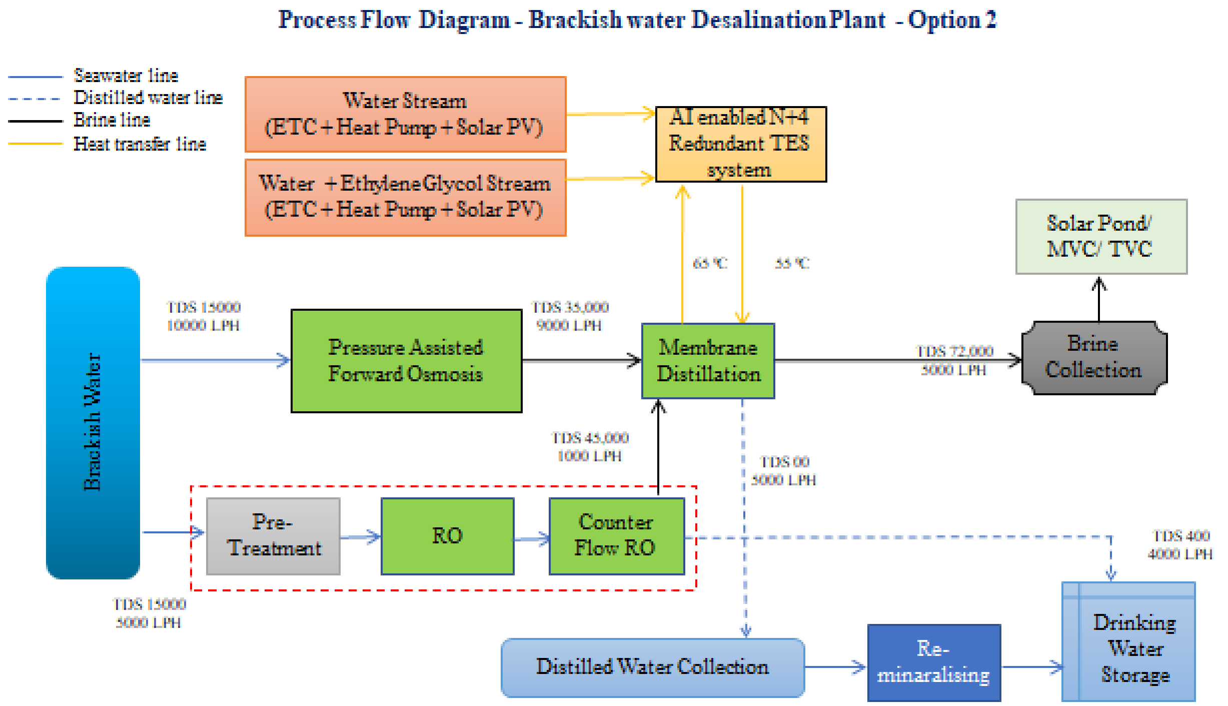

Figure 2

Brackish water desalination system in combination with RO, CFRO, PAFO and MD units

