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Hybridization — a new trend in desalination

A.M. Helal

National Energy and Water Research Center (NEWRC), Abu-Dhabi Water and Electricity Authority (ADWEA), POB 54111, Abu-Dhabi, UAE
Tel. +971 2 694 7018; Fax: +971 2 642 8992; email: amhelal@adwea.gov.ae

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ABSTRACT

A challenging problem that faces planners, designers and operators of power–desalination projects is the optimum selection of power and desalting technology in order to optimize the joint production of water and power by the utility. Previously the basis of selection was minimal costs for stand-alone, baseload production of water and power. Currently, the optimal design of a dual-purpose plant should take into account the individual site demands for electricity and water expressed in terms of the power to water ratio (PWR), the total network situation, the cost of energy, capital costs of plants and then the design is optimized for the lowest cost alternative, depending upon the ratios of water to baseload power and peak to baseload electricity demand. Due to the high cost of power–desalination plants, the Gulf countries are considering feasible alternatives with minimum investment and operating costs and optimal supply of water and power. However, the optimization problem is complicated by the significant seasonal mismatch between water and power demands and the increasing future demand of water over power due to the fast rate of industrial and social development and continuous population growth. Furthermore, choice of the optimal technology in co-generation plants is made more difficult due to the large number of the combinations of desalination technologies and power facilities that could be coupled together. Hybridization of power systems with electrically driven desalination technologies presents promising design alternatives capable of minimizing PWR while satisfying the other constraints of an optimal selection of the power-desalting plant. This paper briefly reviews different desalination technologies, summarizes the main components of power plants utilizing fossil fuels and presents a variety of hybrid configurations for dual-purpose plants emphasizing their advantages and limitations.

Keywords: Desalination; Hybridization; Power to water ratio; Co-generation; Optimization

1. Introduction

Water and power are essential for social and economical development in any country. Seawater desalination represents the main source of water for domestic and industrial use in arid areas having access to the sea. For economic reasons, electricity is produced simultaneously with water in dual-purpose or co-generation plants. Integration of desalination and power production in large-capacity plants improves the overall economics and leads to reduction in water and electricity costs. Desalted water in Abu Dhabi is mainly produced by the multi-stage flash (MSF) desalination technology. This technology is reliable, well proven and suitable for the

*Corresponding author.

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production of large capacities of potable water. Meanwhile, electricity is produced most efficiently in power plants based on the Combined Cycle where a gas and steam turbine-generator are utilized for maximum beneficiation of fuel energy. The water and power sections in a co-generation plant are linked together as follows:

- Exhaust steam from steam turbine is directed to the brine heater at the MSF to supplement heat requirements for the flashing process.
- Part of the power generated at the power plant is utilized to drive the pumping system in the water section.
- The ultrapure water required for steam generation at the power plant is derived from the first few stages in the MSF plant.
- The two plant sections have a common intake and outfall facilities
- The brine heater in the water section acts as a condenser for the power cycle.
- The boiler at the power plant produces steam for the benefit of both power and water sections. A separate boiler would be required if each plant section was to stand alone.

Although the water cost from the MSF process has been reduced significantly since the technology was first commercialized in the 1950s, desalted water by MSF is still unreachable for a large sector of the water starving countries and more reduction in water cost is required to avail the essential water needs and improve the living conditions of the peoples of those countries. In fast-growing and developing countries such as the UAE, reduction in water and power cost will boost social, industrial and economical development and ensure more prosperity of the country.

A challenging problem that faces designers and planners is the seasonal mismatch between water and power demand in the Gulf countries where the power demand in winter drops to about 30–40% only of its value in summer where power consumption is maximum due to the use of air conditioning. This creates a situation that over 50% of power generation is idle in winter. The same argument applies to the daily load variation.

Another challenging problem which opposes efforts made to reduce water and power cost is that the rate of population increase and social and industrial growth make the growth rate of water needs greater than the growth in need for electricity. This contradiction makes it necessary to design power–desalting plants so that the power/water ratio (PWR) is minimum. Besides minimum PWR, the optimal design of a dual-purpose plant should take into account the total network situation, the cost of energy, and capital costs of plants; then the design is optimized for the lowest cost alternative, depending upon the ratios of water to baseload power and peak to baseload electricity demand.

Since water can be stored while electricity storage is not practical, surplus electricity can be utilized for the production of more desalted water by electrically driven technologies such as seawater reverse osmosis (SWRO), and/or mechanical vapor compression (MVC) in combination with low-pressure steam-driven MSF or multi-effect distillation (MED) technology to design an integrated hybrid plant. The excess water produced can be utilized for recharging underground aquifers where it is stored as a strategic water reserve.

Before we discuss the concept of hybridization and feasible hybrid configurations, a brief outline of the relevant research work reported in literature is presented, the dominant thermal and membrane desalination technologies will be briefly outlined emphasizing their advantages and disadvantages.

More discussion of the PWR and its impact on the selection of the optimal plant design and analysis of dual purpose plants will be given in the following text. Finally, the more promising hybrid configurations will be presented and discussed.

Hybridization—related research work: The state of the art in hybrid power/RO/MSF has been recently published by Hamed [1]. Awerbach [2–4] analyzed the dominant desalination technologies and the alternative power plant components, explaining the advantages of hybridization of electrically driven desalination technologies with co-generation power/MSF systems and their impact on the enhancement of overall plant economics. Agashichev [5] conducted an economic study to compare between different alternatives for desalted water and power production based on different economic criteria. He concluded that hybridization of thermally driven plants can provide a number of advantages, including decrease of present expenses, decrease of capital and energy consumption, decrease of the level of carbon tax and decrease of the levelized cost of water. He also reported that incorporation of RO into existing co-generative systems decreases its sensitivity and, in turn, commercial risk of system to fluctuation of nominal interest rate, cost of primary fuel and rate of carbon tax.

Al Sofi et al. [6] recommended integration of nanofiltration (NF) to create either di- or trihybrids of NF–MSF and NF–SWRO or NF–SWRO brine reject–MSF in order to expand water and power production at reduced capital and operating costs. They came to the conclusion that the option of feed water heating for membrane process(s) in winter season deserves consideration in hybridized desalination processes.

Almulla et al. [7] performed a techno-economic study searching for the optimal solution to integrate essential daily resources in the Emirate of Sharjah to reduce cost of power and water generation and to meet increasing demand of water and power. They used managerial aspects to find best integrated solution, applied hybridization to existing thermal desalination plants, used annual water and power demand to optimize the hybridization alternative. They concluded that implementation of hybrid systems to meet the increasing water demand using surplus seasonal power and spinning reserve at Layyah plant, Sharjah–UAE, is considered an effective tool in better utilization of existing resources.

Altman [8] presented a new concept for a power/RO co-generation design which is said to be the most suitable technique from an energy point of view for reliably producing desalted water of the required specification with the lowest possible prime energy consumption. The main feature of the proposed design is that the feed pump of the RO plant is driven by a steam turbine. The co-generation plant equipment include a gas turbine, generator, heat recovery steam generator, live steam turbine, a steam condenser/feed preheater, RO feed pump, energy recovery device, RO membranes. The plant is characterized by a high degree of flexibility in operation and low PWR.

In an optimization study on a hybrid RO/MSF desalting plant which is based on minimum water cost and saving in intake cost, Al-Mutaz et al. [9] reported that in most instances it is recommended to build large-capacity RO or MSF plants rather than building a hybrid plant of the same capacity. To investigate the feasibility of the hybridization idea of RO and MSF technologies, Al Sofi et al. [10] conducted a theoretical optimization study on six different designs of hybrid plants coupled with an electric power generation plant. The designs included different levels of integration of the desalination plants. They based their study on the maximization of the overall plant recovery. In their study they compared the performance and recovery ratios of the different hybrid power–RO/MSF combinations with the cases of isolated power–MSF and power–RO plants. It was reported that the favorable hybrid design resulted in a percent recovery of 39.8% compared to 19.9% only for the isolated power–MSF and RO plants.

