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Cost analysis and scheduling of the desalination vessel using reverse osmosis technology

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Abstract. Water scarcity issue becomes severe due to climate change and increase of water needs, globally. In order to provide fresh water in islands, small-scale desalination plants (< 100 m^3/day) had been installed using reverse osmosis technology. To decrease high desalination cost of small-scale SWRO plants in islands in Republic of Korea, the desalination vessel having RO system (300 m^3/day) was recently suggested. The desalination costs of the small-scale SWRO plants in islands and desalination vessel which can provide desalinated water to several islands were analyzed and were compared. The operational schedule of the desalination vessel in Shinan-gun, Republic of Korea was suggested considering the water demands, velocity and water storage of the desalination vessel, and distances between target islands. It was found that the water production cost could be saved when the desalination vessel was applied in Shinan-gun, Republic of Korea.

Keywords: cost analysis; desalination vessel; reverse osmosis (RO); small-scale desalination; vessel routes

1. Introduction

The climate change occurring has been caused the water scarcity globally. In Republic of Korea, the water shortage has been happened severely for the coastal areas and islands (Park *et al.* 1997) because precipitation could be the only possible water source and water storage system is not sufficient (Yang *et al.* 2020). The southeastern islands group (Sinan-gun) in Republic of Korea have been experienced severe drought these years (The KoreaTimes 2017) and the government had to provide the bottled drinking water to the islands by helicopter or ferry for emergency. As an alternative water source in islands, submarine pipeline to transport tap water and small-scale desalination process based on the reverse osmosis (RO) have been applied in Republic of Korea. The RO process is the cheapest and the most commonly applied (112 plants out of 331 desalination plants in the world) desalination technology among the thermal (multi-stage flash (MSF) and multi effect distillation (MED)) or membrane (seawater RO (SWRO) and brackish water RO (BWRO)) desalination technologies (Shemer and Semiat 2017, Wittholz *et al*. 2008). However, only near islands (up to several km distance from the mainland) have been connected with the submarine pipeline due to its high cost of the construction and small-scale desalination process required high cost due to frequent maintenance and membrane replacement resulted from intermittent operation. The fouled RO membrane could be cleaned or reused in other membrane purposes to decrease the replacement cost (Ng *et al*. 2020, Jung *et al*. 2021).

A mobile floating desalination system (vessel having desalination plant on it) has been employed to provide the drinking water for people in the isolated islands. It was utilized as a temporary water supplying solution in Saudi Arabia in 2009, Cypriot in 2008 and Thailand in 2006 at the meantime of the permanent land-based desalination plants were under construction (Kokubun 2014). In addition, a fully seagoing desalination vessel carrying two 1,250 m^3/day multi-stage flash (MSF) distiller was implemented to provide water for the towns along the coast and on the islands in Abu Dhabi Emirate (Fadel *et al*. 1983). 120,000 m3 per day desalinated water were produced on the mobile desalination vessels on Algeria to provide the fresh water to the human living at the ports and towns on the shores of arid areas and deserts with hot and dry climatic weather. Similarly, a mobile floating desalination plant (Preussag conversion system, PCS) of 50,000 m^3/day was implemented to provide potable water to the arid coastal regions in Germany (Lampe *et al*. 1997). The mobile plant employed SWRO (20,000 m^3/day) to supply potable water to Limassol city and surroundings in Moni, Cyprus (Gasia-Bruch *et al*. 2011).

The desalination vessel can provide the water flexibly to the various water demanders in the isolated islands because the vessel can produce water during its locating or moving then deliver water to the islands upon request as well as move to escape the disasters like hurricane and immediate come back to supply water. In addition, a desalination vessel shows some advantages in comparison to the conventional land-based installations on each site, such as

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the short construction time due to the no site (buildings, roads and so on) moving and civil work, low required energy for intake and brine disposal as well as high intake seawater quality because of the vessels locate on the sea, use the available tanks and infrastructure on the vessel and shorter transport time of water to the customers (Fadel *et al*. 1983, Lampe *et al*. 1997).

Recently, the DREAMs (Desalination by Resilient, Energy-efficient, & Advanced Mobile System) project launched in Republic of Korea and suggested the water supply method by using the desalination vessel for the coastal area and the islands. The desalination vessel mounted the SWRO system (300 m^3/day) will be tested. In order to prepare the real operation of the desalination vessel, it was required to understand the cost feasibility of the desalination vessel compared to the small-scale desalination plants in islands and its operational schedule to provide the water to islands group. There were many studies on the cost analysis of the SWRO plants capacity from the small-scale of 200 m^3/day to the large scale of 100,000 m^3/day (Feo-García *et al*. 2016, Guler *et al*. 2015, Hafez and El-Manharawy 2002, Im *et al*. 2020). However, studies with respect to the cost of desalination vessel or small-scale RO plant (< 100 m3/day) are limited.

