Workshop on "Physics for Renewable Energy"
October 17 - 29, 2005

301/1679-10

---

# "Advanced Applications: Desalination"

**V. K. Sharma**
**TRISAIA Research Centre- Matera**
**Italy**

# WORSHOP ON PHYSICS OF RENEWABLE ENERGY

ICTP, Trieste Oct. 17-29, 2005

# SEAWATER DESALINATION

V.K. Sharma*, G. Fiorenza and G. Braccio

*e-mail: sharma@trisaia.enea.it

Trisaia Research Centre

# Table of contents

# Some data about water

**Water shortage**

involves more than 80 countries and 40% of the world population

around 25% has inadequate supply, both for quality and quantity

use of unhealthy water causes about 80% of all diseases and more than 30% of all deaths in developing countries

**Water needs**

daily consumption of fresh water per person is about 3 and 150 litres for alimentary and global domestic needs, in developed countries

this amount rises remarkably considering also industrial and agricultural needs

WHO estimates approx. 1,000 $m^3$ the yearly minimum quantity of fresh water per person to guarantee health and development

# Forecasts

forecasts for 2020

resources approximately constant

needs in remarkable growth

over 60% of humanity will be exposed to water shortage

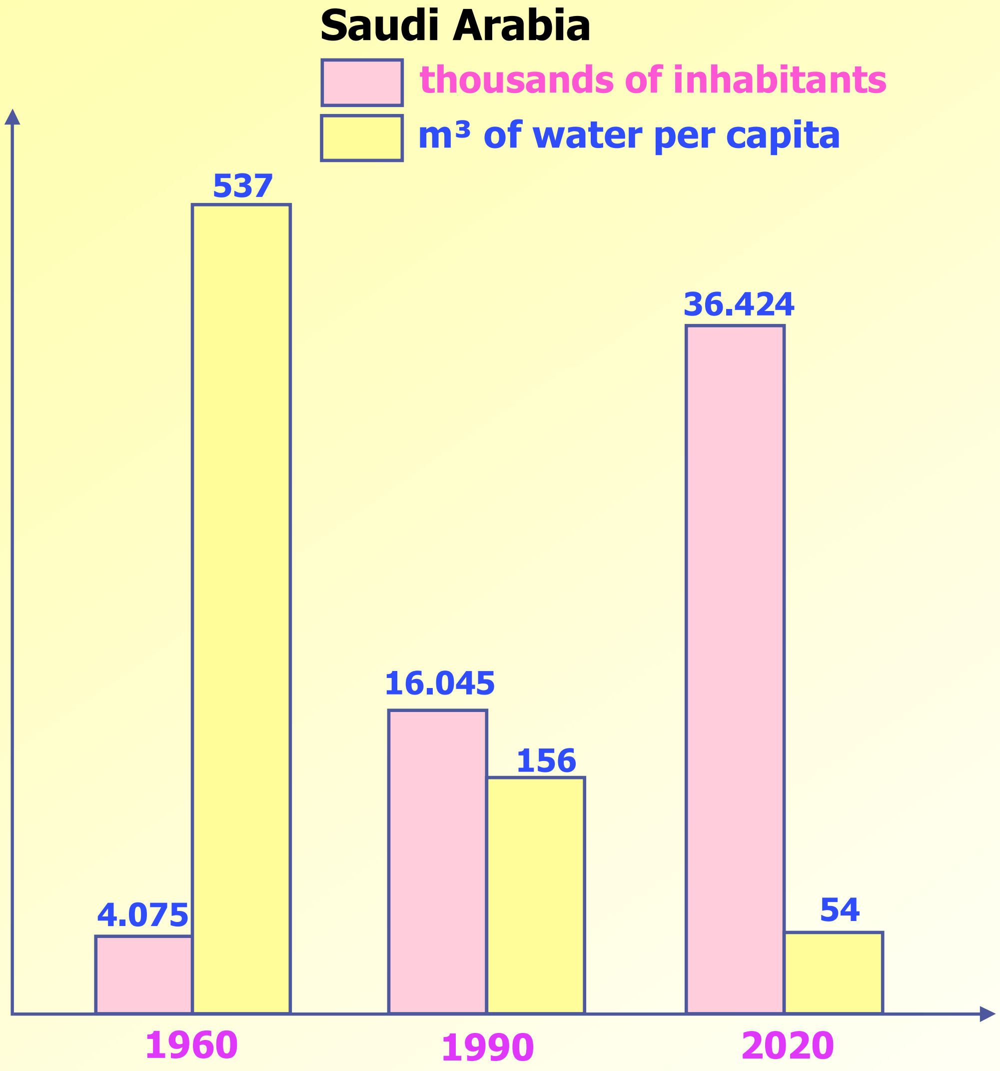
**main causes**

⇒ demographic growth, mostly concentrated in developing countries

⇒ further contamination of ground and surface water, as a result of industrial and urban development, still in developing countries

⇒ probable negative impact on precipitation of climatic changes

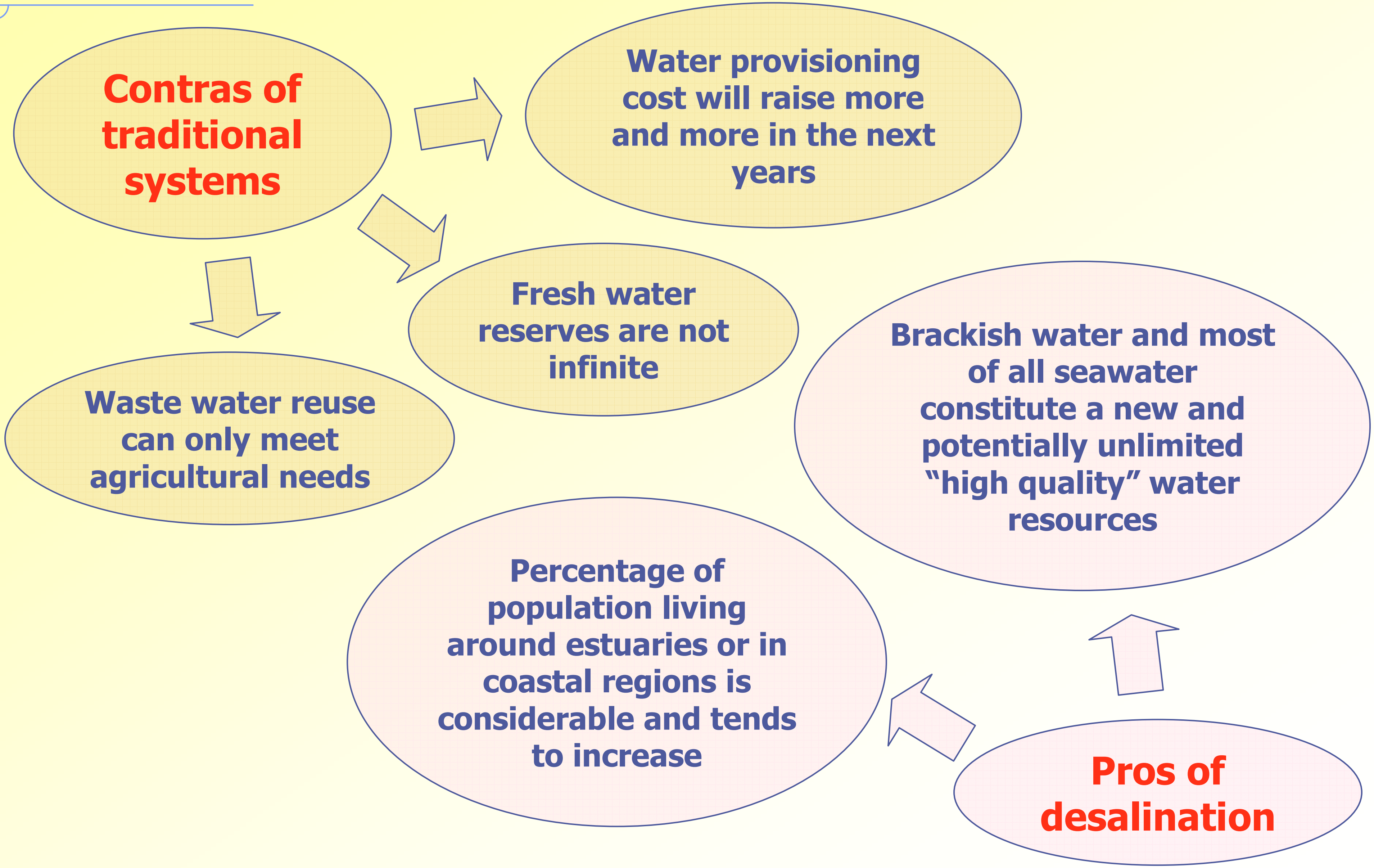
# Situation in Middle East and North Africa