Based on the different hybrid plant configurations suggested by Al Sofi and his co-workers, Helal et al. [11,12] performed an optimization study for the prediction of the minimum water cost from these RO/MSF desalination plants. The power section is excluded from this study and it is assumed that the plants import steam and electricity from an external source at fixed prices. The MSF plants are either of the brine recycle or the once-through flow type. These are coupled with a single stage SWRO unit with energy recovery system. For comparison, the minimum water costs from a stand-alone, two-stage SWRO unit and a stand-alone brine recycle–MSF plant were also calculated. The study revealed that the two-stage SWRO plant yields the lowest cost per cubic meter of product water. Results show that hybridization of the RO and MSF processes may produce better economics and operation characteristics than those corresponding to the MSF process.

2. Thermal desalination technologies

2.1. MSF process

MSF desalination technology is the dominant distillation method amongst commercial methods that utilize thermal energy. This technology has a sizable share of the seawater desalination market, which is close to 50%. The success of the MSF process is attributed to the following advantages:

- Simple suitability for very large capacities.
- Large MSF units with production capacity ranging between 50,000–75,000 m^3/d (11.1–16.65 migd) are being installed in different countries [13].
- High performance reliability.
- Considerable operating experience.
- Produces very pure water.
- Low-pressure steam (low-cost steam) can be used as a source of thermal energy.
- Less susceptible to scale formation than other thermal processes, e.g. MED.
- Lends itself to co-generation.
- Water cost from MSF competes with other technologies, e.g. MED and RO.

If well maintained, MSF plants can continue to operate satisfactorily for 40 years. This fact will contribute to reduction in water cost from the MSF plants as the plant capital represents 30–40% of the unit product cost.

Design considerations: The MSF process has some properties that can be complementary to other desalination technologies such as RO. Meanwhile other properties can be complemented by RO or other processes.

- MSF product is characterized by very low salinity (high quality), about 25 ppm TDS.
- Unlike the case of RO, increased feed water temperature results in reduction in MSF plant production.
- The product water is hot with high seawater feed temperature (RO feed is not heated).
- The MSF process is not sensitive to feedwater salinity. RO is significantly affected by feedwater salinity.
- Low-pressure steam is available at low cost in MSF plants. This LP steam can be used in other desalination processes.

Although the major plant costs could be very site specific, it is always useful to have some idea about the contribution of the various cost components to the cost of the unit product. The following breakdown of the MSF capital and operating costs helps in this aspect [14]:

Capital costs:	
Heat transfer surfaces (tubes, etc)	up to 40%
Evaporator shell	30%
Pumps	15%
Piping	25% of the plant
Material cost	47% of labour cost
Operating costs:	
Steam	60–80%
Labor	10%
Chemicals and materials	5%

The following percentages represent the capital cost breakdown of a typical medium sized (below 20 migd):

Evaporator	50%
Seawater supply	15
Brine recycle/blowdown	7
Instruments and controls	6
Electrical	5
Chemical Treatment	2
Miscellaneous	5

Disadvantages — The main disadvantages of the MSF process are summarized in the following points:

- Performance ratio is limited, maximum 10 kg of product/kg of input steam.
- Larger specific area of heat transfer due to the low values of the operating heat transfer coefficient.
- Less flexibility in operation. Cannot operate below 60% of design capacity.
- Slow start-up and sluggish dynamics. Start up requires considerable care.
- Leaks in tubes deteriorate product quality.
- Large and expensive intake facilities.
- Specific capital cost is high.
- Large amounts of concentrated effluents, blowdown and acid wash effluents can disrupt marine life.

2.2. MED technology

The main advantages of the MED technology are:

- The plant is operated at a low top brine temperature, 60–70°C. This feature reduces scale formation and corrosion.
- Operation at low top brine temperature makes it possible for the MED process to utilize low-grade heat energy.
- The performance ratio (PR) is closely tied to the number of effects and values as high as 16 kg water/kg of input steam is not unusual. This means that the process is thermally efficient.
- The process is adaptable to co-generation.
- The use of spray-type horizontal tube evaporators ensures significant heat transfer characteristics and high heat transfer coefficients.
- Process economics are best suited to small- to medium-size plants. Recent MED installations in the UAE include the Umm Al-Nar MED plant with a unit capacity 15,911 m^3/d (3.5 migd) and the Sharjah plant with a unit capacity of 22,730 m^3/d (5.05 migd). Recent studies show the availability of MED unit capacity up to 40,000 m^3/d (8.9 migd) [15].
- The spray-type horizontal tube MED process is characterized by high heat transfer coefficients. For the same heat load and temperature difference, MED requires less heat transfer surface, therefore less capital.
- Pumping power is less than the MSF process, about one-third relative to MSF. Similarly, the recovery fraction is higher than in MSF; therefore, the specific chemical consumption is lower. In general, the operating cost is less compared to the MSF process.

Table 1 presents a comparison between the MED and MSF process. [16].

2.3. Electrically driven MVC

MVC desalination plants include mechanical compression coupled with a single effect (SEE–MVC) or multi-effect evaporation (MED–MVC) system. In vapor compression processes, water vapor from saline feed water is collected and compressed, thereby condensing the vapor. The heat for evaporating the saline feed water comes from the compression of vapor rather than from direct exchange of heat from steam produced in a boiler. In VC units, the heat given off during condensation is transferred back to the feed water to enhance its evaporation. In this process, the major energy input is provided by the compressor, which not only increases the pressure of the vapor and consequently its saturation temperature, but also reduces the vapor pressure in the vaporization chamber.

A single effect evaporation MVC process normally consists of the following major components:

- A mechanical vapor compressor
- An evaporator/condenser heat exchanger
- Preheaters for intake seawater
- Brine and product pumps
- A venting system

The commercial availability of MED–MVC systems is limited. Existing units have no more than four effects and production capacities of less than 5000 m^3/d. Unit design limits the top brine temperature (TBT) to less than 70°C

Table 1
Comparison of thermal seawater desalination processes

	MSF–BR (brine recycle)	MSF–OT (once-through)	MED (thin film arrangements)
Principle of steam generation	Flashing	Flashing	Boiling/evaporating
Maximum practical GOR	10	12	25
Combination with heat pump (vapor compression)	Increases GOR by 10–30%, however not found commercially	Increases GOR by 10-30%, however not found commercially	Very economical in certain cases
Antiscaling additive consumption	0.01 kg/m^3 products @T_{max} =90°C 0.02 kg/m^3 products @T_{max} =100°C	0.022 kg/m^3 products @T_{max} =115°C 0.03 kg/m^3 products @T_{max} = 130°C	0.022 kg/m^3 products @T_{max} =115°C 0.03 kg/m^3 products @T_{max} = 130°C
Pumping power requirements	Highest (4 kWh/m^3 product) excluding product treatment and transfer	Highest (3.5 kWh/m^3 product) excluding product treatment and transfer	Highest (1.5 kWh/m^3 product) excluding product treatment and transfer
Cost of piping and valves	Highest	High	Lowest
Resistance against fouling (on-line cleaning with rubber sponge cleaning system)	High (possible)	Lower than MSF-BR (possible)	Same as MSF–BR (not possible)
Cost of plant same GOR and same temperature, and with same construction materials	Highest	About 15% less than MSF–BR	About 15% less than MSF–OT
Maintenance cost	Highest	Lower than MSF–BR, same as MED	Lower than MSF–BR, same as MSF–OT
Reliability	High	Higher than MSF–BR	When GOR >12, like MSF–OT; When GOR <12, highest
Corrosion risk	Same for all processes at same top temperature	Same for all processes at same top temperature	Very low at GOR <12 owing to the low top temperature
Potential for further improvements	Very low	Low	Medium
Largest sizes in operation or under construction	75,000 m^3/d	12,000 m^3/d	36,000 m^3/d
Largest practical unit	75,000 m^3/d	72,000 m^3/d	60,000 m^3/d

and the temperature drop per effect to 2°C. As a result, the temperature increase in the compressor is limited to a range of 8–15°. A four-effect system with a 2°C temperature drop per effect would produce nearly four times as much product water as a single effect system with the a similar degree of vapor compression.