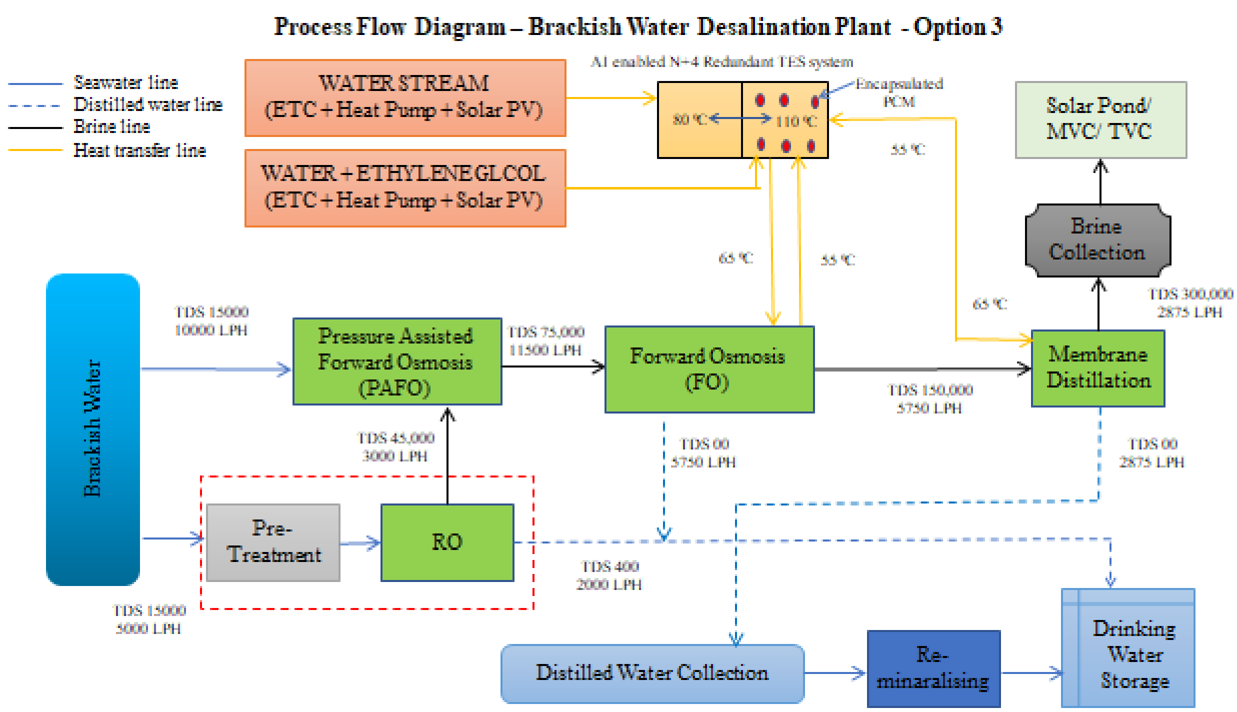

Figure 3

Brackish water desalination system in combination with RO, PAFO and FO units

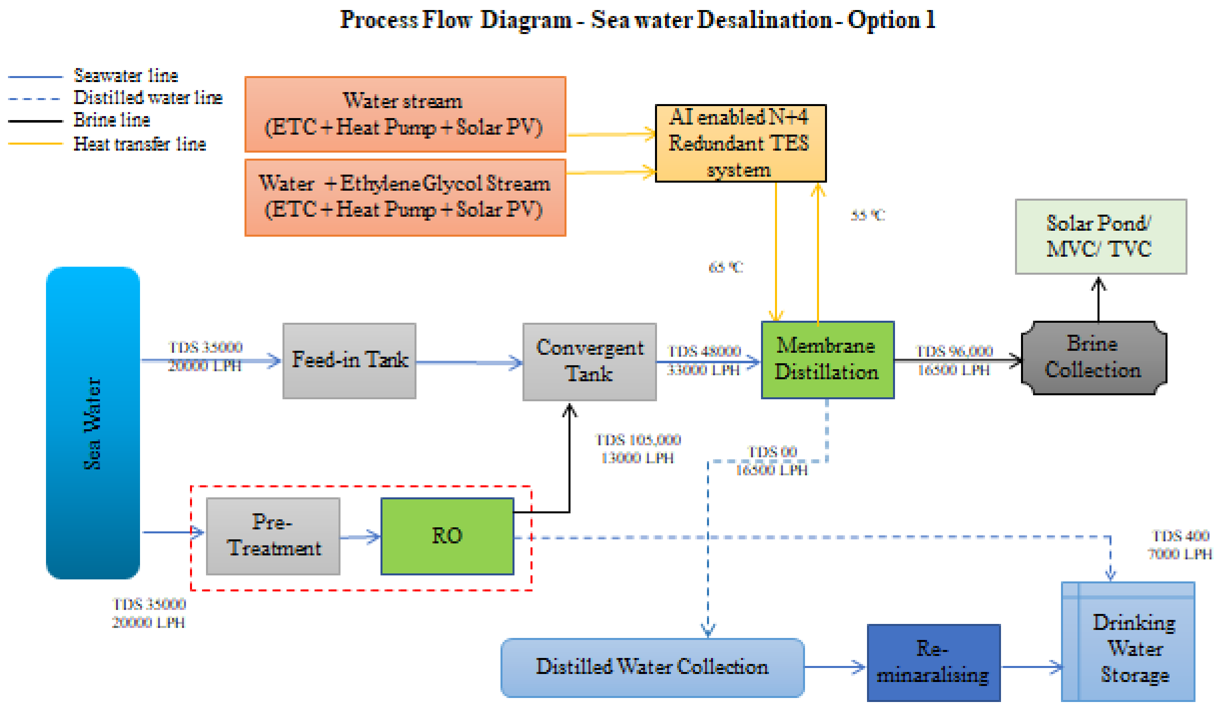

Figure 4

Seawater desalination system in combination with RO and MD units

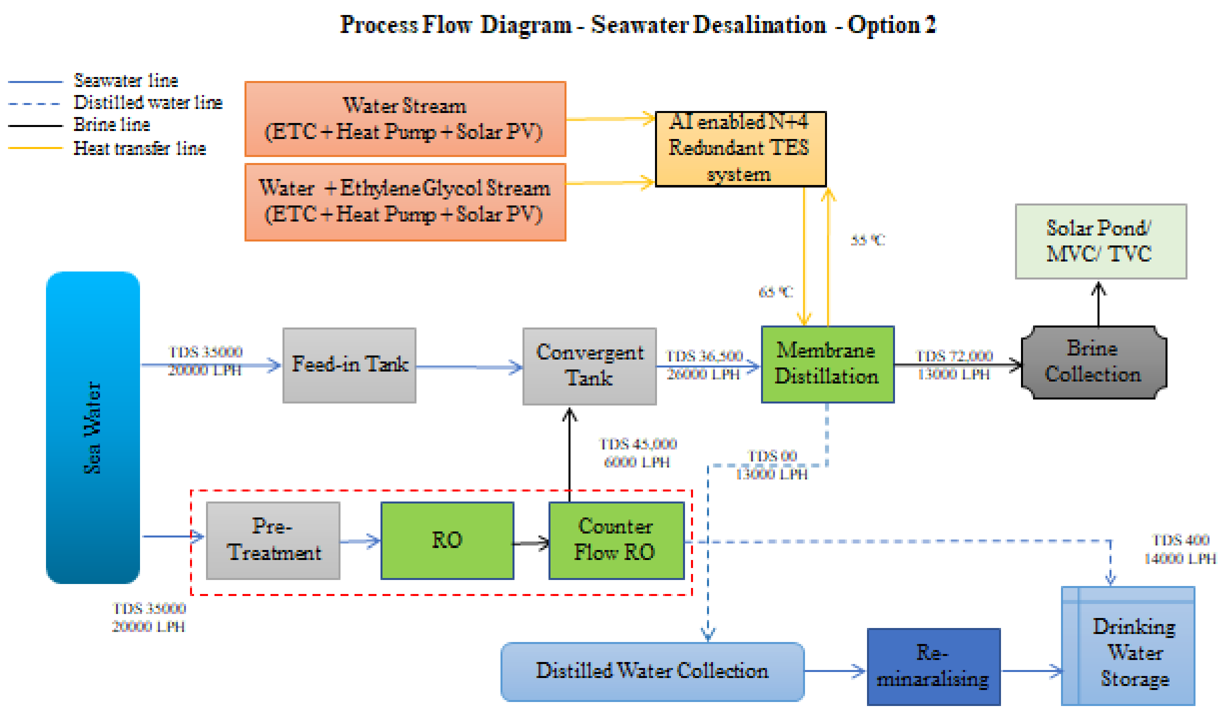

Figure 5

Seawater desalination system in combination with RO, CFRO and MD units

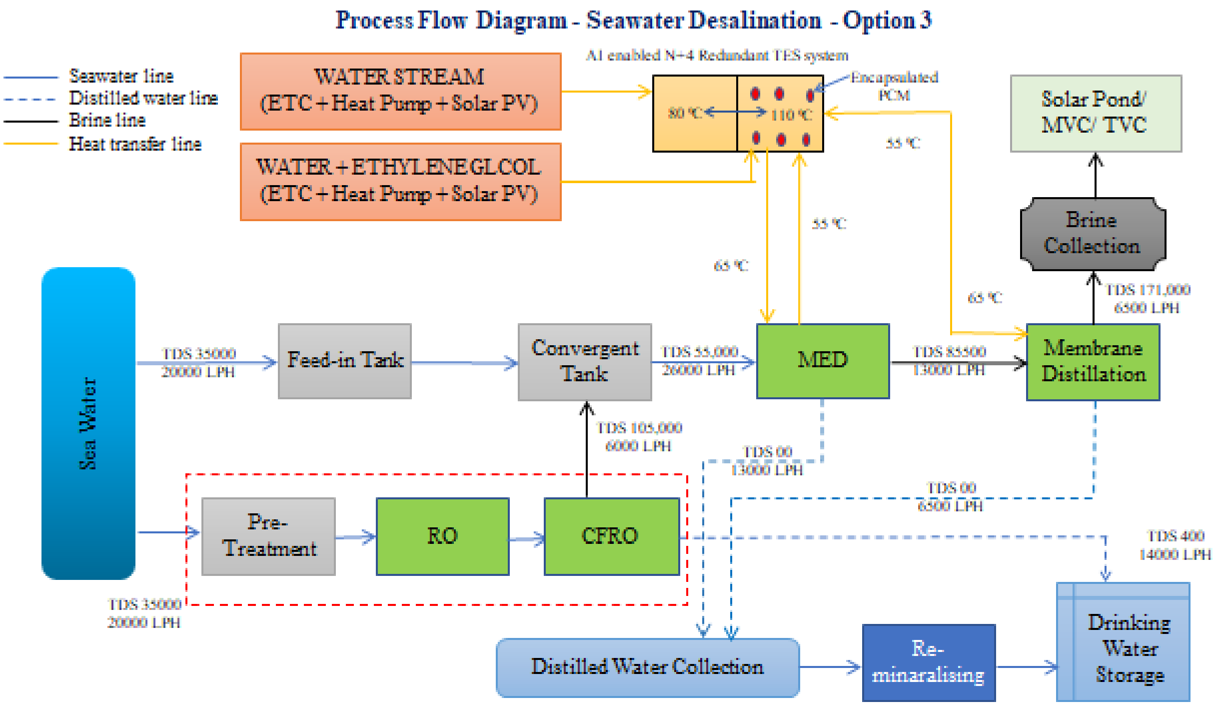

Figure 6

Seawater desalination system in combination with RO, CFRO, MED and MD units