Therefore, in this study, cost analysis of the small-scale RO system (10-500 m^3/day) and desalination vessel having the RO system was conducted based on the summary of the published data. The operation schedule of the desalination vessel is also suggested based on the candidate islands group in Republic of Korea for future real operation of the desalination vessel.

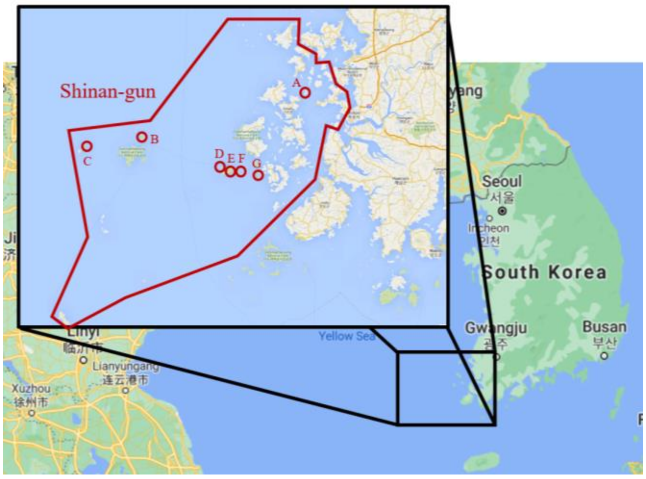


Fig. 1 Target islands in Shinan-gun, Republic of Korea (Edited from google map)

2. Materials and methods

2.1 Target area

The research area was the Shinan-gun (group of islands) which is located at the southwestern part in the Republic of Korea peninsula as shown in Fig. 1. The seven islands ((A) Dangsa-do (island), (B) Damul-do, (C) Hong-do, (D) Ui-do, (E) Seosoui-do, (F) Dongsoui-do, and (G) Sin-do) which had small-scale desalination plant in Shinan-gun, Republic of Korea were selected as the target area for water supply by the desalination vessel. The distance to the next neighboring islands and the desalination capacities on the target islands were presented in the Table 1.

2.2 Desalination plant and vessel

2.2.1 Small-scale desalination plant

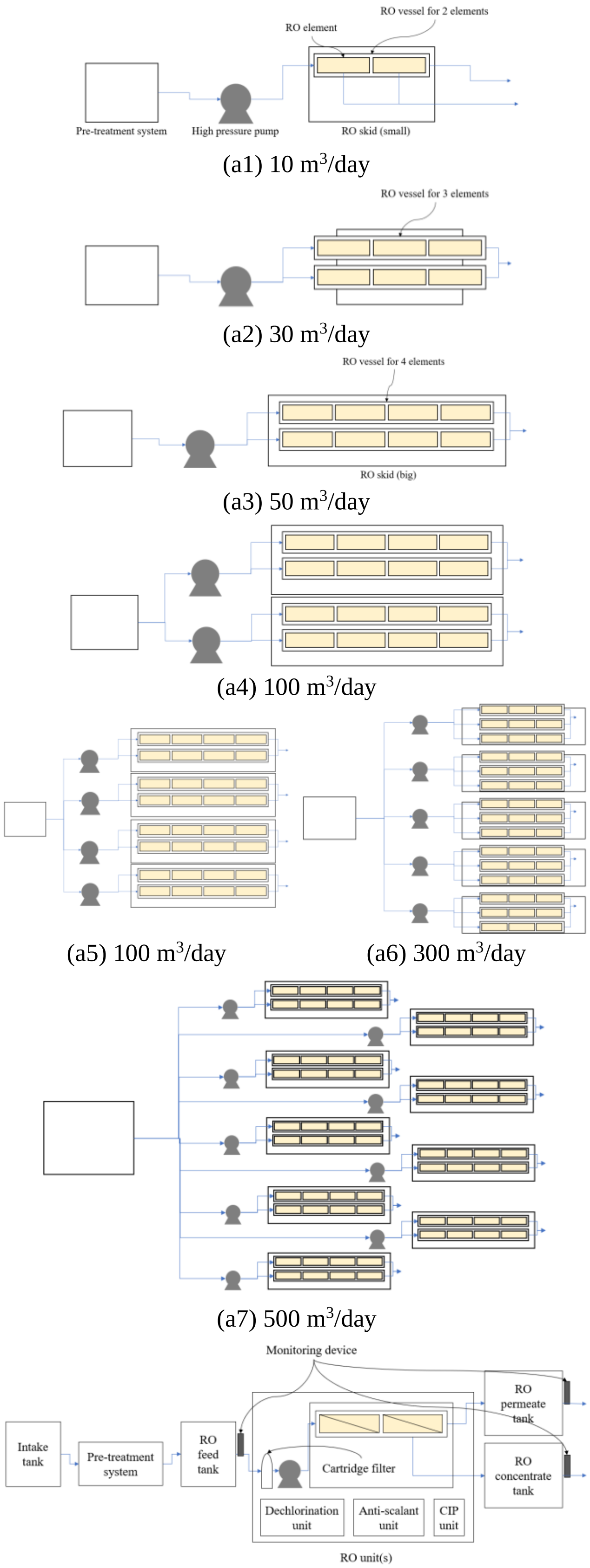
The RO system was designed according to the assumed capacities (10, 30, 50, 100, 200, 300, and 500 m^3/day) and the number of elements, vessels, skids (small or big), and high-pressure pumps as shown in Fig. 2(a). The unit RO element was assumed having the diameter of 4 inches and the length of 40 inches which could produce 7 m^3/day. There are another commercialized RO membranes having the diameter of 8 or 16 inches and the length of 40 inches, however, only one type of RO membrane was used to simplify the calculation of the cost in this paper. The number of the elements for the RO vessel was assumed as 2, 3 or 4 considering commercialized products. Two different sized RO skids (small and big) were assumed to support the RO vessels. The number of high-pressure pumps were selected according to their capacities (67.2 m^3/day per one pump) and the number of the connectable RO elements per one pump (≤ 9). The number of the RO skids were the same as the number of the high-pressure pump in order to assume that the RO skid was operated as one RO unit. Therefore, 1-9 RO units were designed for one RO pilot system according to their capacities.