Since the development of the MVC technology in the late 1960s, progress has been made in system design and operation. Energy requirements of MVC plants have been reduced from 20 kWh/m^3 to 8–12 kWh/m^3, with the potential for further reduction.

The characteristic features of the MVC desalination technology are summarized in the following :

- Single effect evaporation MVC units are characterized by simplicity and compactness.
- Can be operated without recirculation.
- Low pumping power.
- No cooling water required.
- High performance ratio/unit of installed heat transfer area.
- Stable operation.
- Low operating labor cost.
- Lower operating cost than single-purpose MSF plants, though not lower than dual-purpose MSF.
- Can be readily integrated in co-generation plants.

However, the main disadvantages of the MVC technology are:

- Reliability of the unit depends mainly on the compressor, the item most liable to fail during operation. Failure is due to the high running speed and partly because of possible salt buildup on the rotor or the casing if demisters are not functioning properly. The last problem is overcome by using demisters.

- At lower operating temperatures, the vapor specific volume increases. Hence, the compressor load increases. At higher temperatures, possibility for scale formation increases.
- The plant is more likely to be destabilized as a result of any change in the operating conditions. Fluctuations do not have the tendency to be damped out. Also, the changes have the direct effect on the specific energy consumption.
- The capacity can be increased by increasing the number of effects. However, the difference in saturation temperature across the compressor increases. This increases the energy consumption of the compressor and as a result, the performance ratio decreases.

3. Membrane desalination

3.1. Electrically driven seawater RO technology

In the RO process, seawater is pre-treated, filtered and then pumped with a high-pressure feed pump through modules containing semi-permeable membranes. The required pressure is 25–40 atm more than the osmotic pressure because additional driving force is required. At the membrane, most of the salt is rejected. The feed water is separated by the module into two streams: the permeate, which passes through the membrane, and the concentrated brine, which is rejected to the sea through a control valve after energy recovery. Super-saturation should be avoided to prevent salt precipitation, membrane plugging and flux reduction. In some cases when the permeate salinity is higher than desired, it is sent to another RO unit (second stage or brackish water RO unit) or to an ion exchanger to further reduce the salt concentration.

Restrictive pretreatment is essential for the success of the RO process to prevent membrane bio-fouling and scale formation. Water cost from the RO process is strongly dependent on salt concentration in the feed. The process is most suitable for brackish water and low salinity seawater.

The main advantages of the RO technology are outlined in the following points:

- The process is electrically driven, a characteristic that makes it readily adaptable to co-generation.
- Can produce potable water in a single stage.
- Easy and simple operation
- Rapid delivery and installation.
- Fast start-up and shutdown. Adaptable to varying production requirements.
- Easy expansion due to modular concept.
- Low specific energy consumption (5 kWh/m^3).
- The process is highly reliable and needs low maintenance.
- Compact size-less area.
- Low corrosion hazard due to operation at low temperatures. Cheaper material of construction can be used.
- Low reject temperature. Minimal environmental impact.
- Modular concept allows bypassing of a defective module. There is no need to shut down the entire plant if one module is defective.
- The rate of development in RO technology is high compared to the MSF process, a fact that increases hopes in more cost reduction of desalted water produced by RO in the near future.

3.2. Comparison of technologies

In a recent study, Borsani et al. [17] gave a cost comparison of the three most dominant desalination technologies: MSF, RO and MED. The study was based on the plant characteristics given in Table 2 and is focused on a stand-alone RO plant and an MSF and MED plants, each coupled with a 500 MW power plant. The basic parameters for cost calculations are given in Tables 3 and 4 and the cost analysis is outlined in Table 5. Table 5 shows that the specific cost per cubic meter is the same for the thermal plants, MSF and MED while it is about 15% less for the RO.

It is important to mention that the environmental impact of the three plants was not taken into account in the cost estimation. As the thermal processes have more negative effect on the environment, consideration of the environmental impact cost will penalize water cost from those processes. Again, thermal processes are competitive with RO technology only when coupled with a power generation plant.

3.3. Design considerations of RO systems

The following points have to be taken into account when designing an RO desalination system:

1. Product salinity and chloride concentration continue to increase while production goes down with time. Installation of an extra membrane rack space and addition of membranes can solve the problem of product decline as membranes get older. However, increase in salinity and product quality deterioration can only be solved in a stand-alone RO plant by more frequent membrane replacement or by the installation of a two-stage system. Another solution that enables a single-stage RO plant with a long membrane life while satisfying the WHO requirements regarding product water salinity is to blend the RO permeate with the MSF pure distillate in a hybrid RO/MSF plant.

2. RO is an electrically driven technology where electric power is used to drive the high-pressure pump

Table 2
Characteristics of MSF, RO and MED Plants

Parameter	MSF	RO	MED
Plant type	Cross flow–brine recirculation	Spiral-wound membranes	MED–TVC
Production, m^3/d	205,000	205,000	205,000
Potable water quality	WHO	WHO	WHO
Number of units/trains	3	20 for 1st stage; 12 for 2nd stage	9
Number of membranes 1st pass (8" dia., 1 m length)	NA	18,000	NA
Production per unit, migd	15	2.25	5
Performance ratio	8.5	NA	8.5
Seawater inlet temperature, °C	35	35	35
Brine water outlet temperature, °C	45	NA	45
Seawater TDS, ppm	45,000	45,000	45,000
Top temperature, °C	112	NA	70
Recovery ratio	NA	2	NA
Number of stages/effects	19	2	6
Power required, MW	34	42	28
Seawater flow, m^3/h	58,000	22,000	58,000
Heat input, MJ/s	650	0	650

Table 3
Parameters for estimating investment and operational cost

Parameter	Unit	Value
Depreciation period	Years	20
Interest rate	%/y	7
Net present value factor	a	10.59
Annual operation time	h	8520
Cost of electric energy	C$/kWh	3
Fuel price of natural gas	$/MWh(th)	4.5
Cost of thermal energy for desalination	C$/MJ	0.05
Membrane replacement ratio	%/y	20
Cost of manpower (mean value)	$/y	25,000

Table 4
Breakdown of O & M cost (in kUS$)

Type of cost	MSF	MED	RO
Chemical products for operation	1500	1000	2500
Chemical products for cleaning	50	100	250
Operational people	400	600	500
Maintenance people	100	175	100
Membrane replacement	NA	NA	2000
Other maintenance cost including spare parts	300	200	250

and other auxiliaries. Typical values for specific power consumption in a single purpose RO plant with 30% recovery are: 42 kWh/1000 gal of product water without energy recovery on brine discharge and 29 kWh/1000 gal of product water with energy recovery on brine discharge.

