Modeling of environmental aspects related to reverse osmosis desalination supply chain

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Iran is in the state of water stress and dehydration which per year. With any of the internationally accepted indices, per capita renewable water is less than 1700 cubic meters are estimated to be 110 to 130 billion cubic meters per year. “30%” is groundwater (1). Iran’s renewable water resources than 68% is locked up in polar ice and glaciers, and the rest total water, while freshwater is only 2.5%, of the total, more

Introduction

Although water accounts for about 71 % of the earth surface, freshwater scarcity is one of the most important worldwide issues. Oceans and seas contain about 97.5% of total water, while freshwater is only 2.5%, of the total, more than 68% is locked up in polar ice and glaciers, and the rest “30%” is groundwater (1). Iran's renewable water resources are estimated to be 110 to 130 billion cubic meters per year. With a population of more than 80 million, the country's per capita renewable water is less than 1700 cubic meters per year. With any of the internationally accepted indices, Iran is in the state of water stress and dehydration which necessitates the use of desalination.

The worldwide capacity for desalination projects increased dramatically from 326 cubic meters per day in 1945 to more than 95.6 million cubic meters per day in 2016 (2). Among the existing desalination technologies, reverse osmosis membrane technology accounts for 66% of the capacity utilized, followed by multi-stage flash and multi-effect distillation with 20% and 7% of the capacity utilized, respectively (3). Seawater accounts for 58% of the world's desalination water feed (4). Environmental impacts of seawater reverse osmosis (SWRO) desalination can be broadly classified into three categories, including energy consumption which releases carbon dioxide (CO₂) into the atmosphere, intake and...
brine discharge (5,6). Desalination effluent results in known environmental effects on seagrass habitats and phytoplankton, invertebrates and fish communities in areas surrounding effluent discharge (7,8). Overall, enclosed and shallow sites with abundant marine organisms are more sensitive to effluent discharge than the offshore sites capable of diluting and dispersing plant rejected water (2,9).

The previous studies have shown the variable effects of desalination plants on the salinity of the received water. Based on the studies, the effects of saline effluent discharge can be observed for tens or hundreds of meters (10,11), or in extreme cases, several kilometers from the effluent discharge site (12). Few studies on the environmental issues of intake and brine discharge of SWRO, have shown that proper design of SWRO based on the environmental impact analysis, can minimize the environmental impacts and the costs of environmental protection for desalination plants were analyzed (5,13-16).

Most of the above-mentioned models focused on optimizing the economic dimension of water supply systems and often overlook the details of the environmental aspects. This research expanded the economic model presented by Al-Nory et al (17) regarding the water supply chain of the desalination plant by emphasizing environmental details. Environmental details include modeling the reduction of salinity and chemical components of the rejected brine water (RBW) from plants by diluting the effluent before being entered the sea according to a standard that permits discharge into the receiving water. Note that, CO\textsubscript{2} emissions have also been modeled as an environmental impact. Desalination supply chain activities include obtaining feed water and chemicals needed for the desalination processes, desalination process systems, water storage and distribution of freshwater to end-users (18). The importance of examining the economic and environmental impacts of water purification using desalination technology and the provision of desalinated water allows decision-makers to examine the system as a whole (19). For instance, any delay in the distribution of water from storage tanks to consumers could disrupt the desalination process and affect the overall performance of the desalination water supply chain. In this study, due to the importance of environmental issues in terms of produced water costs and environmental protection aspects, this subject is evaluated and modeled in Hormozgan province as the center of the desalination of Iran.

Materials and Methods
This analytical research is conducted in 5 cities of Bandar Abbas, Qeshm, Hormoz, Sirik, and Abu Musa in Hormozgan province (Figure 1) for 18 months from February 2018 to September 2019. In addition, the operational and environmental data of desalination plants for a period of past 20 years were obtained from the Hormozgan Water and Wastewater Company; then entered in the model and analyzed. The study plan was classified into eight phases encompassing: 1) Defining research problem, 2) Data collection, 3) Preliminary data analysis and decision criteria, 4) Mathematical modeling, (5) Model validation, 6) Information preparation, 7) analysis and 8) Discussion, Conclusions and suggestions. In the present study, the typical SWRO plants are studied. The main parts of typical SWRO plants are included in the Intake section, pretreatment (generally coagulation and granular filter), high-pressure pumps and membrane modules. After that, a post-treatment unit is located to add some minerals to the RO water product (Figure 2). Modeling fundamental data include the rate of raw water intake, water production, and brine water flow rate, type of discharge into receiving waters, and investment cost and operating costs such as the consumed power used chemicals, manpower, and the other economic and environmental aspects.