For each RO unit, it was assumed that a cartridge filter and three chemical units for dechlorination, anti-scalant, and CIP were included (Fig. 2(b)). Each chemical unit has a chemical pump and a chemical tank. The cost of pipes and angles for RO unit was also considered. The three monitoring devices including electronic conductivity meter, pressure gauge, and flow meter were expected to be installed for one RO pilot system to measure the water quality and flow characteristics of the RO feed, RO permeate, and RO concentrate. Four tanks for intake, RO feed, RO permeate, and RO concentrate were designed for one RO pilot system.

Table 1 Capacities of the installed small-scale reverse osmosis (RO) plants in the target islands and the distances among them in Shinan-gun, Republic of Korea

Island	(A) Dangsa	(B) Damul	(C) Hong	(D) Ui	(E) Seosoui	(F) Dongsoui	(G) Sin	(A) Dangsa	Total
Distance (km)	0*	69.1**	22.7	59.5	2.5	1.3	8.5	35.9	199.5
RO capacity (m^3/day)	60	100	50	40	50	15	20	60	335

* Starting point / ** The distance between the island the former island in the Table (i.e., (B) – (A))



(b)

Fig. 2 Schematic diagram of the designed small-scale desalination systems (a: designs of RO systems according to their capacities and b: design of desalination plant)

Table 2 Information of designed and reference vessels

Information	Designed vessel in this study	Reference vessel (Nikolaisen, 2014)
Vessel type	Desalination vessel	Ferry (M/F Tysfjord)
Length (m)	69.3	84.0
Breadth (m)	24	16.8
Draught (m)	4.5	4.5
Tonnage (ton)	3,000 (DWT)	3,695 (Gross tonnage)
Velocity (knots)	10 (max) 5 (transit)	16 (max) 14 (transit)
Engine	800 PS (588 kW) (Main) 480 PS (352 kW) (Generator)	2,650 kW (Main) 253 kW (Generator)
Fuel type	-	Marine gas oil (MGO)
Capital cost ($)	5,000,000 (Expected expenditure in the project fund including development cost)	3,200,000 (26,500,000 NOK)

2.2.2 Desalination vessel

The detailed information of the designed and reference vessels was listed in Table 2. The desalination vessel was designed to have a SWRO system (capacity of 300-350 m^3/day) which can be operated with variations of the capacity. The desalinated water storage in the designed vessel was 660 m^3.

2.3 Cost analysis of the desalination systems

2.3.1 Cost analysis for the small-scale SWRO system

The capital cost was separated into sub-costs such as costs of RO system, pre-treatment, post-treatment, brine disposal, infra-structure, professional and financing, and intake (Hafez and El-Manharawy 2002). The costs of RO system were calculated based on the market price of the RO element, RO vessel, RO skid, high pressure pump, monitoring devices, cartridge filter, chemical units, tanks as listed in Table S1 (Appendix). The cost of the RO system was calculated detailly based on the market cost and price quotation result from engineering company in Republic of Korea. The piping cost (pipes and angles) of the RO cost was estimated from the reference (Hafez and El-Manharawy 2002).