Table 5
Water cost for each process

Parameter	MSF	MED	RO
Cost of thermal energy (M$)	105	105	0
Cost of electric power (M$)	92	76	114
Cost of O & M (M$)	25	22	60
Cost of desalination plant investment (M$)	180	195	170
Total cost (M$)	402	398	344
Net present value of production (M m^3)	770	770	770
Water cost c$/$m^3$	52	52	45

This qualifies the RO process for integration within an MSF/power co-generation plant where such an integration would result in significant reduction in export power production.

3. Recovery ratio is a key parameter in RO system design which determines the size of feed water handling system (intake, pretreatment system and high pressure pumping). The higher the recovery ratio, the less the cost of feed water handling system and less electricity and chemical consumption. Meanwhile, the increased recovery ratio requires more frequent membrane replacement and leads to higher product water salinity than specified by the WHO) due to the salt rejection characteristics of the available membranes. This problem can be alleviated by blending the ultrapure water produced in MSF desalination plants with the RO permeate in a hybrid RO/MSF plant.

4. De-chlorination is an important pretreatment step in RO technology to protect the membranes from the small amounts of residual chlorine normally used for disinfection. In this step, residual chlorine can either be reduced by large amounts of sodium bisulfite or deaeration followed by the use of significantly reduced amounts of sodium bisulfite. Some membranes are also sensitive to oxygen which calls for the use of deaerators. Feed water de-aeration also reduces corrosion significantly, which makes it possible to use less expensive construction materials for the RO piping system. In MSF plants, low-pressure steam suitable to be used for RO feed water deaeration is readily available at low cost. This makes it more economically advantageous to combine the RO and MSF technologies in one process.

5. Water flux of RO membranes increases by about 3% per ºC of increase in feed water temperature. To ensure obtaining the required production capacity, the RO plant is designed for the lowest feed temperature. As a result, the membrane portion of a stand-alone RO plant is thus oversized with respect to the increased temperature of feed water normally practiced in summer at desalination plant locations. If the RO plant is operated around the year at a higher feed temperature, then we can avoid waste in membrane capital due to the extra membrane area built to meet capacity requirements only in winter. This constancy in feed temperature to the RO plant can be realized by utilizing part or all of the reject cooling water in the MSF plant as a feed to the RO plant in a hybrid RO/MSF system.

4. Dual-purpose power–desalting water plants

Substantial savings (in both capital and operating costs) are possible by combining the two different types of single-purpose plants—water and power—in a dual-purpose arrangement. A dual-purpose plant burns fuel to yield two products: water and electricity. Both products are produced commercially from a single source of heat energy. Fuel consumption is reduced drastically. This means that the largest component of the operating cost is reduced.

In modern power plants, heat is generated in boilers at very high temperatures because the usefulness of heat energy depends on the temperature at which it is available. As the temperature is increased, heat becomes more valuable. A typical boiler may produce steam at 550°C. This is near the upper steam temperature limit of boilers. This can be compared to the relatively low allowable top temperature of an MSF desalination plant, 121°C. This temperature restriction is imposed by scaling considerations.

High temperature steam is relatively very expensive in energy terms if it is only used for operating a distiller. From a thermodynamic viewpoint, it is useful to extract maximum work in a turbine before rejecting the steam to a brine heater at the lowest possible temperature. Normal reject steam temperature from a turbine in a single-purpose power plant is 10–15°C above the ambient temperature (which in a hot country might be 40–45°C). By rejecting steam at .such a low temperature, it cannot be used for any purpose except for heating buildings. In hot climatic areas, where MSF distillers are usually required, even this advantage does not exist.

The top temperature of distillation plants is far higher than the normal exhaust temperature of condensing steam turbines. It is also far lower than the temperatures at which steam can be economically produced. So if steam (after passing through a turbine) is to be sent to a distiller, it will have to be exhausted at a higher temperature than is normally done in a single-purpose power plant. If steam is not allowed to condense at the lowest possible temperature, it will not develop its full work potential. By allowing steam to condense at a higher temperature (121°C) in a brine heater, instead of a conventional seawater condenser (at 50–60°C), there occurs a loss of power output. This is compensated for by improved heat utilization. As heat cost considerably affects the water production cost, effective heat utilization can reduce the production cost significantly. Additional cost savings in dual-purpose plants are obtained by constructing combined seawater intakes, outfalls, fuel terminals and other common facilities. In dual-purpose plants, the overall thermal utilization can typically increase to about 80%.

4.1. Advantages and disadvantages of dual-purpose plants

Boilers usually produce steam at a pressure greater than 20 bar. This is far higher than is required in a brine heater. Steam pressure to a brine heater is usually not more than 3 bar. Hence, in a single-purpose plant, steam pressure has to be reduced, thereby losing steam availability. This loss is avoided in a dual-purpose plant.

The primary advantage of a dual-purpose plant is significant savings in fuel, which is the major operating expense in power and desalination plants. Instead of requiring fuel for two plants, it is required for only one. Larger boilers can be used. The larger the size of a boiler, generally the lower the unit cost of steam. Fuel consumption is not halved, but it is still economically viable as the unit cost of energy is decreased. The cost of water from a dual-purpose plant is generally lower than from a single-purpose plant.

Maximum advantage is obtained when both components of a dual-purpose plant (distillers and turbines) are operated as much as possible near their rated capacities. Hence, the size and characteristics of each plant should be carefully chosen. Another advantage is that electricity is produced internally without any dependence on external supply. In single purpose plants, power has to be purchased. Purchased power is more expensive than internally generated power.

The main disadvantage is that operation becomes more complex and less independent than single-purpose plants. Reliability is not the same as in a single-purpose plant. Failure of one component has an effect on both water and power production. Also, when the power or water demand varies, the need for one component decreases. This has a direct effect on the other components. For example, gas turbines are not required for peak duty in winter. However, the water demand remains static and has to be satisfied. This can only be done by keeping additional units (auxiliary boilers) in reserve.

Similarly, if the distiller requires more steam when the steam turbine load cannot be increased due to low power demand, its requirements have to be met through a steam reducing station (which is supplied steam directly from a boiler).

A reverse situation can also occur. Suppose a back-pressure turbine is operating at high load, with low or no water demand at that particular time. Therefore, it has available an undersized condenser or no condenser at all. Such a situation can be avoided by installing a dump condenser. This means an additional expense.

To offset the serious limitations in flexibility, dual-purpose plants often are designed with more complexity. Instead of a series layout (of the boiler, turbine and distiller), a parallel arrangement can be used where a single boiler supplies steam to a distiller and a turbine separately. Plants are also designed with a combination of back pressure and condensing turbines. This gives more flexibility if either the water or power demand varies. If power demand increases without a corresponding increase in water demand, the load on the condensing turbines is increased. If demand increases for both, the back-pressure turbine takes up the load.

4.2. Power/water ratio (PWR)

In order to analyze a dual-purpose plant from an economic viewpoint, the PWR is often referred to. It is equal to:

PWR = (MW of net power exported/migd of net water produced) without supplemental firing

For the case where power alone is produced, it is equal to infinity. For a plant producing water only, it is equal to zero. Fuel savings attainable by co-generation tend to decrease with increasing power to water ratios.

A high PWR is undesirable since it means inefficient utilization of capital invested in the power plant and unsatisfactory economics of the co-generation plant in general. As a result, a solution will be needed to reduce the PWR in order to improve the economics of co-generation and reduce water and power costs.