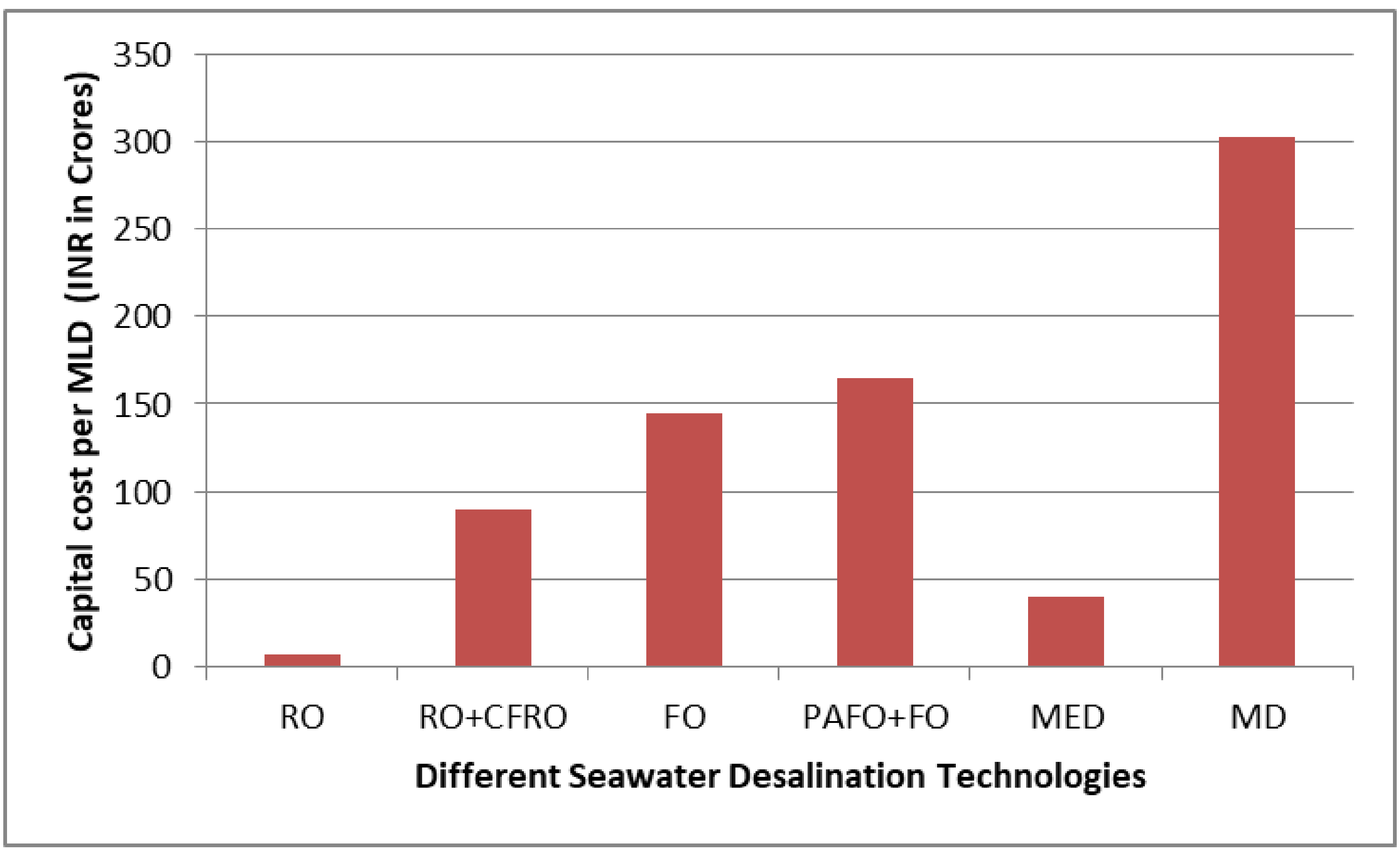

Figure 7

Figure 8. Capital cost of various seawater desalination technologies at approximately 35000 ppm

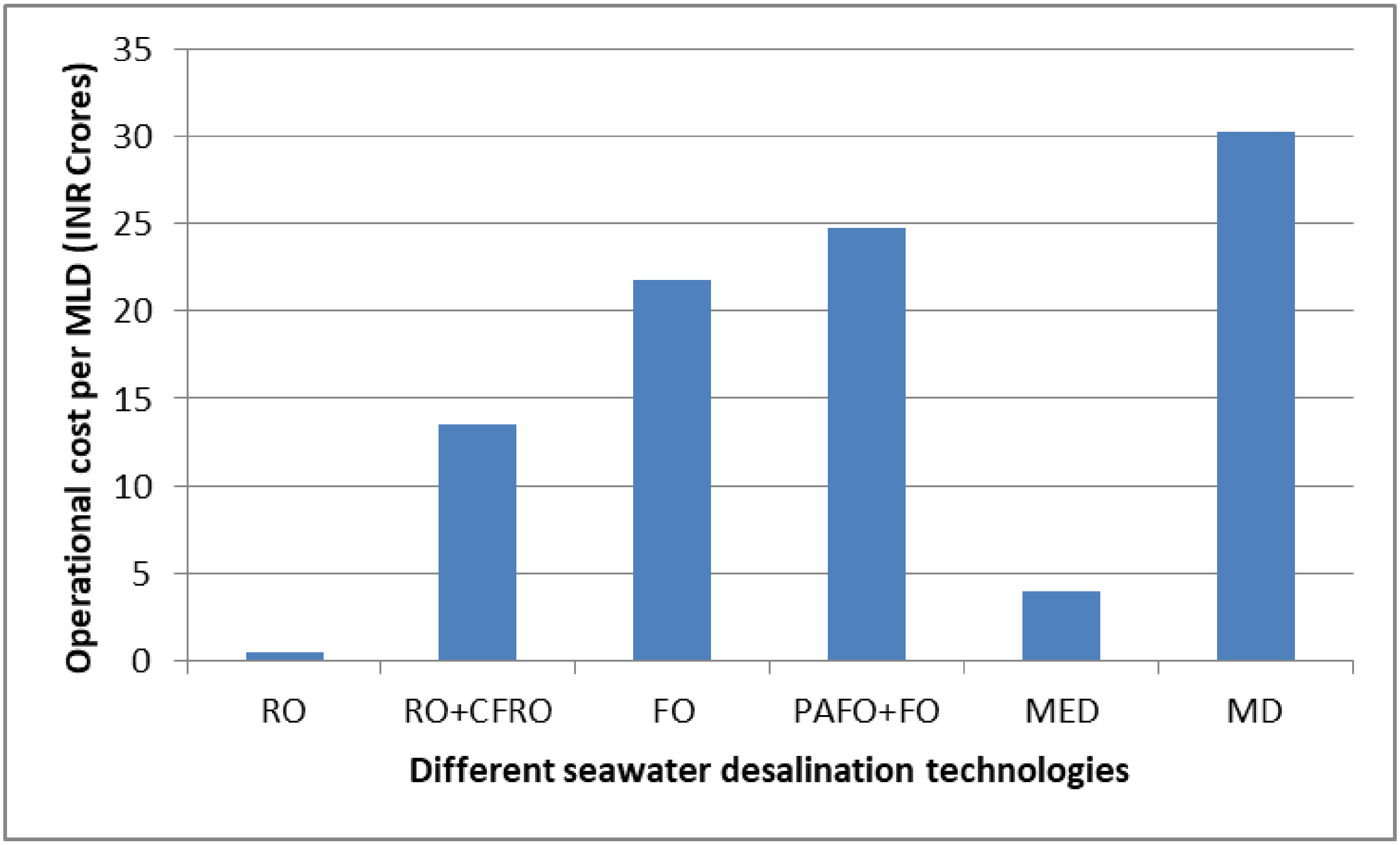

Figure 8

Figure 9. Operational expenses of different seawater desalination technologies at approximately 35000 ppm

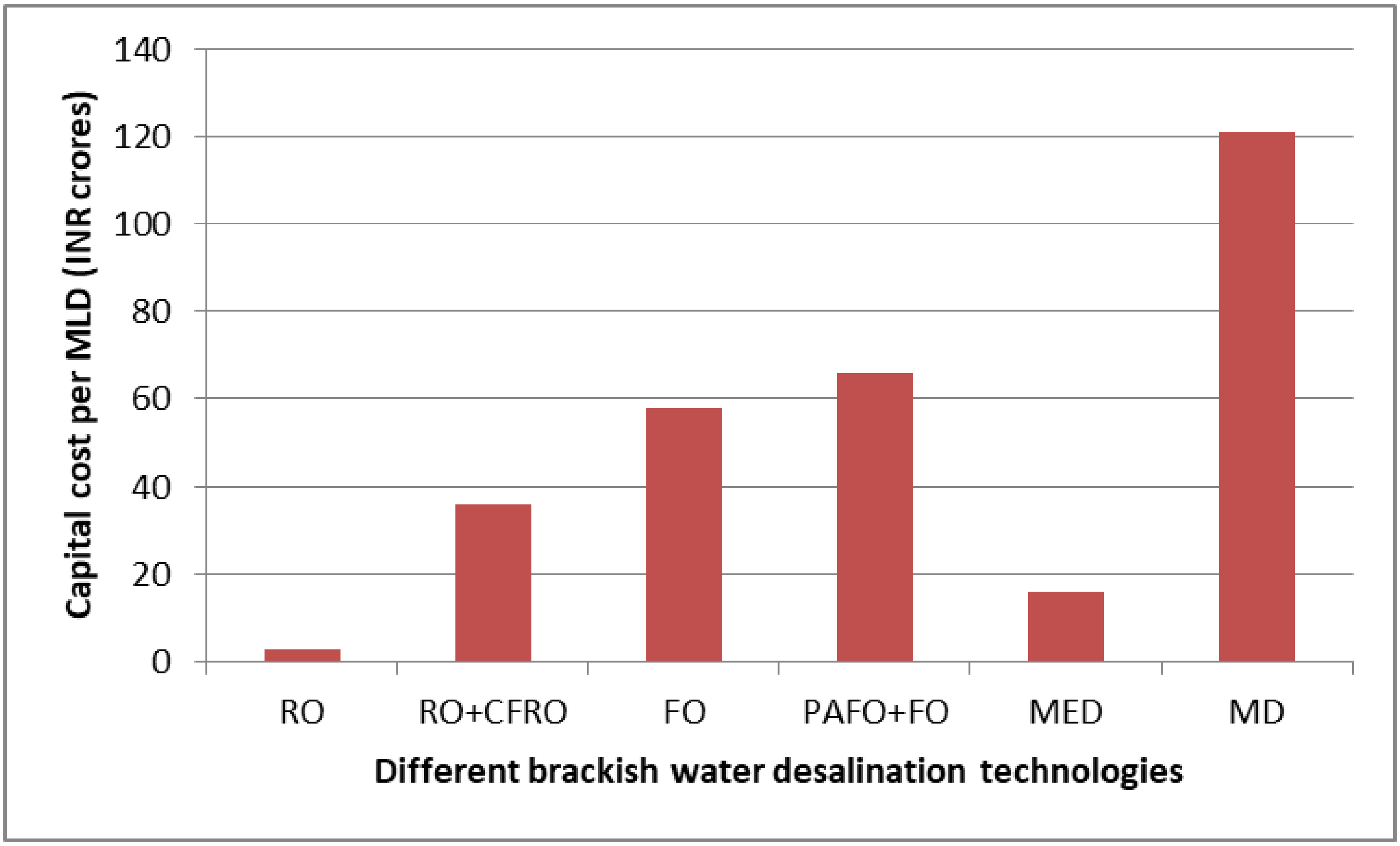

Figure 9

Figure 10. Capital cost of various brackish water desalination technologies at approximately 15000 ppm