The costs of the other sub-costs were all estimated by the reference from the published papers for cases of Republic of Korea, Egypt, Greece, United Arab Emirates, and Spain (Avlonitis 2002, 2003, Feo-García *et al*. 2016, Hafez and El-Manharawy 2002, Helal *et al*. 2008, Kershman *et al*. 2005, Wittholz *et al*. 2008). The life-span of RO system and the interest rate were assumed as 10 years and 5% to calculate annual depreciation, respectively.

The operation and management (O&M) costs of the small-scale RO system were estimated as the sum of labor, energy, maintenance, chemicals and spares based on the references (Avlonitis 2002, 2003, Feo-García *et al*. 2016, Hafez and El-Manharawy 2002, Helal *et al*. 2008, Kershman *et al*. 2005, Wittholz *et al*. 2008). The minimum and maximum costs were summarized and the energy (electricity) cost was classified as 'on-grid' and 'off-grid' because small-scale RO system could use off-grid electricity supply when it was installed in isolated islands.

The water production cost increases with decreasing RO capacity. Moreover, it was hard to get exact amounts of materials due to variations of configurations in RO systems such as intake, pre-treatment, RO process, and post-treatment. Therefore, the cost analysis data only for small-scale RO systems were used even though the papers were published in 2000s.

In order to compare the cost of the desalination system in the capacity of 300 m^3/day, the cost estimator (available for the capacity > 250 m^3/day) provided by the DesalData (GWI DesalData, 2021) of GWI (Global water intelligence).

2.3.2 Cost analysis of the vessel

The costs of fuel, maintenance, and labor were used to calculate O&M cost of the vessel. The fuel cost by using the marine gas oil (MGO) was estimated based on the equations as following (Nikolaisen 2014)

$$FC_{MGO} = \frac{\sum_{i=1}^{5}(t_i \times P_i \times \dot{m}_i)}{k} \tag{1}$$

where, FC_{MGO} (L/km) is the fuel consumption of MGO, t_i (hr) is the time in phase i, P_i (kW) is the average power in each phase, $\dot{m}_i$ (g/kWh) is the specific fuel consumption in phase i, and k (km) is the yearly amounts of kilometres produced. The detailed information on the t_i, P_i, and $\dot{m}_i$ are listed in Table 3. The density of MGO was assumed as 845 g/L.

$$C_{fi} = k \times FC_{MGO} \times P_{MGO\_i} \tag{2}$$

where, C_{fi} is the fuel cost in year i and P_{MGO_i} is the forecasted price of fuel per unit in year i. In this study, the average P_{MGO_i} for 30 years was calculated by the expected increasing MGO cost with time (Nikolaisen 2014).

The maintenance cost of the reference vessel maintained at 3.72 $/km for the whole period of the operation. For this study vessel, the maintenance cost is assumed to account for 20% of 3.72 $/km because this study vessel is totally new and is designed only for the single purpose, desalination. The annual labor cost of the desalination vessel was assumed as $ 108,000 for 3 staffs according to the average annual wage in the statistical yearbook of oceans & fisheries in Republic of Korea (MOF 2018). The vessel was operated by marine gas oil (MGO) engine at the 10 knots of velocity

Table 3 Central values for fuel consumption from the reference (Nikolaisen 2014)

Phase	Duration, t_i (hr)	Average power, P_i (kW)	Specific fuel consumption, $\dot{m}_i$ (g/kWh)
Acceleration	0.083	95	203
Transit	0.833	1,696	191
Retardation	0.083	954	203
At port	Timetable dependent	500	213
At aux	Continuously	125	218

Table 4 The predicted capital costs of the SWRO plants according to their capacities

