ELSEVIER

Desalination 124 (1999) 19–31

DESALINATION

www.elsevier.com/locate/desal

Sustainability assessment of desalination plants for water production

Naim H. Afgan[a]*, Mohammad Darwish[b], Maria G. Carvalho[a]

[a]*Instituto Superior Tecnico, Av. Rovisco Pais, 1096 Lisbon, Portugal*
Tel. +351 (1) 841-7378, Fax +351 (1) 847554, E-mail: nafgan@navier.ist.utl.pt
[b]*Mechanical Engineering Department, University of Kuwait, POB 5969, Safat 13060, Kuwait*
Tel. +965 4811188, Fax +965 484 7131, E-mail: darwish@kuc01.kuniv.edu.kw

Abstract

The paper presents an attempt to assess sustainability of desalination plants for water production based on resource, environmental and economic indicators. Four types of desalination plants are taken into a consideration: single MSF, dual purpose MSF, RO with local energy consumption and RO with PV electric energy production. The analysis is based on data from desalination plants in Gulf countries. In particular, it reflects water production demand and energy sources used for the individual plants. The decision-making procedure in the sustainability assessment of desalination plants is based on the multi-criteria evaluation under uncertainty of complex systems expressed by the General Sustainability Index. Evaluation of different cases reflecting priority of the criteria for evaluation has led to the selection of options, which are in compliance with respective criteria.

Keywords: Sustainability; Desalination plant; Indicators; Resources; Environment

1. Introduction

Water resources are a key element in sustainable development [1]. Agriculture accounts for the largest share, followed by industry and households. The growing future needs will exacerbate the already serious shortfalls in investment, as well as other weaknesses such as poor sector efficiency and inadequate prices. The three main elements of sustainable development are economic, environmental and social. Transnational and global environmental concerns suggest that water resource analysis should develop an even wider perspective. There are several technology options for water production of which desalination is the most promising.

There is a number of desalination processes presently in use on an industrial scale [2]. About 60 % of worldwide desalting plants capacity are located in the Arabian Peninsula. The

---

* Corresponding author.

Presented at the Conference on Desalination and the Environment, Las Palmas, November 9–12, 1999, European Desalination Society and the International Water Services Association.

PII: S0011-9164(99)00085-5

three main processes are multi-effect distillation, multi-stage flashing and reverse osmosis. There have been a number of attempts to evaluate advantages of each of the processes taking into consideration different criteria [3]. Most of these studies are devoted to the economic aspect of desalination plants. Recently, some attention has been given to the environmental aspect of those plants. But still there is a need for the complex approach, which will reflect sustainability of the desalination processes taking into a consideration resource, environmental, social and economic aspects with generalized criteria for the priority assessment.

Particular attention is focused on the assessment of the different energy sources to be used for the desalination processes. The following options have been considered: single purpose MSF plant, dual purpose MSF plant, reverse osmosis plant with electric power from the local network and reverse osmosis plant with solar energy.

2. Desalting plants in the Gulf area: a new outlook

The countries of the Gulf area depend on desalting seawater to satisfy their needs for potable water. In these arid areas where temperatures easily reach 50°C most of the summer days in Kuwait for example, more than 70% of their power production is used to operate air-conditioning systems. The continuous rise in the standard of living increases the demand for more power and desalted water. The electric power generation and desalted water production in large quantities can be realized by using one of the following options:

1. Separate power plants, and separate desalting plants,
2. Dual purpose power-desalting plants using steam turbines and MSF desalting systems,
3. Separate power plants and reverse osmosis desalting plants (using only mechanical energy) systems,
4. Reverse osmosis plant with a PV solar energy system.

These four options are compared with reference to sustainability indicators with a practical example from Kuwait.

Most desalinating plants operating in the Gulf countries, consist of steam turbines, each having 300 MW electric power capacity and combined with two multi stage flash (MSF) units of 6 mlgd each. Steam of moderately low pressure and temperature, (compared to the turbine throttling conditions), is extracted from the turbine to the two MSF units through a cross over pipe between the low and medium pressure turbines to provide the thermal energy needed. Each one mlgd is consuming about 15 MW thermal energy. Moreover, about 5 kWh mechanical work per m^3 is needed for pumping.

2.1. The MSF desalting system energy consumption

The MSF desalting system consists of heat input section (HIS), heat recovery section (HRS), and heat rejection section (HJS). The system is a big consumer of both thermal and mechanical energy. For small units thermal energy may be supplied directly from a boiler to the system. This method utilizes high available fuel in producing low availability steam (at moderately low pressure and temperature) suitable for supplying the MSF desalting system. Large MSF desalting units in the Gulf countries are combined with co-generation steam turbines. Steam supplied to the desalting units is generated at high temperature and pressure, and is expanded in the steam turbine to the conditions required by the desalting system. Thus the steam produces work before supplying the desalting units. So, the amount of fuel supply to the steam generator of a co-generation power desalting plant to produce both the power output and desalted water should be allocated between these two products.