Table 6
Typical power/water ratios for different technologies [4]

Technology	PWR (=MW required/migd)
Steam turbine BTG–MED	3.5
Steam turbine BTG–MSF	5.0
Steam turbine EST–MED	7.0
Steam turbine EST–MSF	10.0
Gas turbine GT–HRSG–MED	6.0
Gas turbine GT–HRSG–MSF	8.0
Combined cycle BTG–MED	10.0
Combined cycle BTG–MSF	16.0
Combined cycle EST–MED	12.0
Combined cycle EST–MSF	19.0
Reverse osmosis	0.8–1.5
Vapor compression distillation MVC	1.4–1.6

BTG, back pressure turbine generator
EST, extraction steam turbine
GT, gas turbine
HRSG, heat recovery steam generator or waste heat boiler
MED, multi-effect desalination technology
MSF, multi-stage flash desalination technology
RO, reverse osmosis
MVC, mechanical vapor compression technology

Hybridization can solve the problem of high PWR where load leveling is achieved through coupling of the power/MSF plant with an additional desalination unit that depends on an electrically driven technology such as RO and MVC.

Table 6 shows the PWR for different technologies including dual-purpose and single-purpose plants [4]. An important remark on the figures given is that hybrid plants comprising the more energy efficient power systems (combined cycle power plants) are characterized by the highest PWRs, while single-purpose water plants with electrically driven technologies such as RO and MVC have a relatively very low PWR. These figures reveal that a hybrid plant that combines a combined cycle power plant together with MSF and another large-scale desalination unit operated with electrically driven technology, e.g. RO, represents a promising hybrid with high energy efficiency, low PWR, and reduced water and power costs.

Performance ratios as high as 15–20 kg of product water/kg of input steam [14] can be obtained from a hybrid MVC/MED/MSF plant as the one shown in Fig. 1. This represents a notable improvement of the thermal performance of the MSF process. However, design complexity will have negative impact on plant operability and

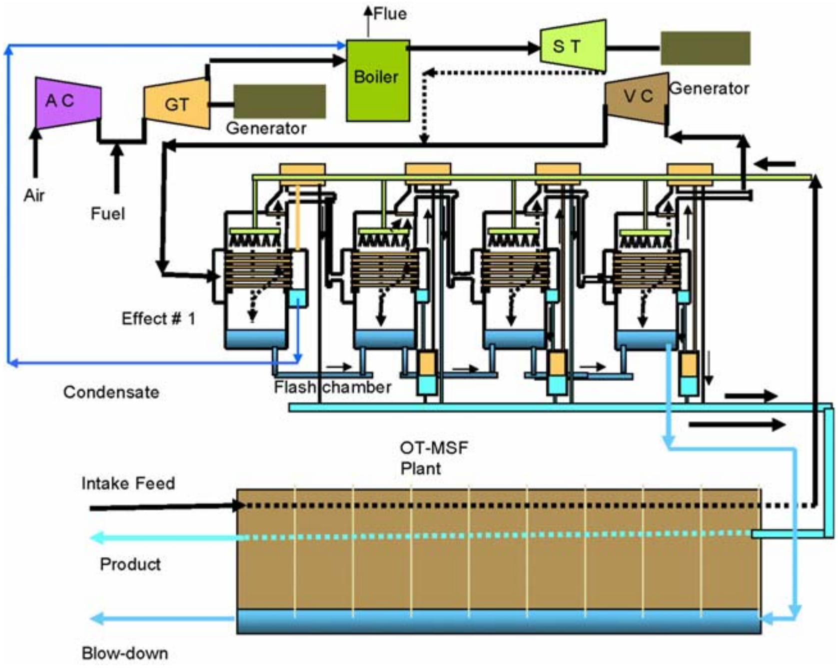

Fig. 1. Hybrid power/MSF/MVC–MED.

process control. In addition continual and sharp increase in fuel costs could deprive the hybrid design from the expected economic benefits.

4.3. Costs

The apportioning of costs, between electricity and water, in dual-purpose plants is fairly complicated. No generally agreed apportioning procedure exists. Complications arise due to the common use of some components. For example, a single-purpose plant producing water is charged the operation and maintenance costs of the boiler supplying it with steam; in a dual-purpose plant, these costs are divided because steam is used to generate both water and electricity. Similarly, cost allocation is complicated for site development, fixed charges, manpower, spares, etc.

5. Hybridization of power/MSF plants with electrically driven desalination technologies

Both of the RO and MVC technologies are characterized by fast start-up and shut-down. This advantage gives flexibility to the hybrid plant where the RO or MVC unit can start to produce water during off-peak hours and the excess water produced is stored or injected into underground reservoirs as a strategic back-up. The RO technology is characterized by its low specific energy requirements. This property helps more water production via utilization of the surplus power at off-peak hours. This advantage will eventually lead to reduction of the PWR.

5.1. Hybrid power/RO/MSF plant (Fig. 2)

Currently, most large-scale seawater desalting complexes are dual-purpose MSF plants producing both power and desalted water at a PWR of 10 MWe/MIGD. In the hybrid MSF/RO desalination power process, a SWRO plant is coupled with either a new or existing dual-purpose MSF/power plant. The hybrid plant will combine the advantageous characteristics of the MSF and RO technologies outlined before.

Based on an economic analysis done by Bechtel [2], it was shown that the product water cost from RO system in a simple MSF/RO plant can be reduced by 10–15% compared to stand-alone RO plant due to a reduction in capital cost and operating costs. The product water cost savings result from elimination of the second stage RO train, use of higher recovery ratio (decreasing size of pretreatment costs which goes up to 50% reduction), and lower energy consumption (about 15% less).

The following benefits can be realized from the integration of the RO technology in the power/MSF plant.

- Since RO technology is electrically driven, coupling of an RO plant with a power/MSF co-generation plant allows the use of off-peak power for more water production .Meanwhile, the short start-up and shut-down time requirements of the RO plant can be utilized to minimize power capacity by shutting down the RO plant daily during peak hours. This feature is attractive in situations where the need for water exceeds that for electricity and where the PWR is to be reduced.

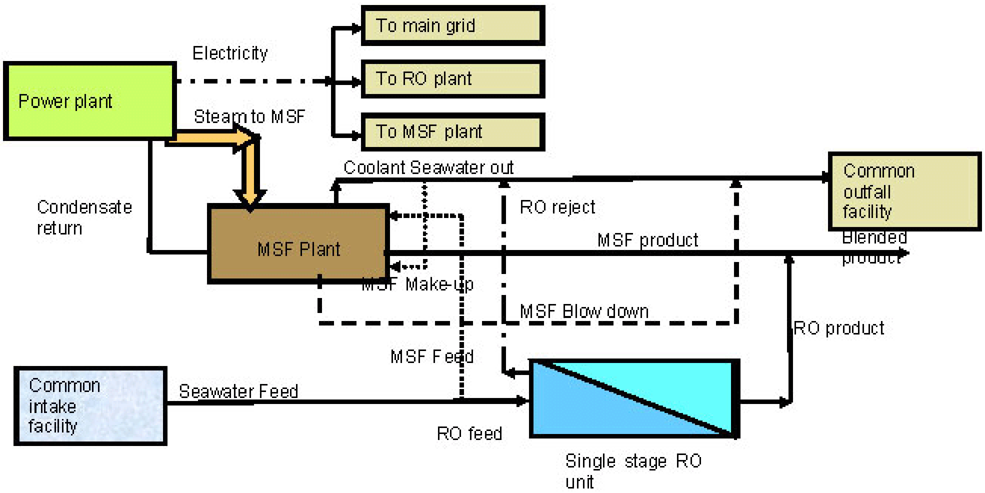

Fig. 2. Simple trihybrid power/RO/MSF desalination plant.