Capacity (m^3/day)	10	30	50	100	200	300	500
Cost of RO system ($)	47,050	50,650	54,000	100,800	194,800	246,900	428,800
RO element	1,000	3,000	4,000	8,000	16,000	22,500	36,000
RO vessel	500	1,200	1,400	2,800	5,600	9,000	12,600
RO skid	450	450	900	1,800	3,600	4,500	8,100
High pressure pump	15,000	15,000	15,000	30,000	60,000	75,000	135,000
Monitoring devices	6,800	6,800	6,800	6,800	6,800	6,800	6,800
Cartridge filter	1,600	1,600	1,600	3,200	6,400	8,000	14,400
Chemical units	2,100	2,100	2,100	4,200	8,400	10,500	18,900
Pipes and angles	19,000	19,000	19,000	38,000	76,000	95,000	171,000
Tanks	600	1,500	3,200	6,000	12,000	15,600	26,000
Cost of pre-treatment ($)	5,000	5,000	5,200	10,400	20,800	26,000	46,800
Cost of post-treatment ($)	750	2,250	3,750	7,500	15,000	22,500	37,500
Cost of brine disposal ($)	639	1916	3,194	6,388	12,775	19,163	31,938
Coat of infra structure ($)	5,475	16,425	27,375	54,750	109,500	164,250	273,750
Cost of professional and financing ($)	1,027	3,080	5,133	10,266	20,532	30,798	51,330
Cost of intake ($)	1,300	3,900	6,500	13,000	26,000	39,000	65,000
Total cost ($)	61,241	83,221	105,152	203,104	399,407	548,611	935,118
Total capital cost ($/$m^3$)*	2.73	1.24	0.94	0.91	0.89	0.82	0.83

*Pay back in 10 years, 5% interest

Table 5 The predicted operational and management (O&M) costs of the SWRO plants according to their capacities

Capacity (m^3/day)		10	30	50	100	200	300	500
Labor ($/$m^3$)		-	1.64-1.72	0.99-1.03	0.49-0.52	0.25-0.26	0.16-0.17	0.10
Energy ($/$m^3$)	on grid	-	0.57-1.08					
	off-grid	0.95	0.85-2.14					
Maintenance ($/$m^3$)		4.1	0.017-0.43					
Chemicals ($/$m^3$)		-	0.0069-0.24					
Spares ($/$m^3$)		-	0.03					
Total O&M cost ($/$m^3$)	on grid	-	2.27-3.50	1.61-2.81	1.12-2.30	0.87-2.04	0.79-1.95	0.72-1.88
	off-grid	8 (2008-2009)	2.55-4.56	1.89-3.87	1.40-3.36	1.15-3.10	1.07-3.01	1.00-2.94

Table 6 The predicted total cost of the SWRO plants according to their capacities

Capacity (m^3/day)		10	30	50	100	200	300	500
Total cost ($/$m^3$)	on grid	-	3.51-4.74	2.55-3.75	2.03-3.21	1.76-2.93	1.61-2.77	1.55-2.71
	off-grid	10.73	3.79-5.80	2.83-4.81	2.31-4.27	2.04-3.99	1.89-3.83	1.83-3.77

3. Results and discussion

3.1 Cost of small-scale SWRO system

3.1.1 Capital cost of small-scale SWRO system

The predicted capital costs of the designed SWRO plants according to their capacities (10, 30, 50, 100, 200, 300, and 500 m^3/day) were listed in Table 4. The costs of RO system and infra structure were dominant among the sub-capital costs. The total capital cost ($) increased with increasing capacity while the unit cost per water production ($/$m^3$) decreased. The unit cost per water production ($/$m^3$) was calculated by using the condition of 10 year pay back with 5 % interest.

3.1.2 Operation and management (O&M) costs of small-scale SWRO system

The collected and predicted O & M costs of the designed SWRO plants according to their capacities (10, 30, 50, 100, 200, 300, and 500 m^3/day) were listed in Table 5. The labor cost was dominant among the sub-O&M costs when the capacity was less than 50 m^3/day, however, energy cost was dominant when the capacity was larger than 100 m^3/day. The other costs for maintenance, chemicals, and spares were minor for all the capacities from 30 to 500 m3/day. It was reported that the maintenance cost and spares were extremely high due to intermittent operation of the SWRO systems (10 m^3/day) (Park *et al*. 2011). Therefore, it could be assumed that the maintenance cost and spares could be increased when the SWRO plants having capacities from 30 to 500 m^3/day might be operated intermittently.

3.1.3 Total costs of small-scale SWRO system

The predicted total costs of small-scale SWRO system were summarized in Table 6. The total desalination cost increased exponentially with the decreasing RO capacity.

3.2 Cost of small-scale SWRO system by using the cost estimator

The expected costs from the cost estimator from Desaldata (GWI DesalData, 2021) were listed in Table 7. The total capital cost (0.97-1.01 $/$m^3$) from the cost estimator was relatively higher than that (0.82-0.83 $/$m^3$) from the estimation in this study about 17-23 %. The cost gap could be explained that some of the sub-costs (tanks, intake/disposal, and infra-structure) were neglected due to the RO system will be built on the desalination vessel. The O&M costs for 300 and 500 m^3/day SWRO systems were obtained by using the cost estimator. The estimated O&M cost included labor cost (0.08 $/$m^3$), energy cost (0.35-1.05 $/$m^3$), and overheads (0.05 $/$m^3$) and all the costs were the same according to the RO capacities. The expected total costs were in the range from 1.49 to 2.19 and from 1.45 to 2.15 ($/$m^3$) for 300 and 500 ($m^3$/day), respectively. The expected costs from the cost estimator were similar to the calculated costs from this study.