A rational basis for allocation is adopted here, but first let us see the amount of thermal energy consumed by the MSF desalting system. The MSF desalting system is rated, from the energy point of view, by different methods. The first is the Gain Ratio defined by the amount of desalted water in kg produced per kg of the supplied steam. As an example, all the desalting plants in Kuwait have a design gain ratio of 8. If steam added to the HIS of the desalting unit is saturated vapor at 100°C leaves as condensed saturated liquid at the same temperature, then the energy consumed per unit mass of the desalted water is equal to the latent heat divided by the gain ratio (which is 8 here). So the thermal energy consumed to produce one kg of desalted water is 282 kJ/kg. More thermal energy is consumed to operate a steam ejector used to reject non-condensable gases from the system stages usually operated at a pressure below the atmospheric pressure. The thermal energy used by the ejector is close to 16 kJ/kg of desalted water but at much higher pressure than steam supplied to the HIS. So the total thermal energy supplied to produce one kg of desalted water is in the range of 300 kJ/kg. If the desalting system is directly operated by a boiler of 80% efficiency, then the fuel energy consumed to supply its thermal energy need is 375 kJ/kg of desalted water.

Moreover, the operation of the MSF pumps (namely re-circulation, cooling water, product, condensate, and brine rejection pumps) consumes mechanical energy. In the case of Kuwait, the mechanical energy consumption in most of Kuwait plants is in the range of 16–20 kJ/kg. When this mechanical energy, is generated from a power plant having 0.35, thermal efficiency, the fuel energy required to produce 18 kJ/kg is 50 kJ/kg. So the total fuel energy needed to produce 1 kg of desalted water from MSF directly driven by boiler is 375+50=426 kJ/kg.

Large MSF plants use bleed steam from a steam turbine to supply its HIS with the required thermal energy. The plant is combined to two MSF desalting units producing 12 mgd (each 1 mgd=4550 m^3/d). The two desalting units, producing 54,600 m^3/day, consume 180 MW thermal energy supplied their HIS (285 MJ/m^3), 10 MW thermal supplied to their steam ejectors (15.8 MJ/m^3), and 10 MW mechanical energy (15.8 MJ/m^3) to operate their pumps. These figures show that when the plant is producing 225 MW power only, the steam generator output is 581 MW thermal energy; and when it produces 225 MW power plus 12 mlgd of desalted water, the steam generator output is 671 MW thermal energy. This means that in order to supply 180 MW thermal energy to the HIS of the two desalting units, the steam generator has to increase its output by only 90 MW. This is almost 50% saving compared to the directly boiler driven case. So, the minimum fuel energy to be charged to the desalination process is 90/0.9=100 MW to account for the heat input section thermal energy, where 0.9 represents an average efficiency of the boiler. More fuel energy should be added to account for the thermal energy consumed by the steam ejectors (10/0.9=11 MW), and the pumping mechanical work (10/0.35=28.6 MW, where 0.35 is power plant efficiency).

A more rational method of evaluating the fuel energy to be charged to the desalting units is to find the equivalent work loss due to the extraction of steam from the turbine to the HIS instead of expanding this steam to the condenser. If it expanded to the condenser, it would produce 40.6 MW mechanical work. This is equivalent to 40.6/0.35=116 MW fuel energy. By using this last method, the fuel energy charged to produce 12 mgd, and accounts for all heat added to heat input section, and ejectors plus the work consumed by the pumps is 116+11+28=155 MW. This is equivalent to 246.6 MJ fuel energy per m^3 desalted water or 86.3 MJ mechanical energy per m^3 desalted water (=24 kWh/m^3 mechanical work).

The average rate of desalted water production (and consumption) in Kuwait in 1997 is 200 mgd (333 million m^3) annual production. For a fuel oil of 40,000 kJ/kg, the fuel energy consumed to produce this amount of water is 2055 million tons per year.

Surprisingly enough, if a reverse osmosis desalting plant is used, with maximum guaranteed energy consumption of 7.5 kWh/m^3 product water (27 MJ mechanical work/m^3 product, or 77 MW fuel energy/m^3), the annual fuel energy consumption would be 643 million tons per year.

To complete the picture, the desalted water produced by MSF desalting units driven directly by boilers requires fuel energy consumption of 437.7 MJ/m^3. In Kuwait, the daily production of 200 mgd requires 3648.7 million tons of fuel.

3. Desalination plant sustainability indicators

The sustainability assessment of a desalination plant should focus on resources, environmental, social and economic considerations. of the desalination plant. These indicators have to meet specific requirements:

- Sustainability. The indicators for respective criteria must represent quantities defined with indicators, which can be measured and are available as physical parameters representing the data, which are possible to obtain with respective quantitative or qualitative form.
- Reliable information. The indicators have to be the data, which you must trust because their totality may be the milestone for the important decision to be made.
- Optimization of the system to minimize energy cost under conditions associated with available material, financial resources, protection of the environment and government regulations, together with safety, reliability, availability and maintainability of the system.