To evaluate the CO\textsubscript{2} production, since the power generation model in Iran is almost similar to the water production by desalination, the mathematical model of electricity production in Iran is used to estimate the amount of CO\textsubscript{2} emitted from desalination plants(20,21) Since the power generation model in Iran is almost similar to the Portuguese power generation model collected from the literature (21), this model was used to estimate the amount of greenhouse gas CO\textsubscript{2} required by the mathematical model.

Model parameters
In this analysis, a mathematical model is employed which its parameters are shown in Table 1. Note that the model is based on AL-Nory et al (17) and Balfaqih et al (1).

Decision variables
Decision variables for the production and investment in desalination plants and transmission lines presented in Table 2. The total cost of water (TWC) is often cited in the literature of the desalination industry as a common comparison between projects. Table 3 shows comparative evaluation of the total cost of the objective functions and their components per cubic meter of freshwater.
Target function optimization

The objective function specified in Eq (1), minimizes the total investment cost and supply chain operation of both the plant and the transmission line. Furthermore, it minimizes environmental impacts.

\[
mintC = \sum_{l \in N^s} c_l^T + \sum_{l \in T} c_l^e e_l + \sum_{l \in E} c_l^N
\]

Model limitations

The model has a few limitations. Equation (2) represents the net present value (NPV) of the total investment cost (CAPEX) of the plant at the location \( l \).

\[
v_f = \sum_{t \in T} cp_{lt} y_{lt} \quad \forall \ l \in N_s
\]

Equation (3) represents the NPV of the operation cost at the location \( l \) in the time of \( h \).

\[
v_{lh}^o = \sum_{t \in T} aopx_{lt} (1 + int)^h \quad \forall \ l \in N_s, h \in H
\]

### Table 1. Mathematical model parameters used in the study

| Parameter | Definition |
|-----------|------------|
| Inf | Inflation rate |
| Int | Interest rate |
| \( cp_{lt} \) | Estimation of investment cost for factory \((t)\) at location \((l)\) at time \((0)\) |
| \( v_{lh}^o \) | Net present value (NPV) of the total operating costs (OPEX) of the factory \((t)\) at the location \((l)\) in time horizon \((h)\) |
| \( aopx_{lt} \) | Estimation of annual operating costs of plant \((t)\) at location \((l)\) |
| \( v_f^l \) | Estimation of the first-year operating costs for each cubic meter of a desalination plant at the location \((l)\) |
| \( v_f^r \) | The value of the plant’s rotation at the location \((l)\) at the end of the planning period |
| \( cp_{lt}^a \) | Estimated the total investment costs per year for each transmission line \((l)\) |
| \( W_{lh}^o \) | NPV total operating costs in the year of zero (OPEX) in Network time of \((h)\) |
| \( aopx_{lt}^a \) | Annual operating cost estimates (OPEX) at transmission line \((l)\) |
| \( opx_{lt}^a \) | Estimation of the first-year operating costs per cubic meter of water at transmission line \((l)\) |
| \( cap_{lt}^a \) | Desalination plant design capacity \((m^3/d)\) \( t \in T \) |
| \( cap_{lt}^w \) | Transmission line capacity \((m^3/d)\) \( t \in E \) |
| \( E_{lh}^o \) | Plant Outlet Pipe Set \( l \in N^s \) |
| \( E_{lh}^o \) | The sum of input influents to the aggregator in place \( l \in N^s \) |
| \( E_{lh}^o \) | The output stream of the collector at the location \( l \in N^s \) |
| \( d_{lh} \) | Demand in place \( l \in N^s \) at the time of \((h)\) |
| \( c_{lh} \) | Plant capacity \( t \in T \), at the location \( l \in N^s \) at the time of \( h \in H \) |
| \( u_{lh}^{co2} \) | \( CO_2 \) emissions produced by the plant \((t)\) at the location \((l)\) for one cubic meter of water \((Kg \ CO_2/m^3)\) |
| \( Er_{lt} \) | Power required by the plant \((t)\) in \((kwh/m^3)\) |
| \( Ef \) | \( CO_2 \) emission factor \((CO_2 \ kg-e/kwh)\) |
| \( opx_{lt}^{co2} \) | \( CO_2 \) cost \( (\$/kg \ CO_2)\) |
| \( Pc \) | The \( v_f^l \) coefficient as the percentage of the total investment cost for the effluent dilution cost |
| \( Po \) | The \( v_f^r \) coefficient as the percentage of the total investment cost for the effluent dilution cost |
Equation (4) represents the NPV of the residual value of the plant at the location (l) at the end of the design period.