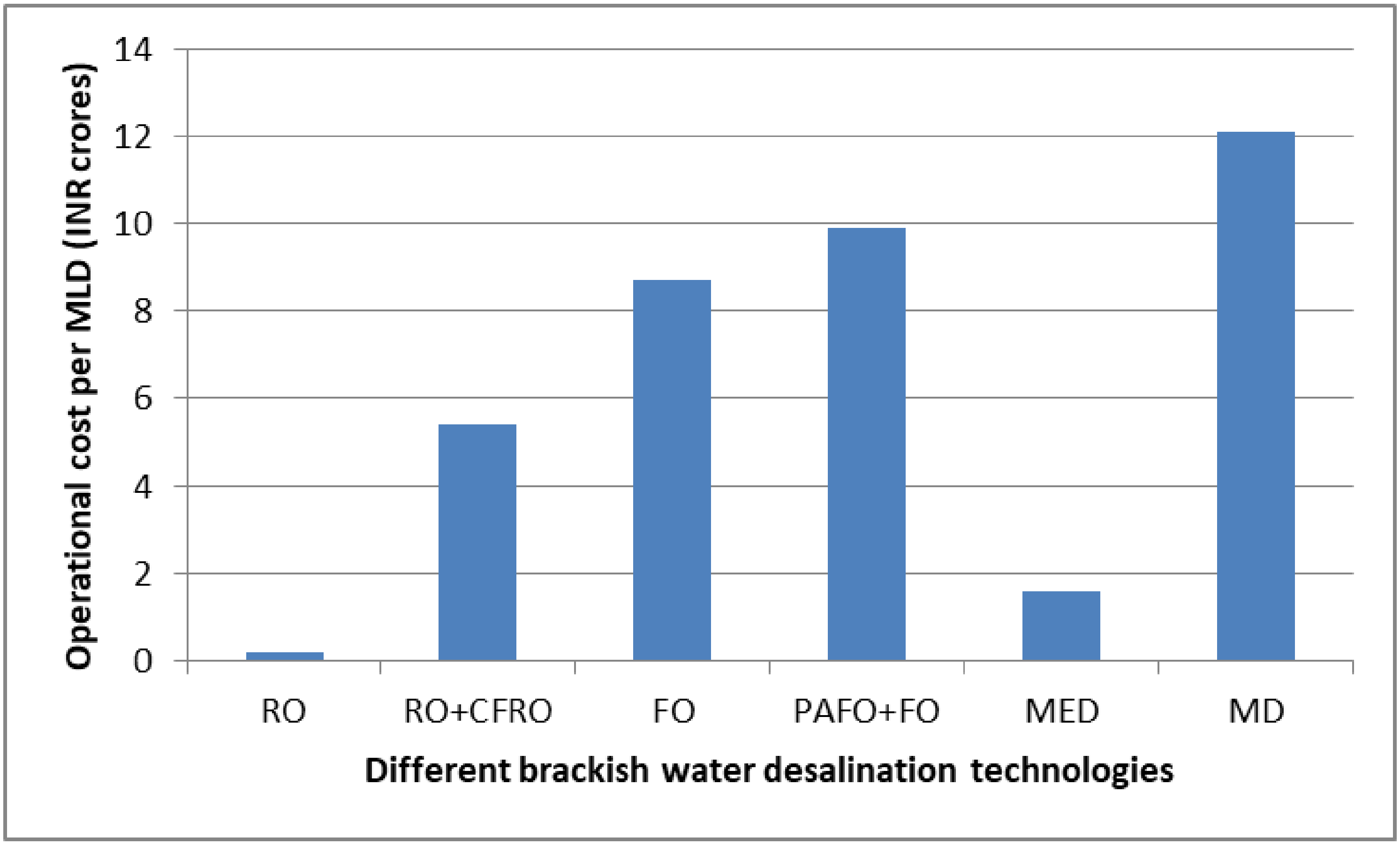

Figure 10

Figure 11. Operational cost of various brackish water desalination technologies at approximately 15000 ppm

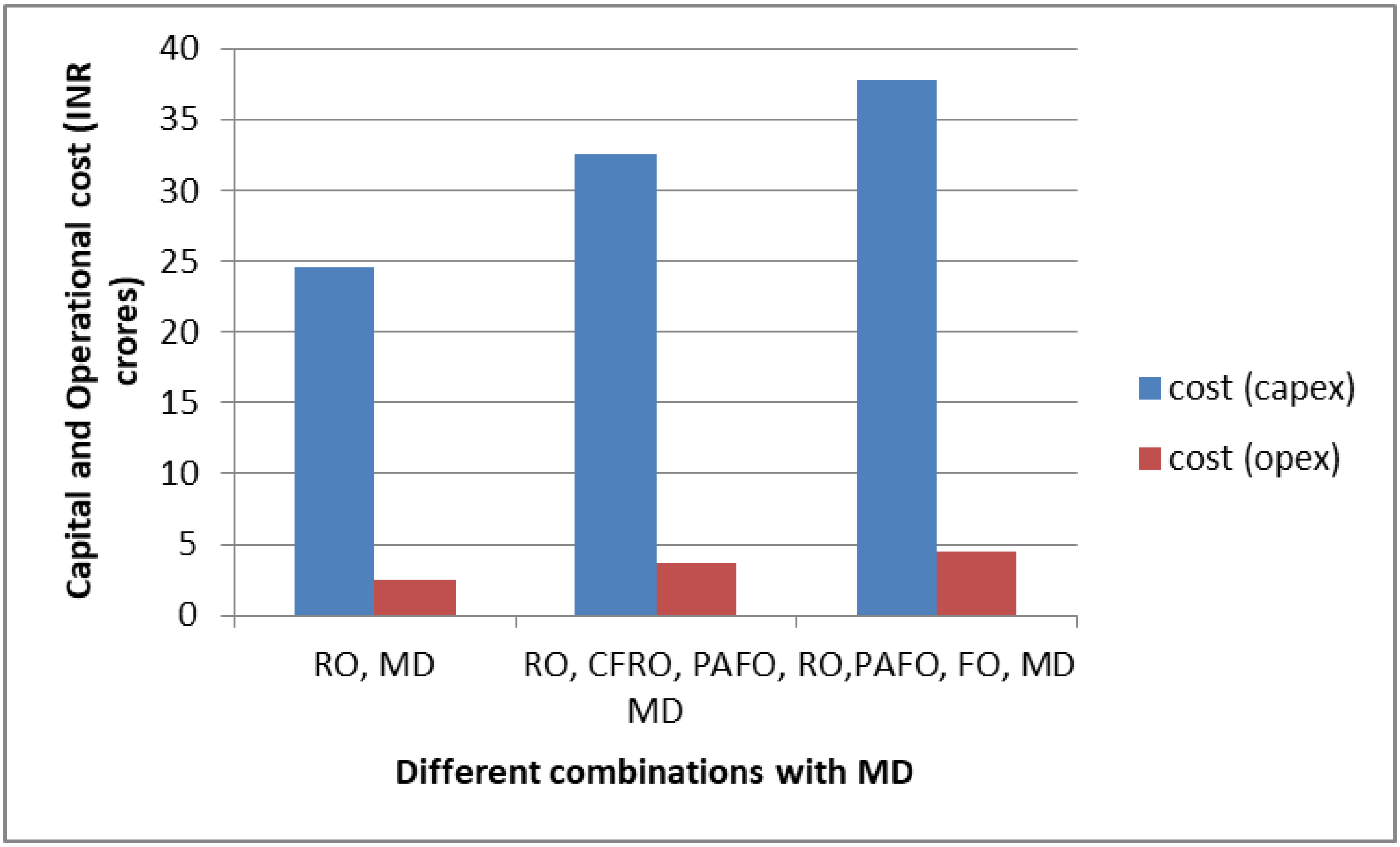

Figure 11

Figure 12. Capital and operational cost of brackish water desalination systems with MD combinations considered for assessment