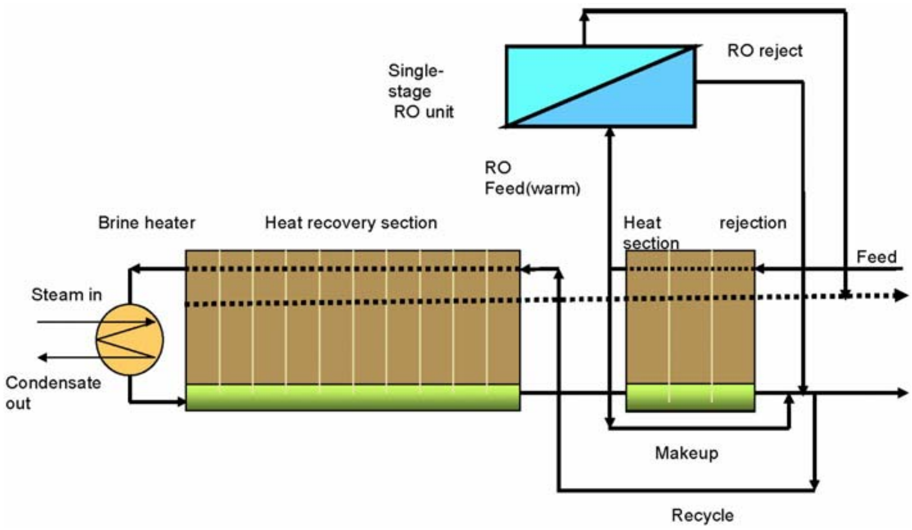

Fig. 3. Integrated hybrid RO/MSF desalination plant (warm coolant reject from the MSF forming the feed to RO plant).

- The capital cost of the combined RO/MSF plant can be reduced where product water from the RO and MSF plants are blended to obtain suitable product water quality. Taking advantage of the fact that the MSF product typically exceeds potable water specifications, the product water specifications in the RO system thereby can be reduced. This advantage enables the usage of a single stage RO plant, extends membrane life and reduce water cost.
- Electric power from the MSF plant can be efficiently utilized in the RO plant, thereby reducing the net export power production.
- By blending distillate from the MSF process with RO permeate, the temperature of the MSF product water is reduced and a common post-treatment plant is used for the combined product.
- The low-pressure steam from the power plant can be used to de-aerate and warm up feed to the RO plant at low cost. This minimizes the corrosion hazard by eliminating residual chlorine and dissolved oxygen. Meanwhile, it reduces specific energy requirements and makes it feasible to use relatively more economical materials of construction for the high pressure piping system, e.g., lower grade stainless steel. However, to ensure full protection of membranes against chlorine damage, sulphite addition and the use of active carbon filtration would still be needed if degasification this way proved to be insufficient.
- A common, considerably smaller seawater intake can be used with regard to the small intake requirements of the RO plants.

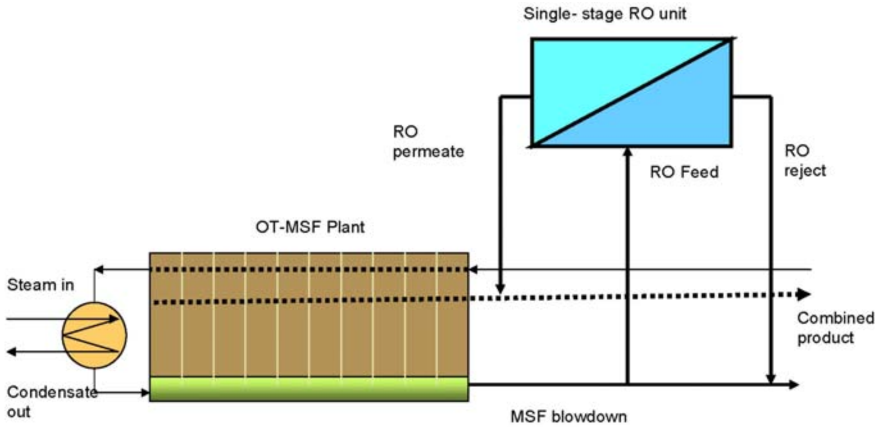

Fig. 4. Hybrid RO/MSF plant with part of the MSF blowdown forming the RO feed.

Researchers continued to believe that full integration of the RO and MSF plants provides better control of the feedwater temperature to the RO plant by using the warm reject coolant water from the MSF heat rejection section as in Fig. 3 In a pilot study on a hybrid RO/MSF desalination plant, El Sayed et al. [18] observed a remarkable enhancement in RO water production. Experimental data revealed that water production increased by 42–48% by preheating the feedwater to the RO plant section up to 33°C compared to a sole RO plant operated with a feed temperature of 15°C. On the other side, it is known that higher feed temperatures could lead to deterioration of the mechanical strength of the membrane material and possibly a change in its nature. This is why the maximum feed temperature is normally limited by the manufacturers to about 40°C. In fact, a number of limitations present practical difficulties to the utilization of the warm MSF reject coolant or sterilized blowdown (Fig. 4) as a feed to the RO section. These limitations are explained below.

In the MSF process, shock dosing of chlorine into the intake seawater is applied continuously three times daily over a period of 20 min where the residual chlorine in the intake water reaches a value of 5–10 ppm. Continuous application of these high levels of chlorine would develop bio-fouling at the RO membranes if the warm coolant reject from the MSF were to be fed to the RO section. High concentrations of chlorine would result in the degradation of the membrane polymer material so that biodegradable decomposition products are produced. These biodegradable materials represent a good substrate for bacteria to feed on and multiplicate. This is why a separate intake was built for each section at Al-Fujairah, UAE, hybrid plant where intermittent chlorine dosing is practiced at the RO plant intake once a week for 2 h. At the Al-Fujairah plant (design capacity 100 migd), the MSF section contributes 62.5 migd and the RO section produces the rest, 37.5 migd. The two sections have a common outfall and the RO section is a two-stage plant so that it can stand alone in case the MSF plant is shut down with a product having a TDS of 180 ppm. The two plant sections are operated independently. Table 7 outlines the general design parameters at the Al-Fujairah plant. A full description of the plant, design parameters and performance characteristics are given by Ludwig [19].

Table 7
General design parameters at the Al Fujairah plant (power and water production at full load conditions)

Power production gross, MW	662
Power production net, MW	500
Water production net, m^3/d = 100 migd	454,600
Power to water ratio (PWR), MW net/migd	5
Combined cycle gas turbine/waste heat boiler with supplementary firing/steam turbine configuration	
Desalination configuration:	
Multi-stage flash, m^3/d (=62.5 migd)	284,125
Reverse osmosis, m^3/d (=37.5 migd)	170,475

In the Gulf region, intake seawater temperature may go up to a temperature above 35°C in summer, especially during low tide periods. In the MSF process, reject coolant stream temperature is normally 6–10°C above intake temperature. In such a case, if this warm reject is to be fed to the RO plant, its temperature (41–45°C) will be beyond the safe limit defined by the manufacturer. To avoid this problem, design complexity will be a penalty.

5.2. Hybridization of power/MSF/MVC–MED plants

An economically promising hybrid configuration is that integrating an MVC–MED with a power/MSF unit in a co-generation plant. The MED process is characterized by its high performance ratio (PR), which means more efficient utilization of the thermal energy in the heating steam, hence better process economics. For low-compression ratios, the specific energy consumption of the

MVC will be low, which is in favor of the overall process economics. The MED is normally operated at low TBT, which means less corrosion and scaling, hence the possibility of using cheaper construction materials, a longer lifespan of the plant and less consumption of chemicals.