\[ v_f^l = \sum_{t=1}^{T_f} \frac{ndp_{it} \ast (1 + int)^{H_{it}+2} \ast y_{it}}{(1 + int)^{H_{it}+2}} \quad \forall \ l \in N_s \]  

Equation (5) represents the NPV of the total cost of the plant at the location (l).

\[ c_f^l = v_f^l + \sum_{h \in H} w_{th}^N - v_f^l \quad \forall \ l \in N_s \]  

Equation (6) represents the NPV of the total investment cost (CAPEX) of the transmission line at the location (l).

\[ w_{th} = \frac{opx_{th}^N \ast (1 + int)^h \ast z_{ih}}{(1 + int)^h} \quad \forall \ i \in E \]  

Equation (7) represents the NPV of the total operational costs (OPEX) for the transmission line at time (h).

\[ c_{th}^N = w_{th}^N + \sum_{h \in H} w_{th}^p \quad \forall \ i \in E \]  

The binary variable is the establishment or non-establishment of the plant as Eq (9). Moreover, the binary variable is the establishment or non-establishment of the transmission line as Eq (10).

\[ Y_i = 0 \text{ or } 1 \quad (9) \]
\[ Y_i = 0 \text{ or } 1 \quad (10) \]

Equation (11) shows the water produced rate by the plant (t) at the location (l) in the time horizon (h) limited by the plant capacity at the location (l) with the \( c_{th}^N \) capacity coefficient.

\[ x_{ith} \leq cap_i^N \ast y_{it} \quad \forall \ l \in N_s, t \in T_l, h \in H \]  

Equation (12) denotes the amount of freshwater that responds to the locations water demand at location (l) in the time period (h), which is equal to or greater than the demand.

\[ \sum_{i \in E} z_{ih} \geq d_{ih} \quad \forall \ i \in N_s, h \in H \]  

Equation (13) shows the amount of fresh water entered into and out of the aggregator; input amount is equal to the output.

\[ \sum_{i \in E_{in}} z_{ih} = \sum_{i \in E_{out}} z_{ih} \quad \forall \ l \in N_s, h \in H \]  

The total amount of water produced by the desalination plant (t) at the location (l) enters the transmission line according to Eq (14).

\[ \sum_{t \in T_l} x_{ith} = \sum_{i \in E} z_{ih} \quad \forall \ l \in N_s, h \in H \]  

The flow rate of water at the transmission line (i) at the time (h) is limited to the capacity of the transmission line (i) and is as Eq (15).

\[ z_{ih} \leq cap_i^N \quad \forall \ i \in E, h \in H \]  

The CO\(_2\) emission value of the desalination does not exceed the emission limit for CO\(_2\) emissions and is as Eq (16).

\[ u \leq u_{max} \]  

The total amount of CO\(_2\) emissions at the location (l) is as Eq (17).
The CO₂ emissions produced by the plant (t) at the location (l) for one cubic meter of water is as Eq (18).

\[ u_{lt}^{CO_2} = \sum_{t \in T} x_{lt} \times u_{lt}^{CO_2} \quad \forall \ t \in N^t \]  

(17)

The opx CO₂ is the cost of CO₂ in $/kg CO₂. The NPV is the cost of diluting the brine discharge to reduce the salinity and effluent chemicals is as Eq (20).

\[ opx_{lt}^{CO_2} = \sum_{h \in H} u_{lt}^{CO_2} \times apxCO_2 \times (1 + inf)^h \times (1 + int)^h \]  

(19)