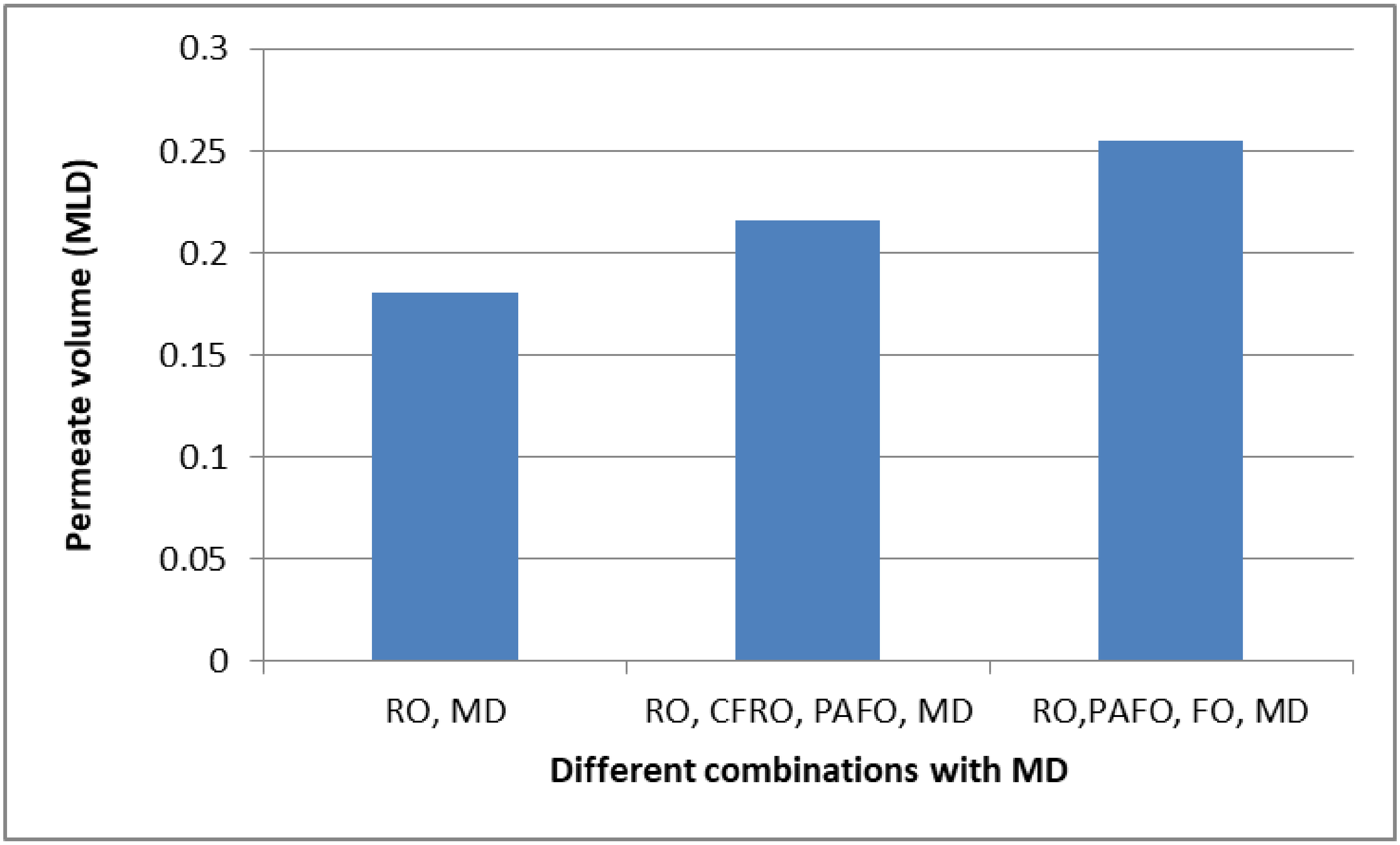

Figure 12

Figure 13. Permeate volume of various brackish desalination systems with MD combinations considered for assessment

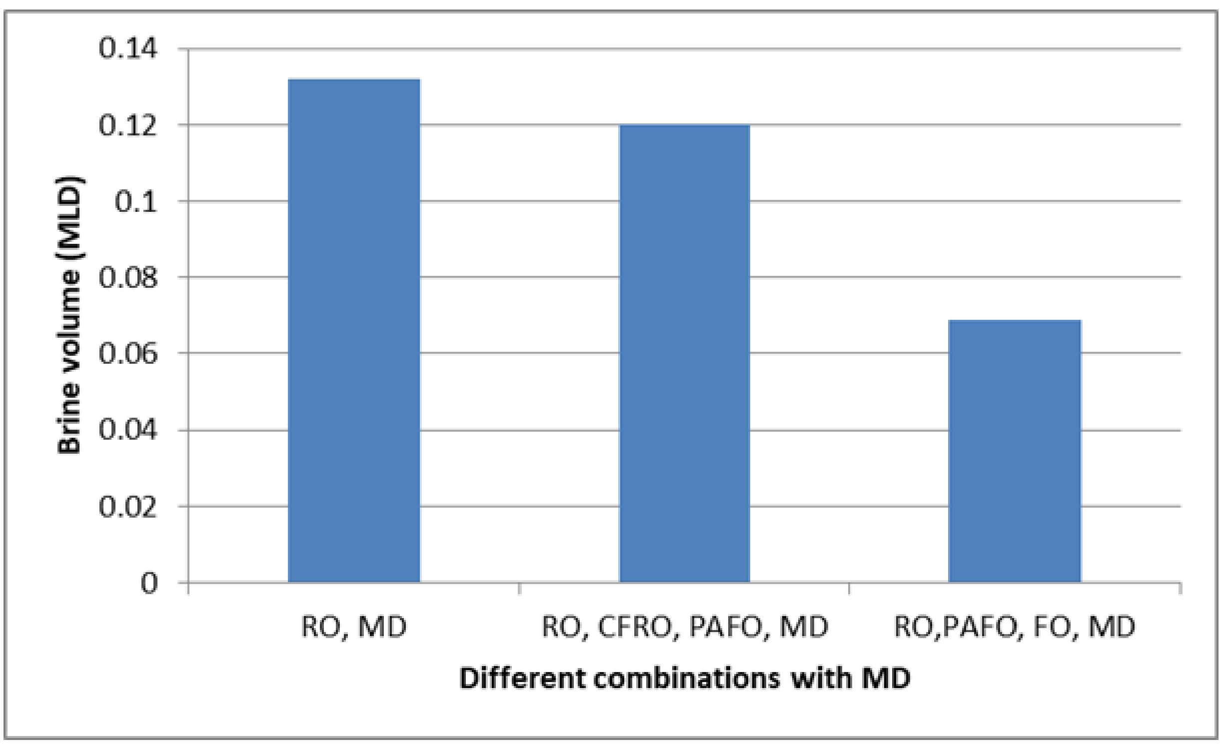

Figure 13

Figure 14. Brine volume of various brackish desalination systems with MD combination considered for assessment