WRI *"World Resources Report", 1997*

- A similar trend is observed for Libya, Yemen, Jordan, etc.
- In general situation is critical in all MENA (Middle East and North Africa) countries
- As on today, situation of water availability in Malta is very serious though no appreciable growth in population is foreseen for this country
- Though countries, such like Egypt or Morocco, which currently do not suffer a dramatic water shortage, in 2020, will be under the limits, fixed by WHO

# Reasons pro desalination



**Contras of traditional systems**

Water provisioning cost will raise more and more in the next years

Fresh water reserves are not infinite

Waste water reuse can only meet agricultural needs

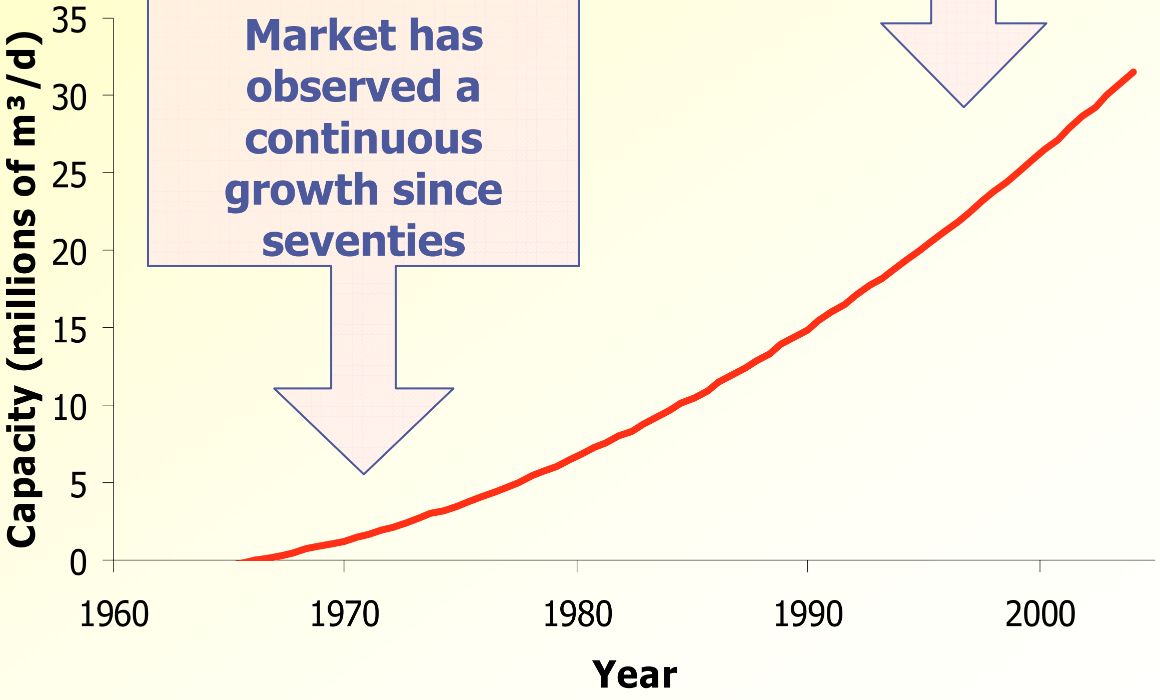
**Pros of desalination**

Brackish water and most of all seawater constitute a new and potentially unlimited "high quality" water resources

Percentage of population living around estuaries or in coastal regions is considerable and tends to increase