The opx CO₂ is the cost of CO₂ in $/kg CO₂. The NPV is the cost of diluting the brine discharge to reduce the salinity and effluent chemicals is as Eq (20).

\[ c_t^{redTDS&chem} = pc \times v_t^e + po \times \sum_{h \in H} v_{lh} \]  

(20)

The NPV is the total cost of reducing the environmental impacts of the desalination plant which is expressed in Eq (21).

\[ c_t^{envT} = opx_{lt}^{CO_2} + c_t^{redTDS&chem} \]  

(21)

The cost of operating one cubic meter of water at the opxₙ plant is presented in Eq (22).

\[ opx_{lt} = \frac{aopx_{lt}^e}{cap_{lt}^e \times c_{fth} \times 365} \]  

(22)

Remark that the capacity of the capₙ, plant is expressed as m³/d. The coefficient capacity of capₙ is considered for the plant of t∈T, at the location of l∈Nₕ at time h∈H. The estimation of the opxₙ operating costs per cubic meter of water in the transmission line l is as Eq (23).

\[ opx_{lh} = \frac{aopx_{lt}^N}{cap_{lt}^N \times 365} \]  

(23)

Remark that the capacity of the transmission line capₙ is expressed as m³/d. The total cost of the water supply chain (TWC) for comparing the objective functions and its components per cubic meter of freshwater is as follows. To make the target functions understandable and comparable, it is expressed in terms of TWC, the total cost per cubic meter of freshwater (US$/m³).

**TWC₁ plant.** Total Investment, operation and environmental costs (Salinity Reduction + CO₂) as US$/m³ of freshwater as Eq (24).

\[ TWC_1 = \frac{\sum_{l \in L} c_t^{T} + c_t^{envT}}{\sum_{h \in H} x_{lh}} \]  

(24)

**TWC₂ plant.** Total Investment, operating and environmental costs (for the salinity reduction) without CO₂ control cost as US$/m³ of freshwater as Eq (25).

\[ TWC_2 = \frac{\sum_{l \in L} c_t^{T} + c_t^{redTDS&chem}}{\sum_{h \in H} x_{lh}} \]  

(25)

**TWC₃ plant.** Total investment and operating, without environmental costs as US$/m³ of fresh water is as Eq (26).

\[ TWC_3 = \frac{\sum_{l \in L} c_t^{T}}{\sum_{h \in H} x_{lh}} \]  

(26)

**TWC for transmission line.** Total investment and operating costs as US$/m³ of fresh water is as Eq (27).

\[ TWC_4 = \frac{\sum_{l \in L} c_t^{N}}{\sum_{h \in H} x_{lh}} \]  

(27)

**TWC₅ for plant plus transmission line.** Total investment, operating and environmental costs (salinity+ CO₂) in US$/m³ per cubic meter of freshwater as Eq (28).

\[ TWC_5 = \frac{\min TC}{\sum_{h \in H} x_{lh}} \]  

(28)

**TWC₆ for plant plus transmission line.** Total investment, operating and environmental costs (salinity reduction) without CO₂ control in US$/m³ per cubic meter of freshwater is as Eq (29).

\[ TWC_6 = \frac{\sum_{l \in L} c_t^{T} + c_t^{redTDS&chem} + \sum_{l \in L} c_t^{N}}{\sum_{h \in H} x_{lh}} \]  

(29)

**TWC₇ for plant plus transmission line.** Total investment and operating without environmental costs in US$/m³ of freshwater is as Eq (30).

\[ TWC_7 = \frac{\sum_{l \in L} c_t^{T} + \sum_{l \in L} c_t^{N}}{\sum_{h \in H} x_{lh}} \]  

(30)

**TWC₈ environmental.** The cost of (CO₂ + salinity reduction) in US$/m³ of fresh water is as Eq (31).

\[ TWC_8 = \frac{\sum_{l \in L} c_t^{envT}}{\sum_{h \in H} x_{lh}} \]  

(31)

**TWC₉ environmental.** The cost (CO₂) in US$/m³ of fresh water is as Eq (32).

\[ TWC_9 = \frac{\sum_{l \in L} opx_{lt}^{CO_2}}{\sum_{h \in H} x_{lh}} \]  