For desalination plants assessment the following indicators are used:

- Resource indicators. Fuel — amount of fuel per m^3 of desalinated water, kg_{fuel}/m^3. Materials — amount of material used in construction of the plant per m^3 of desalinated water, kg_{mat}/m^3.
- Environmental indicators. Environmental indicators comprise reflection of the environmental pollutants produced by the desalination plant. This group of indicators strongly depends on the quality of the fuel. In our assessment we consider three gases produced by desalination plants: CO_2 — amount per m^3 desalinated water, kg_{CO_2}/m^3; SO_2 — amount of SO_2 per m^3 desalinated water, kg_{SO_2}/m^3; and NO_x — amount of NO_x per m^3 desalinated water, kg_{NO_x}/m^3.
- Economic indicator is defined as a unit cost of desalinated water, US\$/m^3. The cost will include capital cost, operation and maintenance cost and fuel cost. Since data on economic validation of individual plants are proprietary and scarce, in this evaluation we will use publicly available information.

4. Desalination plant option selection

This analysis is aimed to introduce the decision making process in the assessment of the process. The following options are taken into a consideration:

1. Option 1 — Single purpose MSF desalination plant
2. Option 2 — Dual purpose MSF desalination plant
3. Option 3 — Reverse osmosis desalination plant with local electric energy consumption
4. Option 4 — Reverse osmosis desalination plant with photovoltaic energy production

4.1. Option 1 — Single purpose MSF desalination plants

A single purpose desalination plant using MSF desalination units requires the use of boilers to supply the desalting units with its thermal energy needs (as steam at moderately low pressure of 1–3 bars), and to supply steam ejectors to eject non-condensable gases from the units. This is a wasteful process from thermodynamics principles, since high fuel of high availability is burned to produce stem of low availability. This can be clearly shown by calculating the second law efficiency of boilers producing saturated steam at atmospheric pressure (about 15%), and that producing steam at conditions required by modern power plants (160 bar, and 55°C) with second law efficiency of 46%.

The average thermal energy consumption of a typical MSF used in Kuwait of GR equal to 8, (GR = kg of desalted water / kg of supplied steam), is 320 MJ/m^3 including steam supplied to the ejectors. The boiler efficiency for this moderately low-pressure steam, say 80%, is lower than the efficiency of steam generators producing high availability steam (about 88%). Then, a fuel energy consumption to produce 1 m^3 by directly boiler driven MSF units is 400 MJ/m^3. Additional mechanical energy is needed to drive the system pumps, in the range of 4.5 kWh/m^3 (16.2 MJ/m^3 mechanical work). To produce this amount of energy from a power plant of 0.36 efficiency, the fuel energy needed is 45 MJ/m^3. So, the amount of fuel energy required is 445 MJ/m^3 of desalted water. So, the fuel resource indicator for desalting water, expressed by the fuel energy consumed to produce 1 m^3 of desalted water, by directly boiler driven MSF system is RI (fuel/water) = 455 MJ/m^3/40 MJ/kg_{fuel}=11 kg_{fuel}/m^3 desalted water. For this case of directly boiler driven desalting system, other sustainability indicators are shown in Table 1.

Table 1
Sustainability indicators for single purpose MSF plant

Fuel resource indicator, kg_{fuel}/m^3	11
Environmental indicator for CO_2, kg_{CO_2}/m^3	37
Environmental indicator for SO_2, kg_{SO_2}/m^3	0.09
Environmental indicator for NO_x, kg_{NO_x}/m^3	0.06
Economic indicator, US$/$m^3$	2.66

The average daily desalted water production from MSF desalting units in Kuwait in 1997 was 187 mgd or (187×4550 m^3/million gallons) =854 thousand m^3/day. So, the annual desalted water production in 1997 is 311 million m^3. The sustainability indicators for the case of direct boiler driven desalting units producing 311 million of m^3/year are RI (fuel/water) = 11 kg_{fuel}/m^3 desalted water × 311 million m^3/y = 3.4 million tons of fuel/y. The annual fuel cost for water production by single purpose desalting system = 3.4×175 =615 million US$/y.

The specific investment cost of large MSF desalting plants, according to United Nations Report, DEEP 1998, is \$2153/m^3/d. In Kuwait, the installed capacity of the desalting plants is 234 mgd (1 million m^3/day), while the average production in 1997 is 178.7 MGD (0.8 million m^3/day), i.e. the operating load factor is 0.8.

The installed capacity of desalting units is usually planned to satisfy the desalted water needs for a long time (usually 10 years) with the low load factor in the early years of the plant operation. Then the average load factor over the time span of the desalting plants is much lower than 0.8, say 0.65. Then, for expected plant life of 25 years, the specific capital cost capital cost is \$2153/(25×0.65×365) = \$0.36/m^3. The annual capital cost distributed over the plant life is 1.0647×0.65×365× 0.363=\$91.7 million per year. If the operating and maintenance cost represent 1.2 of the fuel cost, then the annual operating cost of desalted water is 615×1.2=738. Then the total annual cost of producing 311 million m^3 a year is equal to 738+91=\$829 million, and this gives a specific cost = 829/311=\$2.66 /m^3.