# The market

Currently about 15,000 desalination units are operating world-wide with a total capacity of over 32 millions m³/d



Market has observed a continuous growth since seventies

Growing trend has become more marked in recent years

**Expected trend**

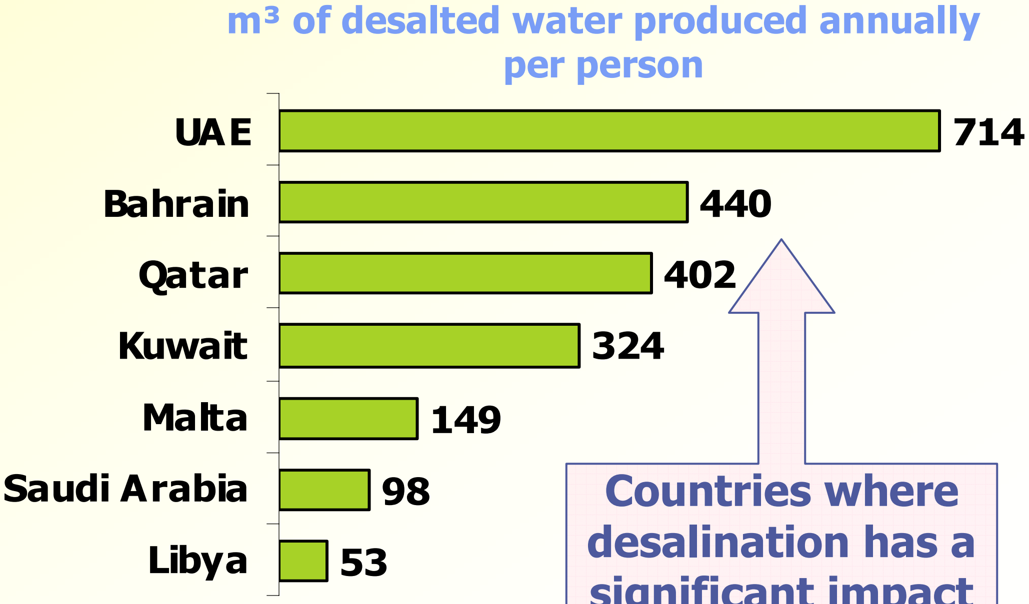
The desalination capacity contracted annually on average is 1 million m³/d which is equivalent to some $ 2,000 millions

*IDA "World-wide Desalting Plants Inventory" Report No.17, 2002*

# World-wide diffusion

- about 75% of the total world desalination capacity is held by 10 countries
- almost the 50% is concentrated in Middle East

| Country | Capacity [$10^3$ $m^3/d$] | World share [%] |
|---|---|---|
| Saudi Arabia | 5922 | 18.3 |
| USA | 5172 | 16.0 |
| UAE | 4929 | 15.2 |
| Kuwait | 2160 | 6.7 |
| Spain | 1864 | 5.8 |
| Japan | 1192 | 3.7 |
| Qatar | 821 | 2.5 |
| Bahrain | 784 | 2.4 |
| Libya | 748 | 2.3 |
| Italy | 743 | 1.8 |