(32)
Table 3. Mathematical model inputs; Interest rate of 18%, Inflation rate of 20% and time period of 20 year; (Ef= 0.77(CO₂ kg-e/kWh), cf₂=0.9, Er₄=4 kWh/m³, opx CO₂= 0.023 US$/ kg CO₂, Po= 0.15, Pm=0.07)

| Input parameter | Unit | Hormoz | Sirik | Qeshm | Bandar Abbas | Abu Musa |
|-----------------|------|--------|-------|-------|--------------|---------|
| Desalination    |      |        |       |       |              |         |
| cap₃             | M³/d | 1750   | 3750  | 6000  | 100000       | 2500    |
| cpx₃             | US$  | 2 300 000 | 4 500 000 | 6 600 000 | 8 000 000 | 30 000 |
| aopx₃            | US$/m³ | 160 000 | 340 000 | 550 000 | 7 300 000 | 230 000 |
| Transport line   |      |        |       |       |              |         |
| capₜ              | M³/d | 1750   | 3750  | 6000  | 100 000      | 2500 |
| cpxₜ             | US$  | 1 000 000 | 870 000 | 2 120 000 | 22 000 000 | 1 400 000 |
| aopxₜ            | US$/m³ | 55 000  | 43 000  | 60 000  | 50 000      | 50 000 |
| Demand            | dₜ   | M³/d   |       |       |              |         |
|                  |      | 1500   | 3300  | 5300  | 89 000       | 2100 |

Table 4. Model output decision variables

| Decision Variables | Unit | Hormoz | Sirik | Qeshm | Bandar Abbas | Abu Musa |
|--------------------|------|--------|-------|-------|--------------|---------|
| xₙₐ               | M³/d | 1500   | 3300  | 5300  | 89 000       | 2100 |
| yₙ              | no   |        | 1     | 1     | 1            | 1       |
| zₙₜ             | M³/d | 1500   | 3300  | 5300  | 89 000       | 2100 |
| vₜ              | US$  | 194 915.2 | 381 359.32 | 559 320.34 | 67 966 10.17 | 25 432 78.88 |
| cₜ              | US$/m³ | 54 215 56.78 | 114 613 38.19 | 18 113 863.08 | 23 648 977.18 | 74 688 777.62 |
| wₜ              | US$  | 847 457.63 | 737 288.14 | 17 966 10.17 | 18 644 067.8 | 11 864 406.8 |
| cₜ              | US$/m³ | 20 247 22.98 | 16 822 39.8 | 3 120 141.83 | 2 975 673.28 | 2 235 277.09 |
| uₜ              | Kg   | 1 686 300.00 | 3 709 860.00 | 5 958 260.00 | 1 000 583 80.00 | 2 308 820.00 |
| opxCO₂          | US$/m³ | 9 685 47.98 | 2 130 805.56 | 3 422 202.87 | 5 746 178.29 | 15 359 967.18 |
| cₜredTDS&chem | US$/m³ | 5 58 744.03 | 11 53 166.96 | 1 78 261.10 | 2 27 885 47.36 | 7 56 006.29 |
| cₜredCO₂ | US$/m³ | 15 27 292.02 | 3 28 397 2.52 | 5 20 841.98 | 8 025 572.65 | 2 11 257.34 |

Discussion

The cost of “environmental target” is investigated in two parts including environmental impacts of CO₂ emissions and environmental effects of saline effluent disposal. For desalination supply chain in Bandar Abbas, Total TWC 5, TWC 3, plant, TWC 4, transmission line TWC 9 CO₂. TWC 10 Wastewater dilution are 0.5334, 0.3640, 0.0458, 0.0885 and 0.0351 US$/m³ respectively, presented in Figure 4.

Environmental costs of CO₂ emissions control

Increased use of fossil fuels for desalination can increase air pollution caused by CO₂ emissions and cause damage to public health and the environment. For energy consumption of 4 kW/m³, the portion of environmental costs related to CO₂ emissions is computed by about 16.59% which equals to 0.0885 US$/m³ (Table 5). As shown in Table 6, the Bandar Abbas desalination plant with a nominal and actual capacity of 100,000 and 89,000 m³/d respectively, annually produces 10,000,800 kg CO₂, assuming 4 kW of energy consumption per a cubic meter fresh water production. Reducing energy consumption leads to a reduction in the amount of CO₂. With more efficient utilization and energy recovery, energy can
be reduced to some extent to descent CO$_2$ emissions. However, the main solution is to use renewable energy instead of fossil fuels.