3.3 Cost of SWRO system integrated vessel

3.3.1 Cost of SWRO system (300 m^3/day) on the desalination vessel

The 300 m^3/day SWRO system was designed to provide water to the inhabitants in the studied area. The cost of the SWRO system integrated on the desalination vessel involves the cost of the vessel based 300 m^3/day SWRO plant and the vessel cost.

The expected capital cost of the SWRO system on the desalination vessel was calculated based on the capital cost of 300 m^3/day system in Table 4. Some of the sub-costs were neglected as followings; The cost of tank for RO permeate in the cost of RO system was neglected due to water storage of RO permeate (660 m^3) in the vessel. The

Table 8 Expected operation and management cost of the reference vessel

	Annual cost ($/year)	Cost per unit water production ($/m^3/day)
Fuel	378,864 (316,503-447,133)	3.25 (2.89-4.01)
Maintenance	54,172	0.50
Labor	108,000	0.99

Table 9 Expected total desalination cost of 300 m^3/day SWRO plant on the reference vessel (vessel transit speed: 10 knots)

Types of cost		Cost ($/m^3)
SWRO O&M cost	Energy (off-grid)	0.85-2.14
	Maintenance, chemicals, and spares	0.05-0.70
SWRO Capital cost		0.48
Vessel O&M cost	Fuel	2.89-4.08
	Maintenance	0.50
	Labor	0.99
Vessel capital cost		1.30-1.52
Total desalination cost		7.06-10.41

cost of tank for RO concentrate and cost of brine disposal was neglected because direct discharge of the concentrate into ocean was assumed. The cost of infra-structure was neglected that no civil work was required on the desalination vessel. And cost of intake was also neglected because open intake system was expected to be installed. Therefore, the capital cost of SWRO system on the desalination vessel was expected as 320,198 $ which is the same as 0.48 $/m^3 (pay back in 10 years, 5% interest).

The expected O&M cost of the SWRO system on the desalination vessel was calculated based on the operation cost of 300 m^3/day system in Table 5. Among the sub costs in the O&M cost, labor cost was neglected that the RO system will be operated unmanned and the crew of the desalination vessel could support the RO operation. And off-grid energy cost was selected for O&M cost calculation because the electrical energy on the desalination vessel was planned to be produced by the diesel engine mainly.

However, some of the energy cost could be saved because the desalination vessel will have the PV panels for solar energy collection. In this study, the additional energy saving by the planned PV panels were not included.

3.3.1 Cost of the reference vessel according to the its operation schedule

The expected O&M costs of the reference vessel was presented in the Table 8. Based on the fuel cost from the reference vessel according to the its operation schedule (Nikolaisen 2014), it costs 11.75 $/km with the MGO engine at the 11.6 knots. The maximum speed of the desalination vessel in this study was 10 knots. So that the fuel consumption is saved about 26% according to the report of Stopford (2009). Furthermore, the fuel cost could be cut down of 50% if tax exemption was available due to the Korean policy for the activities in agriculture and fishery fields. The total distance to travel the target seven islands in Shinan-gun, Republic of Korea in this study was around 199.5 km as shown in Table 1. So that the vessel was estimated to travel 74,825 km/year. Consequently, the total cost for fuel use of the reference vessel was about averagely 378,864 $/year (3.25 $/m^3/day).

3.3.3 Expected total cost of desalination plant on the reference vessel

In order to check the economic feasibility of the desalination vessel, the expected total cost (7.06-10.41 $) of desalination for the reference vessel was summarized in Table 9. The vessel O&M cost was dominant (53.5-62%) among the sub-costs. And it was shown that the SWRO O&M cost (12.7-27.3%) could increase total cost secondly. In O&M cost, energy costs were the major costs. Moreover, the capital cost of the desalination vessel is expected as 1.30-1.52 $/m^3 if the desalination vessel continuously produces 300-350 m^3/day for 30 years when the capital cost of the desalination vessel (5 million $) was paid to the manufacturer at the produced year of the vessel. When it is considered that the average cost of the small-scale desalination plant in Republic of Korea is about 8 $ (KRILA 2015), the desalination vessel could be economical in Shinan-gun area, Republic of Korea. And the major contributor for the cost determination could be the cost of the oil for energy generation and vessel transit.