Countries where desalination has a significant impact on water needs

# Desalination technologies

**Distillation processes**

Drinking water is generated by evaporation and successive condensation of the feed water

- ⇒ multi-stage flash (MSF)
- ⇒ multiple effect evaporation (MEE)
- ⇒ mechanical vapor compression (MVC)

Liquid to vapour passage
(Thermal process)

**Membrane processes**

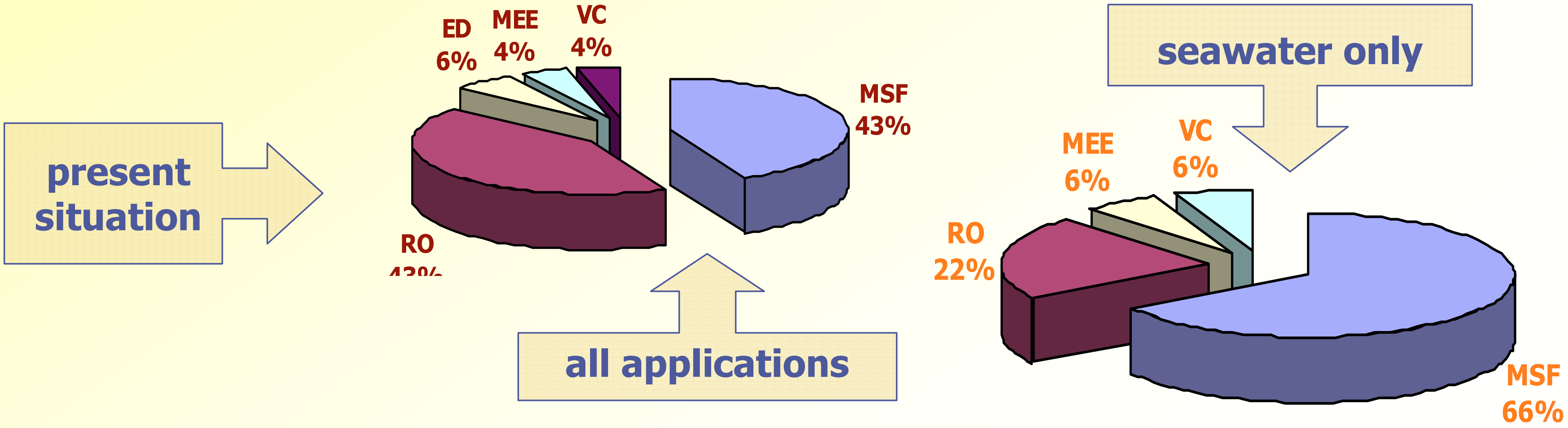
Drinking water is generated by separation of salt from the feed water due to the passage through specific membranes

- ⇒ reverse osmosis (RO)
- ⇒ electrodialysis (ED)

No phase change
(Membrane technologies)

# Market share

- ⇒ Over 65% of all applications concerns seawater desalination
- ⇒ MSF and RO cover together almost the 90% of market whether considering all applications or seawater only
- ⇒ ED is significant only for brackish water desalination due to its technological constraints
- ⇒ Analogous reasons limits the application of RO for seawater desalination
- ⇒ MEE and MVC are applied on a minor scale mainly for seawater desalination