4.2. Option 2 — Dual-purpose power–MSF desalination plant

When the plant is working as a dual-purpose plant and producing 225 MW power and 12 mgd water, the fuel energy input to steam generator, according to the design conditions, is increased to 702.6 MW, compared to fuel energy input of 610 MW when only 225 MW electric power was produced. So, additional 92.6 MW fuel energy is added at the steam generator in order to supply 180 MW to the desalting units. The cost of fuel supply to the steam generator has to be charged to both products, power and desalted water, according to an accepted rule. If all the benefit of dual-purpose plant is given to the desalting process, then 92.6 MW is to be charged to the desalting process for its thermal energy input. However, this is not fair and both production and desalting units arrangement should be benefited for the combination of the power. The steam extracted from the turbine to the desalting units would produce additional 42.8 MW of work when expanded in the turbine to the condensing conditions, instead of being extracted to the desalting units. This is equal to 3.5 MW equivalent mechanical work per one million gallons per day, or 67.1 kJ/kg mechanical work per unit distillate, to account for the thermal energy input (i.e.18.8 kWh/m^3). To produce this amount of mechanical energy in a power plant of 0.37 efficiency (design conditions), 116 MW fuel energy is needed to produce 12 mgd, i.e.183 kJ/kg. So, the ratio of the fuel to be charged to the desalting units should be 42.8/(42.8+225) = 0.16. This means that 116 MW has to be charged for the thermal energy to desalt 12 mgd. Meanwhile the balance, 586.5 MW is to be charged to the power production of 225 MW. This shows a significance decrease in fuel energy charged to desalting process, 116 compared to 180 MW actually added to the desalting units. As for the power production slight decrease in fuel energy is charged, 586.5 MW, instead of 610 MW for single purpose power plant. This is equivalent to raising the design efficiency from 0.37 (for single purpose power plant) to 0.38, or decreasing the design heat rate to 9384 kJ/kWh (compared to 9756 kJ/kWh for single purpose power plant). All these numbers are for design conditions. Additional pumping energy should be considered (16.2 kJ/kg) for the desalting process. Then the total mechanical work accounting for thermal energy supplied to the brine heater and pumping energy is 83.3 kJ/kg mechanical work. Again to produce this amount of work, the fuel energy required is 83.3/0.37=225.7 kJ/kg, (225.7 MJ/m^3).

It should be noted that the fuel energy consumed for desalting seawater is 225.7 MJ/m^3 (compared to 455 MJ/m^3 in a single purpose desalting plant). This means a 50.4% decrease in fuel energy when dual-purpose power water plant is used compared to single purpose desalting plant. So the following sustainability factors for desalting water production will decrease by the same ratio to become:

- The cost of desalted water can be calculated by using the same assumptions made earlier.
- The specific capital cost capital cost is \$2153/(25×0.65×365)=\$0.36/m^3.

The annual capital cost distributed over the plant life is \$252.6 million per year. If the operating and maintenance cost represent 1.2 of the fuel cost, then the annual operating cost of desalted water is 305×1.2=366.2. The total annual cost of producing 311.7 million m^3 by dual-purpose plant per year is equal to 366.2+91.7=457.9 million dollars, and this gives the specific cost = 457.7/311.7=\$1.5/m^3.

Table 2
Sustainability for dual-purpose power–MSF plant

Fuel resource indicator, kg_{fuel}/m^3	6.9
Environmental indicator for CO_2, kg_{CO_2}/m^3	21.1
Environmental indicator for SO_2, kg_{SO_2}/m^3	0.06
Environmental indicator for NO_x, kg_{NO_x}/m^3	0.04
Economic indicator, US\$/m^3	1.5

4.3. Option 3 — Reverse osmosis desalting plants with local electric energy production

The reverse osmosis desalting system is the main competitor of the MSF desalting system. The RO system has become more attractive by the continuous improvement in membrane materials, the raising of both feed pressure and temperature limits, and production of potable water from high salinity water in the Gulf area.

The reverse osmosis desalting plant is used, with maximum guaranteed energy consumption of 7.5 kWh/m^3 product water (27 MJ mechanical work/m^3 product, or 77.1 MW fuel energy/m^3), the annual fuel energy consumption would be 643 million tons per year.

Our concern here is to compare the energy consumption of RO and MSF systems. Consider a practical case similar to Jeddah 1 RO plant phase II of 12.5 mgd reported by Al-Badawi et al. The plant consists of 10 trains. Each train gives a product rate of 5680 m^3/day (65.74 kg/s). The procedure to calculate the power consumption is outlined here for one train of this Jeddah plant.

Since the conversion ratio (product/feed) is 0.35, then the feed flow rate is 187.8 kg/s. The plant actual feed pressure is around 60 bar (the membranes maximum allowable pressure is 70 bars. Assuming an efficiency of the feed pump equal to 0.75, and its driving motor is 0.9, then the feed pump power consumption is Qf, m^3/s × P, kPa / (Ep × Em) = (187.8 / 1000) × (6000) / (0.75 × 0.92) = 1633.3 kW.

By considering 20% more energy is consumed by other pumps (e.g. seawater supply, seawater boost, and chemical dosing pumps) the power consumption is 1.2×1633.3=1960 kW. To calculate the energy recovered in a turbine from the brine blow-down the brine flow rate = 187.8–65.7=122.1 kW. The brine pressure = feed pressure – pressure loss in the feed-brine side = 60–3=57 bars. Recovered energy = brine flow rate, m^3/s × P, kPa × Et = (122.1 /1000) × 5600 × 0.65 = 444.4 kW. Net energy consumption = 1960–444.4=1515.6 kW. Specific work done =1515.6/65.7=23.1 kJ/kg=6.4 kWh/m^3. It may be noticed here that Al-Fujaira plant actual measured power consumption is 6.5 kWh/m^3 but the guaranteed power consumption is 7.5 kWh/m^3. Now to calculate the sustainability indexes when RO are used, the fuel energy required to produce 7.5 kWh/m^3 (27 MJ/m^3) is equal to 27/0.37=73.2 MJ/m^3. So the mass of fuel required to produce 1 m^3 of desalted water is 73.2/40=1.8 kg of fuel/kg of water.