Fig. 1 illustrates a hybrid power/MSF/MVC–MED plant where the intake feed water is preheated in the MSF unit. The warm feed is distributed on the MED effects where the temperature of the feed portion to each effect is increased to the saturation temperature prevailing in the corresponding effect. This temperature increase is accomplished in a series of heat exchangers attached to the different evaporators where part of the vapors generated in each effect is condensed outside the tubes of the corresponding exchanger thus heating up the seawater inside the exchanger tubes. The feed to an effect is distributed over a horizontal tube bundle by spray nozzles forming a thin liquid film over the outside tube surface. This liquid film starts to boil upon receiving the latent heat released by the condensing vapors inside the tubes and which are received from the upstream effect. The generated vapor partly goes to the corresponding exchanger-preheater and partly to condense inside the tubes of the next effect. The two-phase flow, made up of remaining uncondensed vapor and condensate (and possibly non-condensable gases), leaves the other end of the horizontal tube bundle to a flash chamber where the flashed off vapor goes up to the corresponding exchanger, whereas the condensate goes down to the product water main header. Concentrated brine is cascaded down the train of the lower pressure effects where some vapor is flashed off to join the generated vapors over the tubes. Depending on the number of effects and the ambient air temperature, the saturation temperature at the top effect could vary between 60 and 120°C while the temperature drop per effect lies between 5 and 8°C. Lower TBTs are more adequate for the utilization of low-grade heat energy and control of scale and corrosion problems. However, higher TBTs mean a larger cooling range, more effects, higher PR and larger capacity.

Now, the low-pressure steam leaving the last effect is recycled to the first effect through the vapor compressor which is driven by the electricity supplied by the power generation section. The temperature of the compressed vapor is adjusted to match the operating conditions at the first effect.

The power plant includes a combined cycle gas turbine and waste heat boiler connected to a back-pressure steam turbine where part of the exhaust steam is mixed with the compressed vapors from the vapor compressor, thus elevating its temperature, before the combined vapor stream is directed to condense inside the tubes of the top effect. The product and blowdown streams from the MED section are cooled down the cascade of stages in the MSF unit through a series of flashing processes where more water is produced.

5.3. Hybrid power/MSF/MVC co-generation plants

Integration of the MSF unit in a co-generation plant with MVC only is another option where the latter is characterized by its high energy efficiency. An example is given in Fig. 5 where the process feed is first preheated in the MSF plant. The feed temperature is further increased by condensing steam (external heat source) in a brine heater. The hot seawater is then introduced to the brine pool in a single effect, long tube–falling film, evaporator where it starts boiling, giving off vapor. The generated vapor is then compressed in a vapor compressor attached to the evaporator where its temperature is increased by a few degrees over the boiling temperature of seawater inside the tubes. The compressed vapor is returned to the evaporator where it starts to condense outside the evaporator tubes, thus releasing its latent heat to the boiling seawater inside the tubes. The condensate and concentrated brine leaving the evaporator are cooled down in the MSF unit while more water is produced through the flashing process along the train of stages. According to Tleimat [14], the vapor compression section can produce five sixth of the total plant capacity.

The MSF unit functions as a heat recovery unit which is more efficient than the liquid–liquid–liquid heat exchanger normally used downstream in the MVC–single effect evaporators. In an MVC plant, the cooling range of the product and blowdown is similar to the flashing range in the MSF process, a feature that makes this hybrid configuration more attractive.

5.4. Hybridization of power/MSF plants with nanofiltration pretreatment systems

The integration of NF on the seawater feed line to a power/MSF or a power/RO/MSF plant (Fig. 6) will result in water softening and elimination of 90% of the scale forming ions such as sulfate, bicarbonate, calcium and magnesium. Only 50% of the chloride is rejected by NF membranes. This pretreatment step will minimize anti-scalant dosing and enable up-rating the MSF unit through operation at elevated top brine temperature close to 130EC. Awerbuch [4] reported that the distillation plant productivity can be increased between 15% to 45% by increasing the top brine temperature from values as low as90–110EC to 120–125EC.

Utilization of power to drive the pressurizing pump at the NF unit reduces the net power export while increasing water capacity which favors a lower PWR and improves the overall process economics.

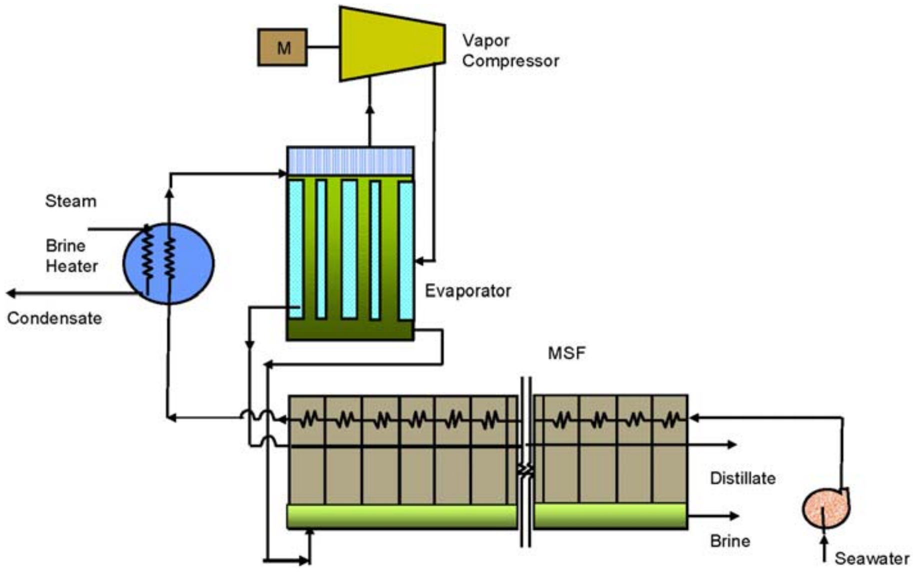

Fig. 5. Hybrid MSF/single effect MVC.

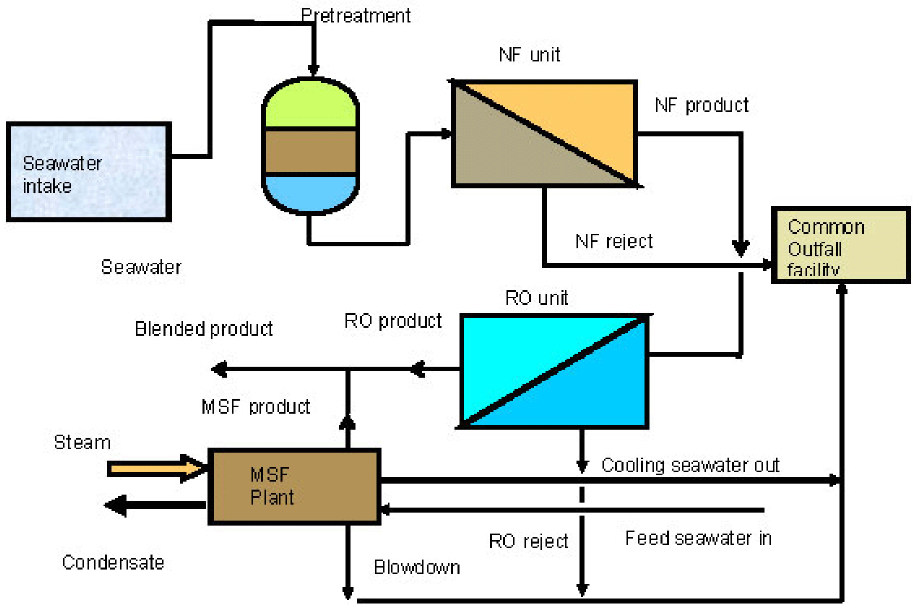

Fig. 6. Hybrid NF/RO/MSF desalination plant.

This coupling reduces the scaling potential of the feed, provides higher concentration factor, hence more water recovery. With the current high quality material of construction and without use of acid, the negative corrosion effects of higher temperature would be minimal.