present situation

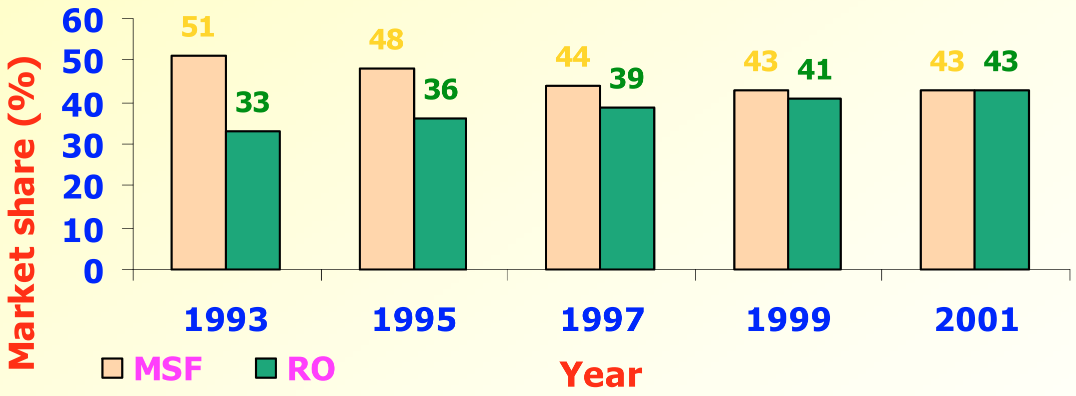
all applications

seawater only

# The trend

- ✓ RO growing trend is more marked than whole desalination market and MSF
- ✓ RO is expanding steadily also for seawater applications only: in 1999 its market share was of 18% versus 70% of MSF

| | Total capacity share (%) | | | | |
|---|---|---|---|---|---|
| **Country** | **MSF** | **MEE** | **MVC** | **RO** | **ED** |
| Saudi Arabia | 64.2 | 0.3 | 1.4 | 32.3 | 1.8 |
| USA | 1.3 | 4.4 | 6.3 | 74.5 | 13.5 |
| UAE | 87.1 | 0.2 | 9.2 | 3.4 | 0.1 |
| Kuwait | 88.9 | 0.7 | 0.0 | 10.0 | 0.3 |
| Spain | 4.5 | 3.5 | 2.8 | 84.3 | 4.9 |

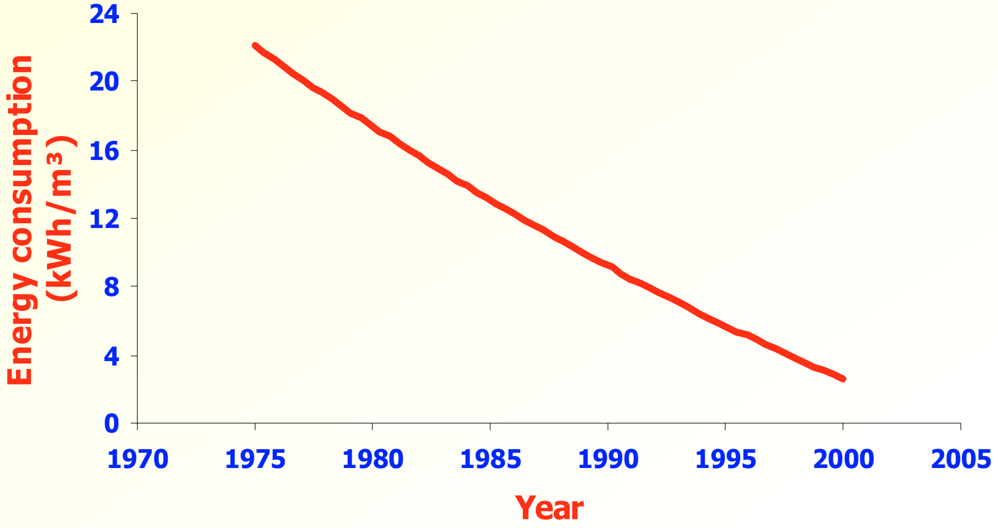


- ✓ MSF demand is mostly supported by MENA countries partly due to techno-economic factors (working conditions, fuel availability) but above all to highly salty water (average 47000 ppm and as high as 90000/95000 ppm)