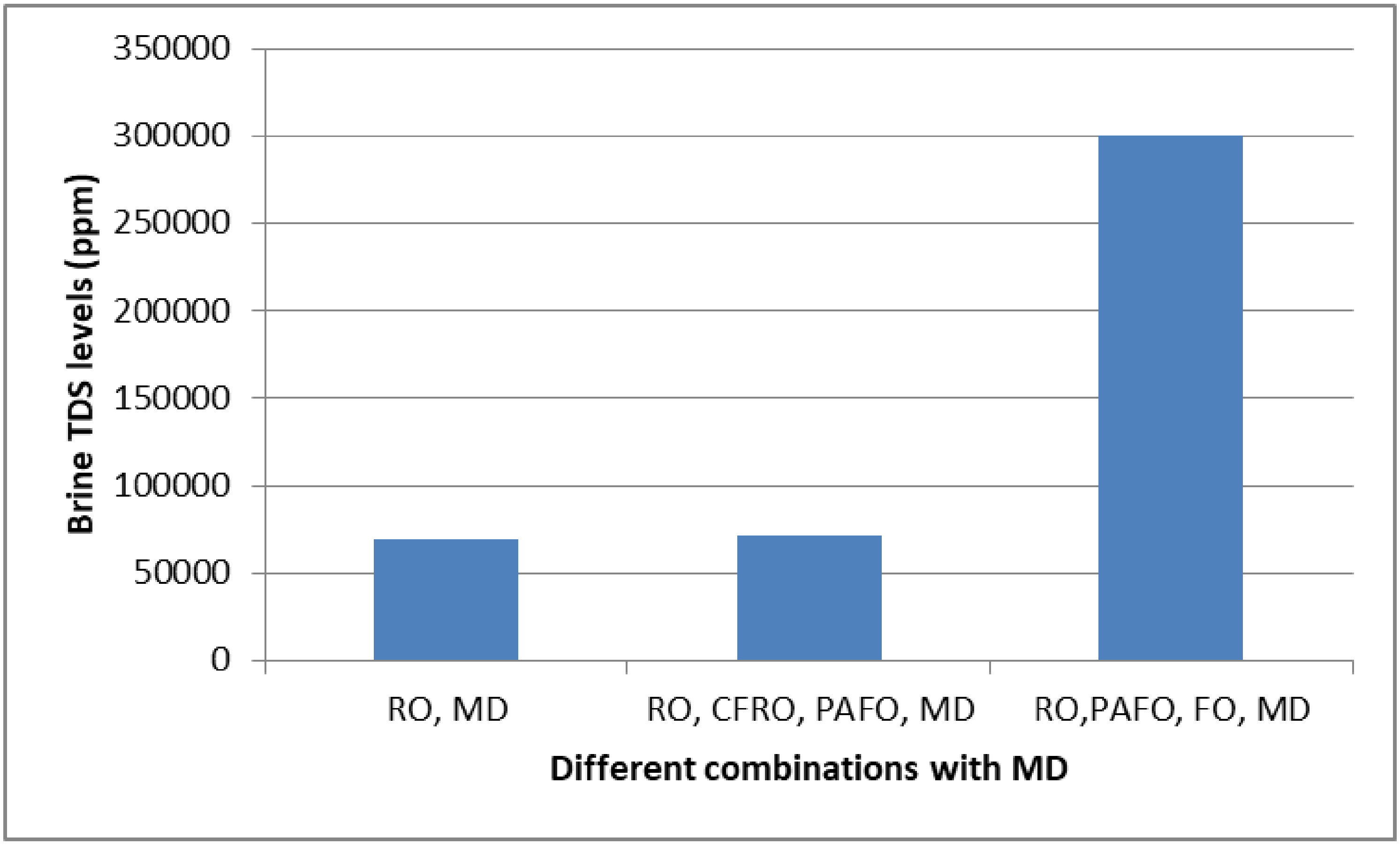

Figure 14

Figure 15. TDS levels of brine reject for various brackish desalination systems with MD combination considered for assessment.

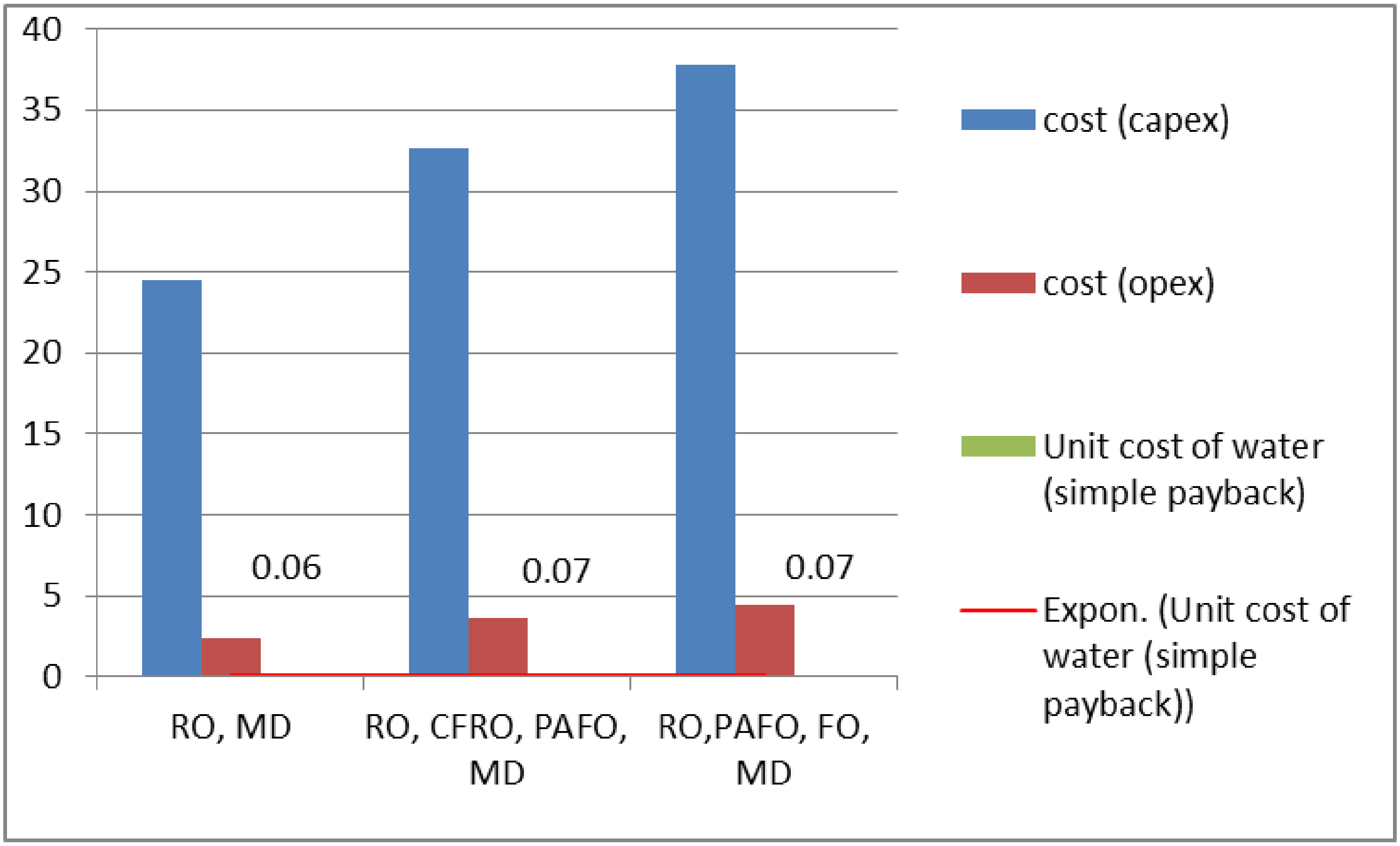

Figure 15

Figure 16. The unit cost of produced water with various brackish desalination systems with MD combinations considered for assessment.