3.4 Cost analysis considering routes for the vessel

The detailed vessel schedule for the water distribution was suggested as Table 10 considering the desalination capacity (300-350 m^3/day), permeate storage (660 m^3), vessel speed (5 knots), distances between the islands (totally 199.5 km), required times (approaching or leaving and water distribution) additionally to the transit, and proper working hours for the staffs (averagely 8 hrs per day).

A journey of the vessel through the seven islands ((A) Dangsa-do (islands) (B) Damul-do, (C) Hong-do, (D) Ui-do, (E) Seosoui-do, (F) Dongsoui-do, (G) Sin-do) starts from (A) Dangsa-do because Dangsa-do, which is the closest to the Korean peninsula among the other islands, is proper place to avoid bad weather conditions such as typhoon or to fix the vessel for the emergency. The docking time was assumed at 0.5 hr for each arriving and leaving time of the vessel. Time for transport the water to each island varied according to the water demand. Totally, 26.72 hr per three days is required for a vessel moving and provide water to the seven islands. To consider the working hours (8 hr per day) for the staffs, the vessel was expected to move from (A) to (B) islands in a day (8.71 hr) and to provide the water of 300 m^3 for (B) islands at the first day. At the second day, the vessel was expected to move from (B) to (D) islands (10.33 hr) providing 270 m^3 of desalinated water to the (C) and (D) islands. As the third day, the vessel was expected to move from (E) to (A) islands (7.69 hr) providing 435 m^3 of produced water to (F), (G) and (A) islands. In order to meet high water demand

Table 10 Suggested operation schedule of the designed vessel (speed: 5 knots)

Target area	Dangsa (A)	Damul (B)	Hong (C)	Ui (D)	Seosoui (E)	Dongsoui (F)	Sin (G)	Dangsa (A)	Total
Water demand (m^3/day)	-	300	150	120	150	45	60	180	1,005
Distance (km)	0	69.1	22.7	59.5	2.5	1.3	8.5	35.9	199.5
Total required time (hr)	0.25	8.46	3.21	7.12	1.02	0.72	1.52	4.43	26.72
Transit time (hr)	0	7.43	2.45	6.43	0.27	0.14	0.92	3.88	21.54
Approaching or leaving time (hr)	0.25	0.5	0.5	0.5	0.5	0.5	0.5	0.25	3.5
Time for water supply (hr)	0	0.50	0.26	0.20	0.26	0.08	0.11	0.30	1.68

Table 11 Expected total desalination cost of 300 m^3/day SWRO plant on the designed vessel operating with the suggested schedule (vessel transit speed: 5 knots)

Types of cost		Cost ($/$m^3$)
SWRO O&M cost	Energy (off-grid)	0.85-2.14
	Maintenance, chemicals, and spares	0.05-0.70
SWRO Capital cost		0.48
Vessel O&M cost	Fuel	2.45-3.46
	Maintenance	0.50
	Labor	1.17
Vessel capital cost		1.30-1.52
Total desalination cost		6.80-9.97

(435 m^3) in the third day according to the operation schedule, the amounts of surplus water for the first (upto 50 m^3) and second (upto 80 m^3) days was stored in the tanks in the desalination vessel.

The time for each phase in Table 3 was used to calculate the fuel consumption of MGO by using the equation (1). The transit time (21.54 hr (2,621 hr/year) in Table 7 was directly used for transit. The approaching and leaving time (3.5 hr (30 min per each island, 426 hr/year)) were distributed to the times for acceleration (5 min per each island, 106.5 hr/year)), at port (20 min per each island, 213 hr/year)), and retardation (5 min per each island, 106.5 hr/year)). The time for water supply (1.68 hr (204.4 hr/year)) was also used.

The calculated fuel consumption of designed vessel with the suggested schedule was 14.9 L/km (fuel efficiency: 0.067 km/L) when the total travel per year was 72,817.5 (km/year). The fuel efficiencies of the ferries for averagely 149-3,400 passengers in the reference (Cottrell 2011) were in the range from 0.02 to 0.20 km/L, which is similar to the fuel efficiencies of the designed vessel operating with suggested schedule.

The total cost of the designed vessel operating with suggested schedule was summarized in Table 11. The labor cost increased for additional 1 hr working hour with 50% increased payment.

The total cost of the designed vessel operating with suggested schedule was lower than that of the reference vessel. In this study, the fuel efficiency was calculated by using the required fuel and required travel distance. The actual fuel efficiency should be proven later when the desalination vessel is actually built. The total expected cost of the desalination vessel operating with the suggested schedule was 6.80-9.97 $/$m^3$, therefore, the desalination cost by the desalination vessel could be lower than the desalination cost for the islands area in Republic of Korea (8 $) according to the fuel cost.