Again the specific investment cost of large reverse osmosis desalting plants, according to United Nations Report, DEEP 1998, is $1280 m^3/day. By assuming the same average load factor considered before over the time span of the desalting plant, say 0.65. Then, for expected plant life of 25 years, the specific capital cost capital cost is $1280/(25×0.65×365)=$0.22/m^3. The annual capital cost distributed over the plant life is 1.1×0.65×365×0.216=$54.562 million per year. If the operating and maintenance cost represent 1.3 of the consumed electric energy cost, then the annual operating cost of desalted water, by assuming that the cost of 1 kWh is 20 Kuwaiti fils (about $0.065/kWh). Then the operating annual cost of producing 311.7 million m^3 a year is equal to 311.7 × (7.5 kWh/m^3)×0.07=152 million $/y. Then the annual total cost of producing 311.7 million m^3 by RO system is 152+54.6=206.6 million $/y. This gives a unit cost of $0.7/m^3. So the mass of fuel required to produce 1 m^3 of desalted water is 73.2/40=1.8 kg of fuel/kg of water.

Table 3
Sustainability for RO plant with local electric energy source

Fuel resource indicator, kg$_{\text{fuel}}$/m^3	1.8
Environmental indicator for CO_2, kg$_{CO_2}$/m^3	6
Environmental indicator for SO_2, kg$_{SO_2}$/m^3	0.005
Environmental indicator for NO_x, kg$_{NO_x}$/m^3	0.009
Economic indicator, US$/m^3	0.7

Then RI (fuel/water) = 1.8 kg_{fuel}/m^3 desalted water; EI (CO_2) = 6 kg/m^3; EI (SO_2) = 0.005 kg/m^3; EI (NO_x) = 0.009 kg/m^3 are presented in Table 3.

4.4. Option 4 — Reverse osmosis desalination plant with PV electric energy production

This option will take into a consideration evaluation of the desalination plant with the same parameters as in Option 3 but energy supply will be from a PV solar power plant. This will imply that the Fuel Resource Indicators and Environmental Indicators will be same, but Economic Indicator will be changed due to change in electric energy cost.

The specific energy consumption for the desalination plant with reverse osmoses is 7.5 kWh/m^3 so that for the plant under consideration the total electric energy consumption is 1633.3 kW. The average irradiation 6.1 kWh/m^2 d or 150 kWh/m^2 a, which will give production 1600 kWh_{AC}/d. It is assumed 0.3 US$/kWh so the total cost of photovoltaic electric energy. With the desalination water production 312×10^6 m^3 the total operational cost is 700×10^6 so that with annual capital cost for desalination plant equal to 54.6 US$/$m^3$ the total annual cost is 755.4×10^6or specific cost per unit desalinated water 2.42 US$/ m^3. Since there is no fuel consumption the Resource Indicator and Environment Indicators are equal zero.

Table 4
RO desalination plant with PV electric energy source

Fuel resource indicator, kg_{fuel}/m^3	0
Environmental indicator for CO_2, kg_{CO2}/m^3	0
Environmental indicator for SO_2, kg_{SO2}/m^3	0
Environmental indicator for NO_x, kg_{NOx}/m^3	0
Economic indicator, US$/$m^3$	2.4

5. Evaluation of the sustainability indicators

In this analysis the following indicators are taken into consideration: Fuel Resource Indicators, CO_2 Environment Indicator and Cost Economic Indicator.

Table 5
Sustainability indicators

Option	Resource indicator, kg/m^3	Environmental indicator, kg/m^3	Economic indicator, c/m^3
1	11.23	37	2.66
2	6.97	21.16	1.47
3	1.88		0.66
4	0	0	2.42
Max	0.15	0.47	16
Min	0.002	0.005	4.4
Difference Max–Min	0.15	0.46	11.6

5.1. The sustainability assessment procedure

The sustainability assessment procedure is based on the Decision Support System's Shell (DSSS) ASPID-3W [5,6], which is a computer realization of so called ASPID method (ASPID — Analysis and Synthesis of Parameters under Information Deficiency) developed by Prof. N.V. Hovanov [7].

It is assumed that a set $X=\{x^{(j)},\ j=1,\dots,k\}$ of *k options* is fixed. In our case there are four options of the desalination plant ($k=4$): $x^{(1)}$ — Option 1, $x^{(2)}$ — Option 2, x^3 — Option 3, $x^{(4)}$ — Option 4.

Each option $x^{(j)}$ is identified with a vector $x^{(j)}=(x_1^{(j)},\dots,x_m^{(j)})$. A component $x_i^{(j)}$ of the vector $x^{(j)}$ is treated as a value of an initial x_i of the option $x^{(j)}$. In our case initial attributes are three indicators of the desalination plant sustainability: x_1 — Resource indicator (RI); x_2 — Environmental indicator (EI); x_3 — Efficiency indicator (FI).