**Dilution costs to reduce environmental impacts**

The desalination plants use significant amounts of chemicals for the pre-treatment of saline and freshwater (25). Excessive salinity of effluent and discharge of large quantities of chemicals into coastal waters results in ecological imbalance and have major effects on receiving waters. To address environmental concerns related to effluent discharge into seawater, the concentration of chemicals and salts in the effluent should be reduced. The target function of “reducing environmental effects due to the effluent salinity” is transformed into a cost function. According to the Table 6 for dilution of different ratios of total dissolved solids (TDS) effluent to TDS receiving water, the percentages of the total cost of wastewater investment and total operating cost are estimated and entered into the model, the results of which are shown in Table 6. As shown in this table, the environmental goals are against environmental costs; hence, by higher costs, it can...
meet better environmental quality related to desalination. More accurate cost estimates should be spent on a specific project and its local data. The cost of “wastewater management” is of great interest as the cost of wastewater disposal increases with the production of freshwater. The dilution cost (TWC 10) for the TDS of effluent to receiving water ratio is the US $ 0.0351/m$^3$. The decision-maker can attract the attention of the environmental organization according to the cost and reduce the environmental impacts. In case the ratio of TDS effluent to TDS intake water is considered to be in the standard range of 1:1, the share of dilution costs will be 7.89%, according to Figure 5.

To dilute the RBW in seawater, diffuser equipment is required, and to achieve a water flow rate of 5 to 8 meters per second, energy should be consumed. Depending on the site-specific conditions, discharge costs to the seafloor for dilution at sea are significant, typically accounting for 10 to 30 % of the total investment costs of the desalination plants (26). Previously many researches focused on supply chain management coordination and optimization challenges in different industries and circumstances (27-30). Even some scholars considered environmental and social issues in their studies (31-33).

**Conclusion**
This study aimed to model optimization of strategic environmental management decisions in the operation of reverse osmosis desalination; emphasizing the costs required for environmental protection during the production of freshwater using reverse osmosis technology. Due to the relatively high costs of controlling environmental pollutants, unfortunately, many of these desalination plants remain neglected. The desalination plants of Abu Musa, Bandar Abbas, Qeshm, Sirik, and Hormoz with water production flow rate of 2100, 89 000, 5300, 3300 and 1500 can generate 2360.82, 100 053.80, 5958.260, 3709.86 and 1686.30 tons of CO$_2$ emissions per year respectively.

This environmental cost model can still be applied if we have access to in-sea effluent dilution technology. This type of wastewater dilution proposed in this study is such that wastewater is diluted before entering the seawater, only consuming higher energy than other methods and does not require sophisticated technology. Therefore, for Iran and the Middle East, where energy is cheaper than in other parts of the world, it can be used to reduce the environmental impact of wastewater. According to the obtained results it requires 1.35, 57.47, 3.42, 2.13 and 0.97 million USD for the control of the amounts of CO$_2$ that mentioned above. For reduction of mal impacts of RBW, 0.75, 22.79, 1.78, 1.15 and 0.55 million USD respectively are required.

On the basis of the applied results of the model, to reduce the environmental impacts of effluent salinity it is recommended to dilute the desalination brine using intake water before entering seawater for desalination up to 50000 m$^3$/d. Eventually for 100000 m$^3$/d water desalination plants and power plants are combined in one place, meaning that using power plant cooling water to dilute the desalination effluent before entering the effluent into the seawater to save the dilution cost. As the pretreatment units are very important determinants in desalination costs, it is suggested that a study should be conducted to evaluate the effects of different pretreatment methods on desalination costs.

The limitations of this study were the non-inclusion of small components of investment and operating costs as well as the non-inclusion of the social dimension of sustainability in the mathematical model as it made the model more complicated.

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**Ethical issues**
The authors hereby certify that all data collected during the research areas expressed in the manuscript, and no data from the study has been or will be published elsewhere separately.

**Competing interests**
The authors declare that they have no conflicts of interest.

**Authors’ contribution**
All authors were involved in data collection, analysis, and interpretation. All authors reviewed, refined, and approved the manuscript.

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