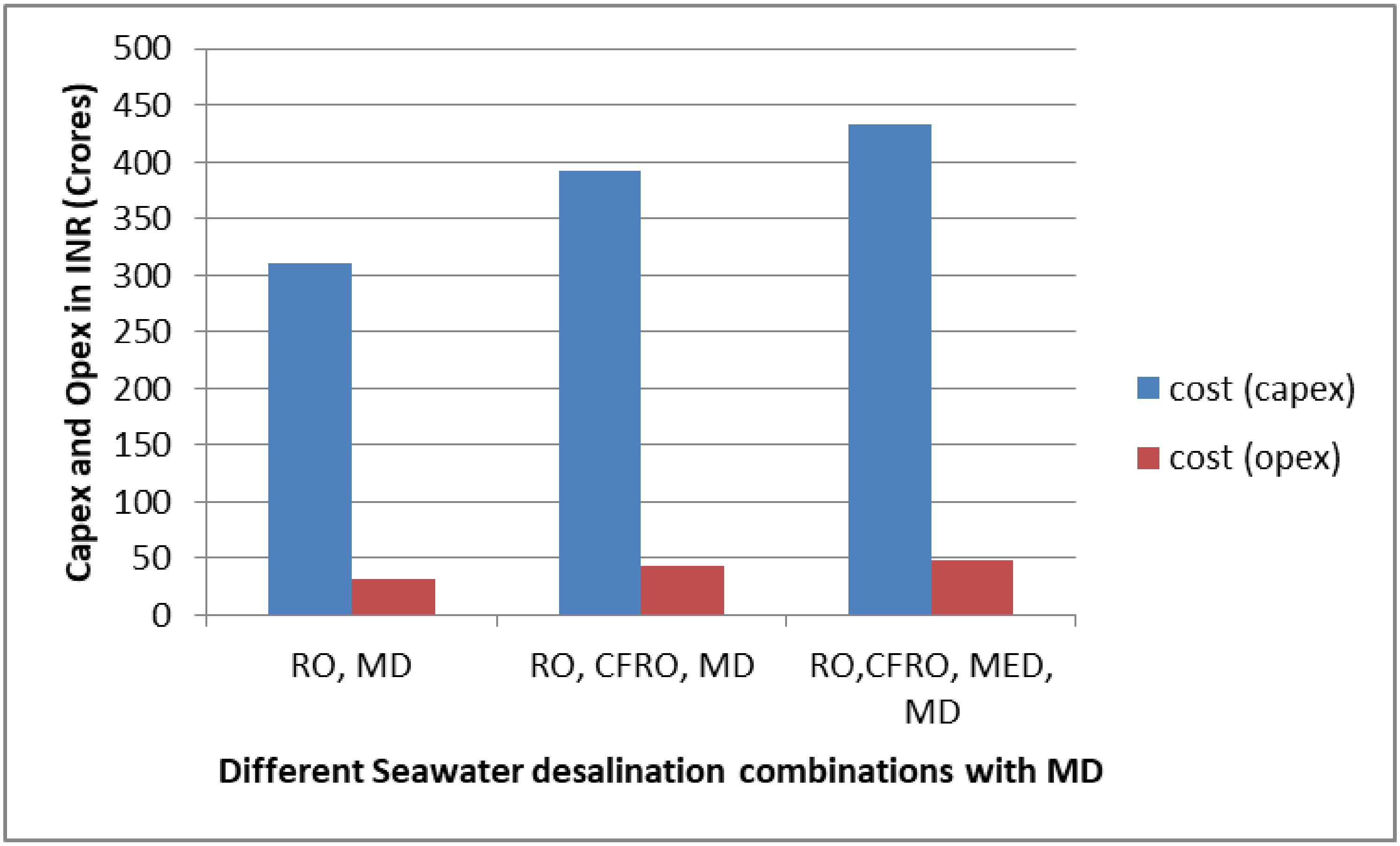

Figure 16

Figure 17. Capital and operational cost of seawater desalination systems with MD combinations considered for assessment

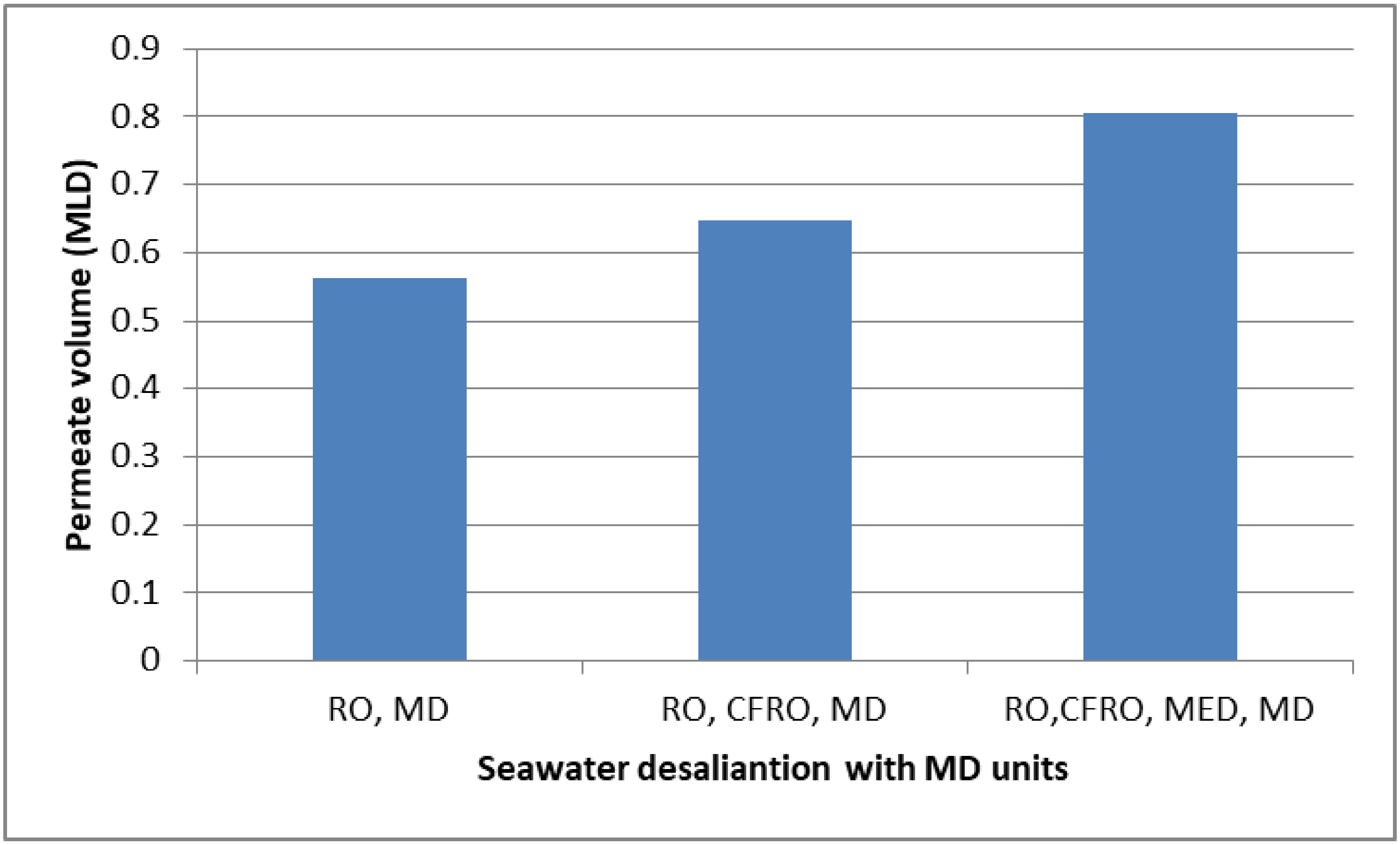

Figure 17

Figure 18. Permeate volume of various seawater desalination systems with MD combinations considered for assessment

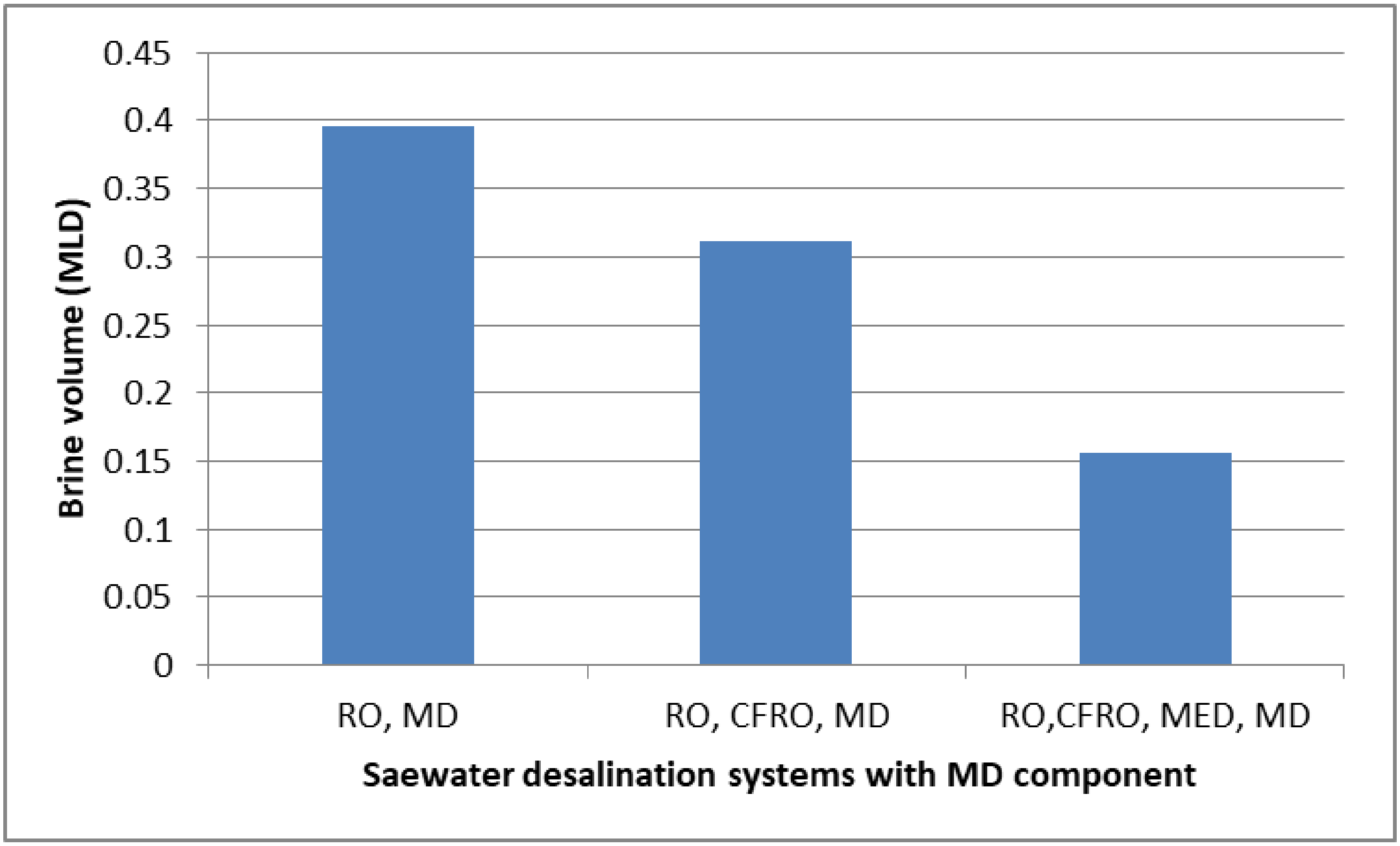

Figure 18

Figure 19. Brine volume of various seawater desalination systems with MD combinations considered for assessment