So, the vector $x^{(j)}=(x_1^{(j)},\dots,x_m^{(j)})$ may be treated as a value of the attribute-vector $x=(x_1,\dots,x_m)$. It is supposed that each indicator x_i is necessary and the whole attribute-vector x is sufficient for a fixed *quality* of option definition. In the context of decision-making the quality under consideration may be identified with the *preference* of the option for a decision-maker.

A fixed quality of option $x^{(j)}$, $j = 1,\ldots,k$, is defined by *criteria* $q_1,\ldots,q_m$ each of them being a function of a corresponding indicator: $q_i = q_i(x_i)$, $i = 1,\ldots,m$.

A value $q_i^{(j)} = q_i(x_i^{(j)})$ of a quality level (degree of preference) of j-th option from the point of view of i-th *specific criterion*. Without the loss in generality it may be supposed that all specific criteria are normalized, i.e. any criterion q_i meets the inequality $0 \le q_i \le 1$. As this *normalization* takes place, the minimal value $q_i^{(j)} = 0$ of i-th criterion is correlated with an object $x^{(j)}$, which has minimal degree of preference (from the point of view of i-th criterion), and maximal value $q_i^{(l)} = 1$ — with an option $x^{(l)}$ which has maximal degree of preference (from the same point of view). So, every option $x^{(j)} \in X$ gets a *multicriteria indicator* $q^{(j)} = (q_1^{(j)},\ldots,q_m^{(j)})$, $0 \le q_i^{(j)} \le 1$, which may be treated as a value of the criteria-vector $q = (q_1,\ldots,q_m)$.

Let us consider linear normalization function $q_i = q_i(x_i)$. If preference of any option is increasing (from the point of view of i-th criterion) with increasing of the argument x_i then we shall use increasing normalization function determined by the formula

$$q_i(x_i;\theta)=\begin{cases}0 \\ \left(\dfrac{x_i - MIN_i}{MAX_i - MIN_i}\right) if \; {}^{if}_{if} \; MIN_i < \\ 1\end{cases} \qquad (1)$$

$x_i \le MIN_i$,

$< x_i \le \; \le MAX_i$,

$x_i > MAX_i$

Table 6
Values of normalized sustainability indicators of the desalination plant options

Process option	q_1	q_2	q_3
1	0	0	0.926
2	0.379	0.428	0.375
3	0.832	0.837	0
4	1	1	1

If preference of any option is decreasing from the point of view of i-th criterion) with increasing of the argument x_i then we shall use decreasing normalization function determined by the formula

$$q_i(x_i;\theta)=\begin{cases}1 \quad\quad if \\ \left(\dfrac{MAX_i - x_i}{MAX_i - MIN_i}\right) \; if \quad MIN_i < \\ 0 \quad\quad if\end{cases} \qquad (2)$$

$x_i \le MIN_i$,

$< x_i \le MAX_i$,

$x_i > MAX_i$,

The value MIN_i (MAX_i) in Eq.(2) may be chosen by the simplest way as the minimal (maximal) value $MIN_i = \min_j \{x_i^{(j)}, j = 1,\ldots,k\}$ $\left(MAX_i = \max_j \{x_i^{(j)}, j = 1,\ldots, k\}\right)$ from the set $\{x_i^{(j)}, j = 1,\ldots,k\}$.

The values $q_i^{(j)}$, $i = 1,\ldots,m$, $j = 1,\ldots,k$, of specific indices $q_1,\ldots,q_m$ for all options from the set X being fixed we can try to compare options *general preference* with help of component-wise preference relation $\succ$ determined on the $X = \{x^{(j)}, j = 1,\ldots,k$ by the condition

$$\forall x^{(j)}, x^{(l)} \in X\left(x^{(j)} \succ x^{(l)}\right) \Leftrightarrow \\ \Leftrightarrow \left((\forall i q_i^{(j)} \geq q_i^{(l)}) \& (\exists s : q_s^{(j)} > q_s^{(l)})\right) \qquad (3)$$

In plain words, option $x^{(j)}$ is more preferable "in general" than option $x^{(l)}$ $\left(x^{(j)} \succ x^{(l)}\right)$ if and only if option $x^{(l)}$ is not more preferable than $x^{(j)}$ from the point of view of each specific criterion q_i $\left(q_i^{(j)} \geq q_i^{(l)}, i = 1,\ldots,m\right)$ and there exists a specific criterion q_s such that $x^{(j)}$ is more preferable than $x^{(l)}$ from the point of view of the criterion $\left(q_s^{(j)} > q_s^{(l)}\right)$.

Two options $x^{(j)}, x^{(l)} \in X$ are named *incomparable* if they meet the condition

$$\left(\exists r : q_r^{(j)} > q_r^{(l)}\right) \& \left(\exists s : q_s^{(j)} < q_s^{(l)}\right) \qquad (4)$$

For example, multicriteria indicator $q^{(1)} = \left(q_1^{(1)},\ldots,q_3^{(1)}\right) \approx (\ )$, $q^{(2)} = \left(q_1^{(2)},\ldots,q_3^{(2)}\right) \approx (\ )$ of Options 1,2 sustainability are incomparable as Option 2 is "better" (more preferable) than Option 1 by the criteria q_1, q_2, q_3, but Option 1 is "better" than Option 2 by the criterion q_4.