In a pilot study, the researchers at the Saline Water Conversion Corporation (SWCC) laboratories in Jubail tested the performance of a trihybrid NF/RO/MSF 20 m^3/d demonstration plant [1]. They could operate the MSF section successfully at a TBT at 130°C for a period of 1200 h (50 days) without antiscalant injection. This way, the product recovery was increased from 35%, a value that is conventionally obtained at MSF plants, to 70%. In a second experiment to establish the operating conditions of the trihybrid plant, the MSF section was operated successfully at a TBT at 130°C for a period of 976 h (about 41 days) with a make-up stream that is entirely formed from the RO reject. A schematic diagram for the trihybrid NF/RO/MSF pilot plant is given in Fig. 6.

Generally, in order to assess the economic feasibility of the full-scale trihybrid plant, savings in chemicals as well as the gain of the additional amount of product have to be weighed against the extra costs of the high pressure distiller shell, the higher enthalpy steam to be used, and the cost of the NF membranes.

6. Existing hybrid plants

6.1. Jeddah complex (owned by SWCC, KSA) (simple hybrid)

This complex includes the Jeddah 1 RO plants Phase I and Phase II, each with 12.5 mgd. Phase I became operational in 1989 and phase II opened in 1994. Both are single-stage plants.

6.1.1. Phase I

- Design: Bechtel.
- Construction: Mitsubishi Heavy Industries Ltd.
- Type of membranes: Toyobo Hollosep double element hollow fine fiber RO modules.

6.1.2. Jeddah II, III, IV dual-purpose plant, power/MSF, producing an additional 80 Mgd and 924 MW

The two RO plants have common intake and outfall facility. The product from the MSF plant is blended with the SWRO permeate.

6.2. Madina and Yanbu RO/MSF complex (KSA)

This was not originally designed as an integrated hybrid plant. The Yanbu complex includes:

- Large RO plant with 28.16 migd (15×1.89 migd) water capacity.
- A dual-purpose power/MSF plant 164 MW, comprising 2×82 MW.
- Back-pressure steam turbines each turbine providing steam to 4×10 migd distillation units.

The RO plants are single-stage. Both MSF and RO products are blended, and both plants share the same intake and outfall facilities.

6.3. Al-Jubail RO/power/MSF hybrid (KSA)

A 20 migd single-stage SWRO desalination plant was annexed to the Al-Jubail power/MSF dual-purpose plant. The RO and MSF plants share common intake and outfall facilities. The distillate from the MSF plant is blended with the RO permeate.

6.4. Al-Fujairah RO/power/MSF hybrid (UAE)

This facility includes:

- 5×12.5 migd distillers = 62.5 migd, MSF capacity
- 37.5 migd two-stage RO plant
- A 500 MW power plant

The salinity of the permeate from the RO plant is 180 ppm, and the products from the two plants are blended. Each of the RO and MSF plants has a separate intake.

7. Conclusions

1. With the large capacity and large number of plants committed to desalination, the security and development of many nations depends on current desalination capabilities and advances in desalination technology.
2. The future of desalination technology will depend largely on: reducing energy costs achieved by optimizing power and water generation.
3. Fully integrated hybrid RO/MSF systems, which combine the best features of distillation and RO, are worth testing and validation.
4. In the near term it can be projected that desalination technology will adopt hybrid systems utilizing large-scale multi-effect distillation plants, and increased use of large-scale vapor compression. Still significant advances in RO technology are expected.
5. Hybridization solves the problem of the mismatch between the greater rate of growth of water demand and the lower rate of growth of electricity demand . It reduces the high values of PWR that would result from the dramatic seasonal variation of power consumption.
6. Hybridization of MSF–RO and MED–RO has many advantages with the ability to cut significantly the PWR.
7. Hybridization of MSF–MED with MVC has the potential of boosting water output through simple or full integration and at the same time reduce the PWR.
8. Hybridization with NF–softening membrane provides the ability to increase desalination output of distillation, MSF, MED and RO plants by reducing scaling potential and salinity of the feed and provide significantly better concentration factors and recovery for all desalination processes, ultimately leading to mineral recovery.
9. Hybrid with RO and MVC electrically driven desalination technologies would allow use off peak power for water production, and minimize power capacity by shutting-down RO or MVC daily during the peak.
10. The seasonal surplus of unused idle power could be used by RO and MVC electrically driven desalination technologies in combination with aquifer storage and recovery.

References

[1] O.A. Hamed, Overview of hybrid desalination systems — Current status and future prospects, Desalination, 186 (2005) 207–214.
[2] L. Awerbuch, Hybrid desalting systems, Proc., Fourth World Congress on Desalination and Water Reuse, Vol. 4, Kuwait, 1989.
[3] L. Awerbuch, Advancements in global water technology, desalination, energy and economics, 2nd Middle East Infrastructure Development Congress, Middle East Private Power Summit, 1997, Dubai, UAE.
[4] L. Awerbuch, New approaches to desalination and power systems, Presented at Gulf 98–MEED Conference, Energy, Infrastructure & Finance in the Middle East, Abu Dhabi, 1998.

[5] S.P. Agashichev, Analysis of integrated co-generative schemes present value of expenses and levelized cost of water, Desalination, 164 (2004) 281–302.
[6] M.A.K. Al-Sofi, A.M. Hassan, O.A. Hamad, A.G.I. Dalvi, N.M. Kither and G.M. Mustafa, Optimization of hybridized seawater desalination process, Desalination, 131 (2000) 147–156.
[7] A. Al Mulla, A. Hamad and M. Gadalla, Integrating hybrid systems with existing thermal desalination plants, Desalination, 174 (2005) 171–192.
[8] T. Altmann, A new power and water cogeneration concept with the application of reverse osmosis desalination, Desalination, 114 (1997) 139–144.
[9] I.S. Al Mutaz, M.A. Soliman and A.M. Daghtham, Optimum design for a hybrid desalting plant, Desalination, 76 (1989) 177–189.
[10] M.A. Al-Sofi, A.M. Hassan and E.E. El-Sayed, Integrated and non-integrated power/MSF/RO plants, Internat. Desalination Water Reuse Q., Part 1: 2(3) (1992) 10–16; Part 2: 2(4) (1992) 42–46.
[11] A.M. Helal, A.M. El-Nashar, E.S. Al-Katheeri and S.A. Al-Malek, Optimal design of hybrid RO/MSF desalination plants, Part I, Modelling and algorithms, Desalination, 154 (2003) 43–66.
[12] A.M. Helal, A.M. El-Nashar, E.S. Al-Katheeri and S.A. Al-Malek, Optimal design of hybrid RO/MSF desalination plants, Part II, Results and discussions, Desalination, 160 (2004) 13–27.
[13] M. Al-Sahali and H.M. Ettouney, Developments in thermal desalination processes, design, energy and costing aspects, Desalination, 214 (2007) 227–240.
[14] A.H. Khan, Desalination Processes and Multistage Flash Distillation Practice, Elsevier, New York, 1986.
[15] A. Ophir and F. Lokiec, Advanced MED process for most economical seawater desalination, Desalination, 182 (2005) 181–192.
[16] Water Desalination Technologies in the ESCWA Member Countries, UN Report, No. 01-0675, New York, 2001.
[17] R. Borsani and S. Rebagliati, Fundamentals and costing of MSF desalination plants and comparison with other technologies, Desalination, 182 (2005) 29–37.
[18] E. El Sayed, S. Ebrahim, A. Al-Saffar and M. Abdel-Jawad, Pilot study of MSF/RO hybrid systems, Third Gulf Water Conference WSTA, Vol. 2, Muscat, 1997, pp. 561–572.
[19] H. Ludwig, Hybrid systems in seawater desalination—practical design aspects, present status and development perspectives, Desalination, 164 (2004) 1–18.