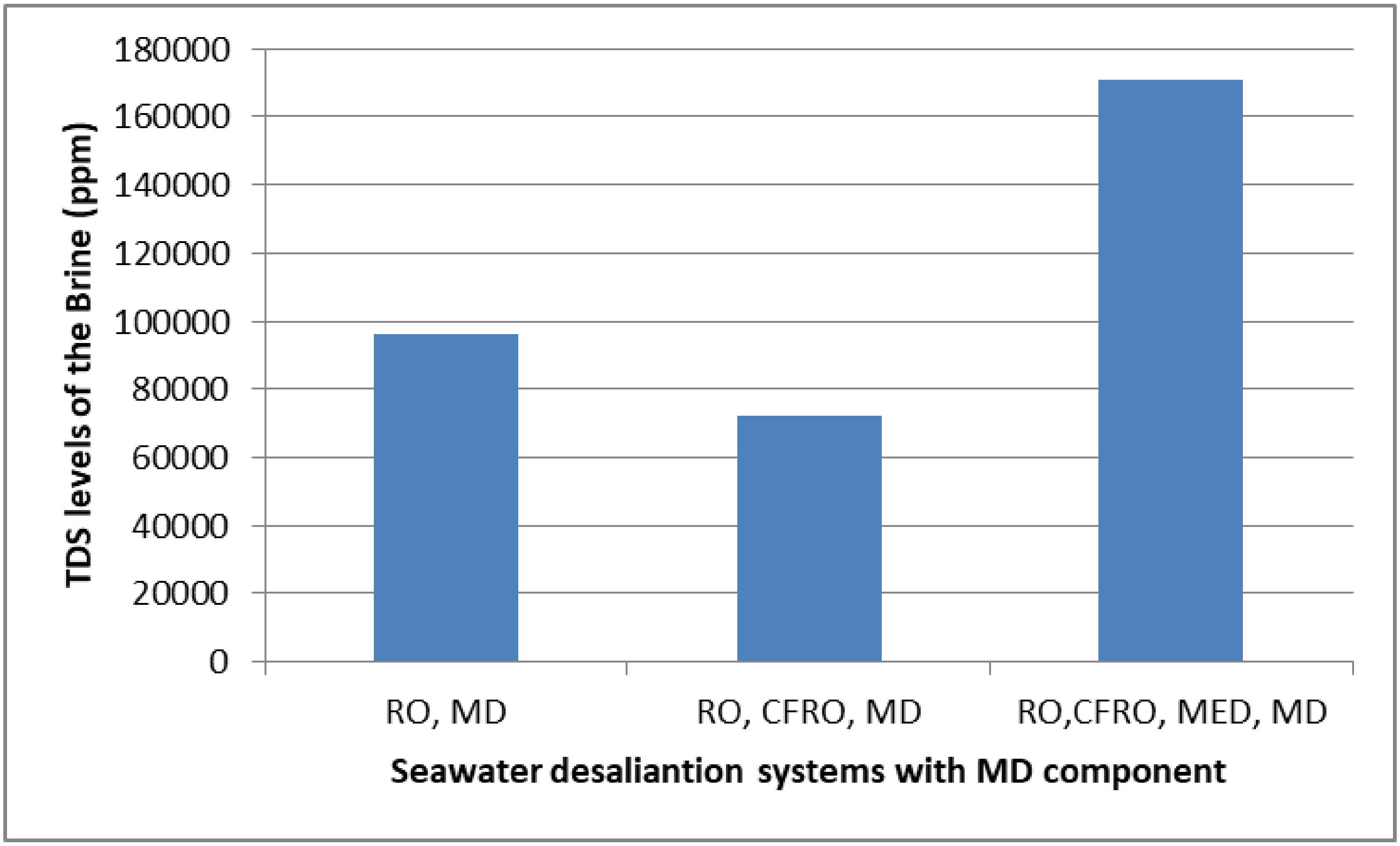

Figure 19

Figure 20. Brine TDS levels of various seawater desalination systems with MD combinations considered for assessment

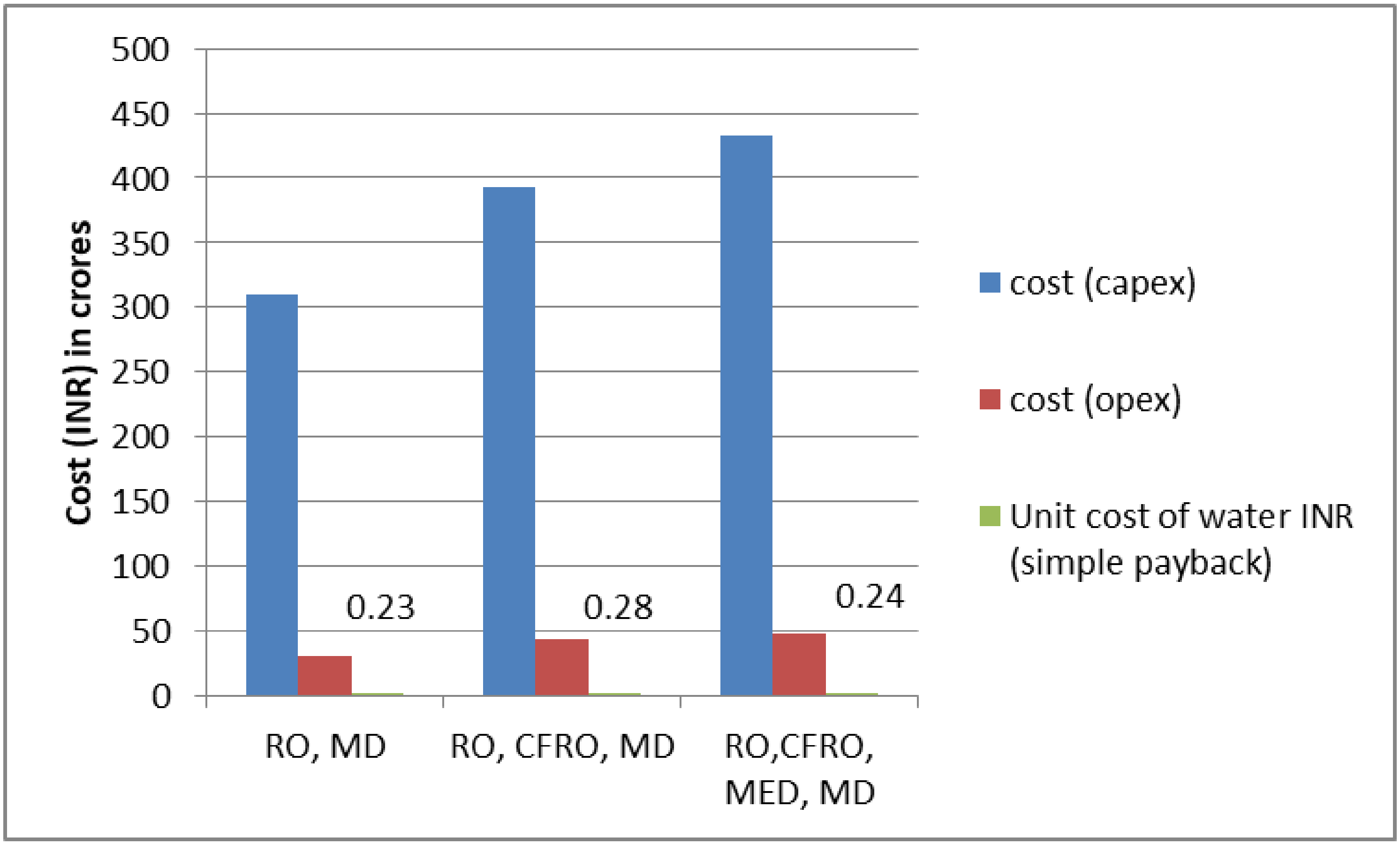

Figure 20

Figure 21. The unit cost of produced water with various seawater desalination systems with MD combinations considered for assessment