The problem of options multicriteria incomparability may be decided by the synthesis of specific criteria $q_1,\ldots,q_m$ into one *general criterion* (index) Q determined by a scalar function $Q = Q(q) = Q(q_1,\ldots,q_m)$, which meets the condition of monotony $\left(\left(x^{(j)} \succ x^{(l)}\right) \Rightarrow \left(Q\left(q^{(j)}\right) \geq Q\left(q^{(l)}\right)\right)\right)$ and fulfills the requirements 1) $Q(0,\ldots,0) = 0$; 2) $Q(1,\ldots,1) = 1$.

Inequality $Q\left(q^{(j)}\right) > Q\left(q^{(l)}\right)$ means that j-th option is more preferable than l-th object. Now all options are comparable as there are only three alternatives for any pair of objects $x^{(j)}$, $x^{(l)}$; $Q\left(q^{(j)}\right) > Q\left(q^{(l)}\right)$; $Q\left(q^{(j)}\right) < Q\left(q^{(l)}\right)$; $Q\left(q^{(j)}\right) = Q\left(q^{(l)}\right)$.

The synthesizing functions Q is the generalized weighted mean, namely *additive function* (*weighted arithmetical mean*)

$$Q_+(q; w) = \sum_{i=1}^{m} w_i q_i \qquad (5)$$

In this formula $w = (w_1,\ldots,w_m)$, $w_i \geq 0$, $w_1 + \ldots + w_m = 1$, is a vector of *weight-coefficients* $w_1,\ldots,w_m$ (*weight-vector*). A weight-coefficient w_i is a *measure of relative significance* of the corresponding specific criterion q_i for aggregate estimation $Q\left(q^{(j)}\right)$ of general preference of an option $x^{(j)} \in X$.

6. Discussion of the general index of sustainability

The analysis is based on the results obtained by the DSSS procedure. In this analysis we will take into a consideration different alternative as regard weighting factors. In our analysis of the effect of individual criteria on the general index of sustainability it is assumed three different cases which will reflect changes in the mutual relation of the weighting factors on the decision-making process.

The following cases are taken into consideration:

1. $I = I_1 = w_1 = w_2 = w_3$ — there is no information about admissible weight-coefficients in our disposal
2. $I = I_2 = \{w_1 > w_2 > w_3\}$ — specific criteria are strictly ranked by their influence on the general sustainability index
3. $I = I_3 = \{w_3 > w_2 > w_1\}$ — We have the ordinal information I_3 about weight-coefficients.

For all three cases input data for DSSS are the same:

- Number of option $k = 4$.
- Number of sustainability indicators $m = 3$.
- Number of steps $n = 10$. So, it is supposed that the measurement of weight-coefficients is accurate to within the step $h=1/n=1/10=0.10$.

Number of all possible variants (of all weight-vectors $w = (w_1, ..., w_m)$) $N(3;10) = 66$.

6.1. Case 1: $w_1 = w_2 = w_3$

Even knowing that it is not a realistic situation, this makes it possible to assess the contribution of individual indicators to the General Index for the priority definition. Fig. 1 shows that Option 3 — RO desalination plant with local electric supply is the first on the priority list based on the general index of sustainability.

6.2. Case 2: $w_1 > w_2 > w_3$

From the total number of variants satisfying adapted conditions we will obtain that only N = 6 will meet this requirement. If the general index of sustainability will be determined, for all those variants the average value of the general index of sustainability is obtained with respec tive standard deviation. Fig. 2 shows graphical presentation of the general index of sustainability. Under imposed conditions of weighting factors mutual relation the priority list based on the general index of sustainability is obtained. Option 4 — RO desalination plant with PV electric energy supply is the first on the list. RO desalination plant with local electric energy supply is on the second place followed by the dual purpose MSF desalination plant.

Case 2 reflects those situations when priority is given to the resource criteria in comparison with the environment and economic criteria. These situations are immanent to the variants leading to the decision based on the resource criteria.

6.3. Case 3: $w_3 > w_2 > w_1$

Case 3 is designed to emphasize economic criteria in comparison with the environmental and resource criteria. It should be kept in mind that the adapted procedure reflects also mutual relation of the individual criteria but requires respective priority as specified in this case. Giving priority to economic criteria it is of specific interest to investigate how strong are other two criteria and to what extent they can contribute to the priority list. It is of interest to notice that the change in priority list is obtained as a result of the change in the criteria priority. This reflects one of the important characteristics of this method. Change from priority in Case 2

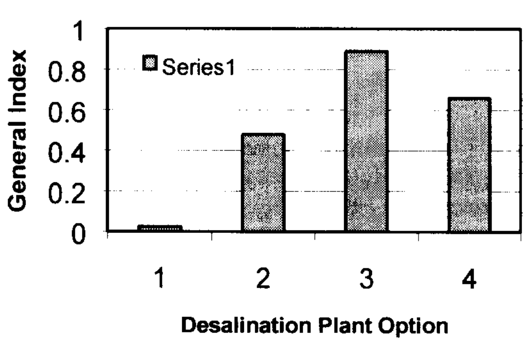

Fig. 1. General sustainability index for case 1: $w_1=w_2=w_3$.