It is worth to mention that desalination vessel cost is affected by the operation schedule. When the desalination vessel has enough water storage for desalinated water, the produced water cost of the desalination vessel become cheaper with the infrequent visits to the target islands. Also, infrequent visit allows low transit speed of the desalination vessel which could reduce the fuel consumption.

4. Conclusions

In order to solve the water scarcity issues in the coastal and islands areas in Republic of Korea, the desalination vessel having SWRO system was suggested as the option for water supply. The economical feasibility was studied by using the cost analysis tools for small-scale desalination system and desalination vessel. It was shown that the designed desalination vessel could be feasible in Shinan-gum, Republic of Korea according to the costs of the fuel for electricity and transit of the vessel and the operation schedule for target islands group. The actual feasibility could be proven when the designed desalination vessel starts to operate in the near future.

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Appendix

Table S1 Collected capital costs of the SWRO system

Name of the component	Spec.	Unit price ($)	No. of required component or equation for cost according to the desalination capacities (m^3/day)							Price source
			10	30	50	100	200	300	500	
RO element	SWRO 4 (inch) × 40 (inch), water production: 7 m^3/day/element	500	2	6	8	16	32	45	72	Dow, USA
RO vessel for 2 elements	1,000 Psi vessel	500	1	0	0	0	0	0	0	Pentair Codeline, USA
RO vessel for 3 elements	1,000 Psi vessel	600	0	2	0	0	0	15	0	
RO vessel for 4 elements	1,000 Psi vessel	700	0	0	2	4	8	0	18	
RO skid (small)	SUS316L	450	1	1	0	0	0	0	0	Quotation from domestic company, Korea
RO skid (big)	SUS316L	900	0	0	1	2	4	5	9	
High pressure pump	Flow rate: 5.6 m^3/hr	15,000	1	1	1	2	4	5	9	Grundfos, Denmark
Monitoring devices - electrical conductivity meter	Seawater	1,300	3	3	3	3	3	3	3	Horiba, Japan
Monitoring devices - pressure gauge	Seawater	700	2	2	2	2	2	2	2	Newark Electronics, USA
Monitoring devices - flowmeter	Seawater	500	3	3	3	3	3	3	3	Flowtech, India
Cartridge filter	Flow rate: 8 m^3/hr	1,600	1	1	1	2	4	5	9	Quotation from domestic company, Korea
Chemical units - chemical pump	Chemical	600	3	3	3	6	12	15	27	Marco, USA
Chemical units - chemical tank	Chemical	100	3	3	3	6	12	15	27	Enduramaxx, UK
Tank	1 m^3	150	2	0	0	0	0	0	0	Dezhou Huili Environmental Tech., China
	2 m^3	150	2	2	0	0	0	0	0	Hengshui Jinghua Trading Company, China
	5 m^3	600	0	2	2	0	0	0	0	Hebei Dongding Chemical Trade Company, China
	10 m^3	1,000	0	0	2	2	0	0	0	Qingdao Dejun Environment Tech., China
	20 m^3	2,000	0	0	0	2	2	0	0	
	30 m^3	3,000	0	0	0	0	0	2	0	
	40 m^3	4,000	0	0	0	0	2	0	0	
	50 m^3	5,000	0	0	0	0	0	0	2	
	60 m^3	4,800	0	0	0	0	0	2	0	
	100 m^3	8,000	0	0	0	0	0	0	2	
Pipes and angles	SUS316L	19,000	1	1	1	2	4	5	9	Quotation from domestic company, Korea
Pre-treatment - media filtration	10-30 m^3/day	5,000	1	1	0	0	0	0	0	
Pre-treatment - media filtration	50 m^3/day	5,200	0	0	1	2	4	5	9	
Post - treatment	Cost ($) = 75 ($/m^3/day) × desalination capacity (m^3/day)									Birnhack *et al*. 2011
Brine disposal	Cost ($) = 0.175 ($/m^3) × produced brine (desalination capacity (m^3/day) × 365 (day))									Panagopoulos *et al*. 2019
Infra - structure	Cost ($) = 1.55 ($/m^3/day) × desalination capacity (m^3/day)									Hafez and El-Manharawy, 2002
Professional and financing	Cost ($) = 0.28 ($/m^3/day) × desalination capacity (m^3/day)									Hafez and El-Manharawy, 2002
Intake	Cost ($) = 130 ($/m^3/day) × desalination capacity (m^3/day)									WRA, 2012