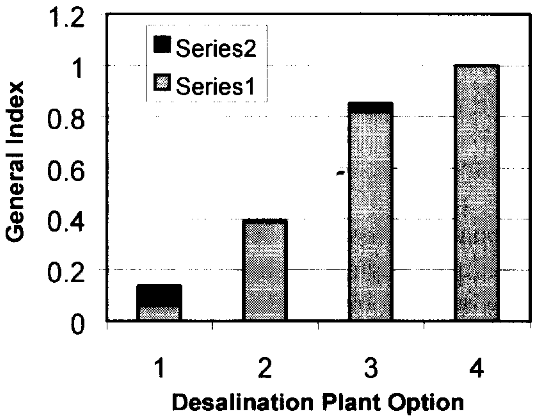

Fig. 2. General sustainability index for case 2: $w_1>w_2>w_3$.

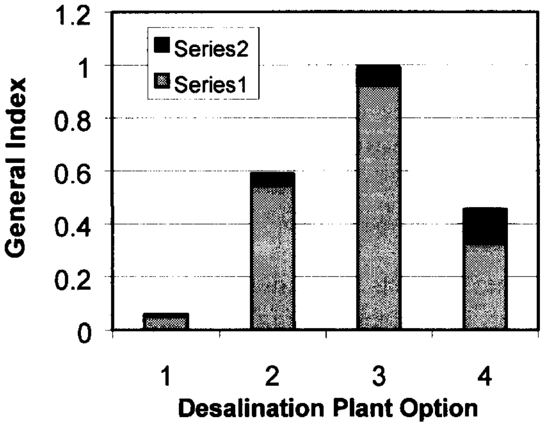

Fig. 3. General sustainability index for case 2: $w_3>w_2>w_1$.

to Case 3 implies the change of the emphasis from the resources priority to economic priority, has lead to the change in the priority list of the options under consideration.

The standard deviation for the individual option is somewhat higher but not to the extent that it may influence the priority list. It is also of interest to mark the change in the priority list as regards others options under consideration in this case: Option 2 has got a priority in relation to Option 4 and Option 1. Again, the decision-making procedure is sensitive to the change of the priority of criteria.

7. Discussion of the results

Even we should recognize the deficiency of the data used in this analysis, due to its limited accuracy and reliability, it can be seen that the examples show that the potential direction which have to be followed in the future assessment of quality of desalination plants. It should be emphasized that the demonstrated cases of the desalination plant evaluation proved that the decision-making procedure is very much dependent on the priority given to the specific criteria. Also, it is of interest to recognize that the priority list for the selection of appropriate choice is dependent on standard deviation of the specific option. As can be seen there is no difference in standard deviation for the Case 1 but in the Case 2 and Case 3 there is difference in standard deviation for the individual options under consideration.

It should be mentioned that this procedure is exercised by a limited number of possible variants. In the case if the weight-coefficient scale will be adopted with higher accuracy the obtained results will lead to the higher accuracy in the decision-making procedure. The accuracy of the method presented for sustainability assessment of desalination plants strongly depends on the accuracy of data used in this type of evaluation. In this analysis, we have used only publicly available data, which has limited quality of decision obtained by the presented method. If this type of the analysis will be done by the respective professional selection of data, the reliability of decision could be justified with lower uncertainty.

It is of interest for the decision-making process to use more criteria then presented in this analysis. In particular, if the local condition have to be recognized, it may be of interest to present criteria reflecting social indicator and availability of material indicator in the design of the plant.

As regards the selection of desalination plant for a specific location, it will be of interest to take into consideration not only technical and technological aspects of the water production but also geographical and water availability criteria. This may lead to the recognition of a number of options, which are of interest for specific conditions.

References

[1] N.H. Afgan, D. Al-Gobaisi, M.G. Carvalho and M. Cumo, Renewable and Sustainable Energy Reviews, 2 (1998) 235.
[2] M. Darwish, Proc., IDA World Congress on Desalination and Water Sciences, Abu Dhabi, 1 (1995) 149.
[3] P.G. Doroszlai, B. Oukili and S. Bouquecha, Proc., IDA World Congress on Desalination and Water Sciences, Madrid, 1 (1997) 199.

[4] C.J. Winter, R.L. Sizman and L.L. Vant-Hull, Springer –Verlag, Berlin, 1991.

[5] K.N. Hovanov and N.V. Hovanov, Decision support system's shell "Analysis and Synthesis of Parameters under Information Deficiency - 3-d modification for Windows". Registered by Federal Agency for Computer Programs Copyright Protection (Russian Federation), (1996) No. 960087.

[6] N. Hovanov, V. Kornikov and I. Seregin, Proc., Intl. Con. "Informatics and Control", St. Petersburg , (1997)808.

[7] N. Hovanov N. Analysis and Synthesis of Parameters under Information Deficiency. St. Petersburg State University Press, St. Petersburg, 1996 (in Russian).