# Desalination barriers

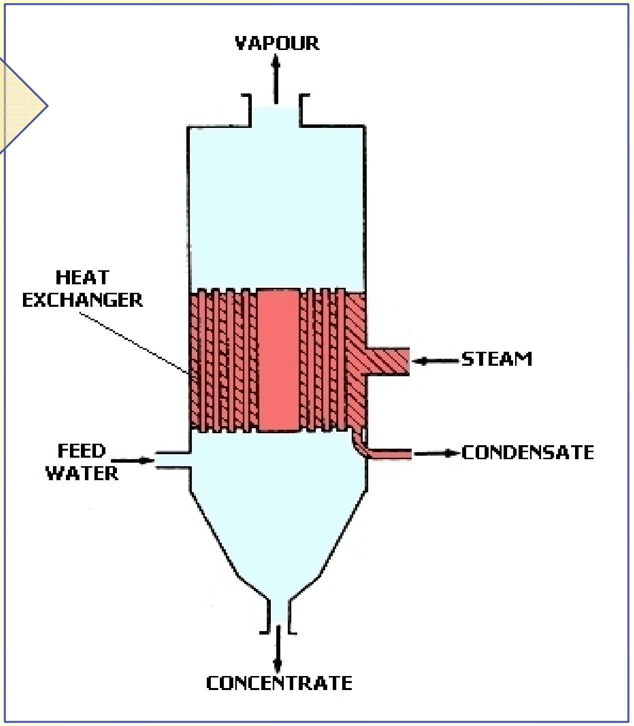
- ⇒ Brackish or seawater must be easily accessible
- ⇒ Advanced processes need a considerable know-how
- ⇒ Construction and running of the plant have a significant impact on the environment
- ⇒ A vast initial investment is required
- ⇒ Water production cost is markedly higher than traditional provisioning value in ordinary conditions
- ⇒ Energy must be available in large amounts and at a reasonable price

Equivalent electric energy consumption with the best available technology of the time has strongly decreased through the years but still remains a noteworthy value

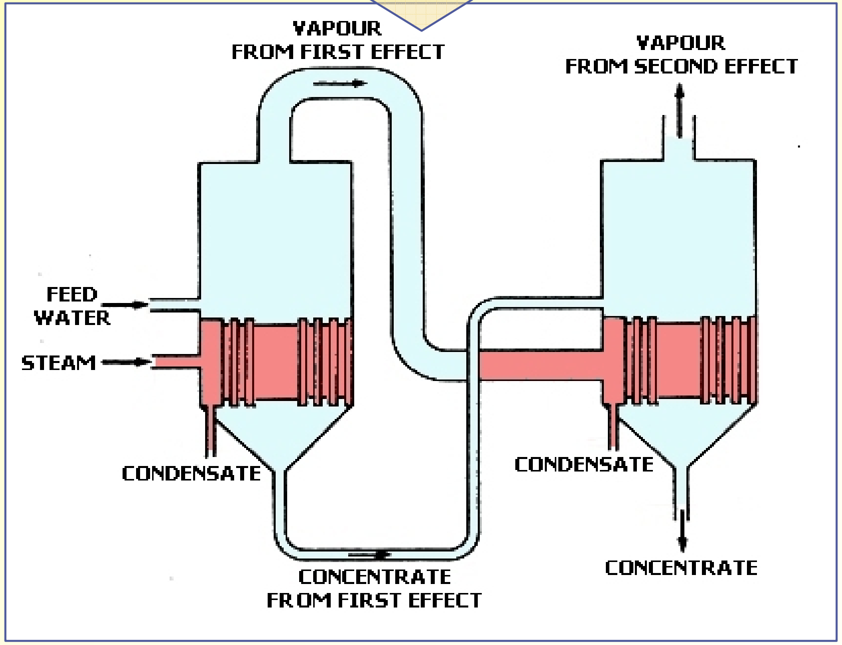


# Multiple Effect operation principle

A single-effect evaporator is essentially a heat exchanger in which feed seawater is boiled to give a vapour almost devoid of salt. Required heat is supplied by the condensation of the motive steam



The low pressure steam generated by the evaporator can be used for further heating in a following effect

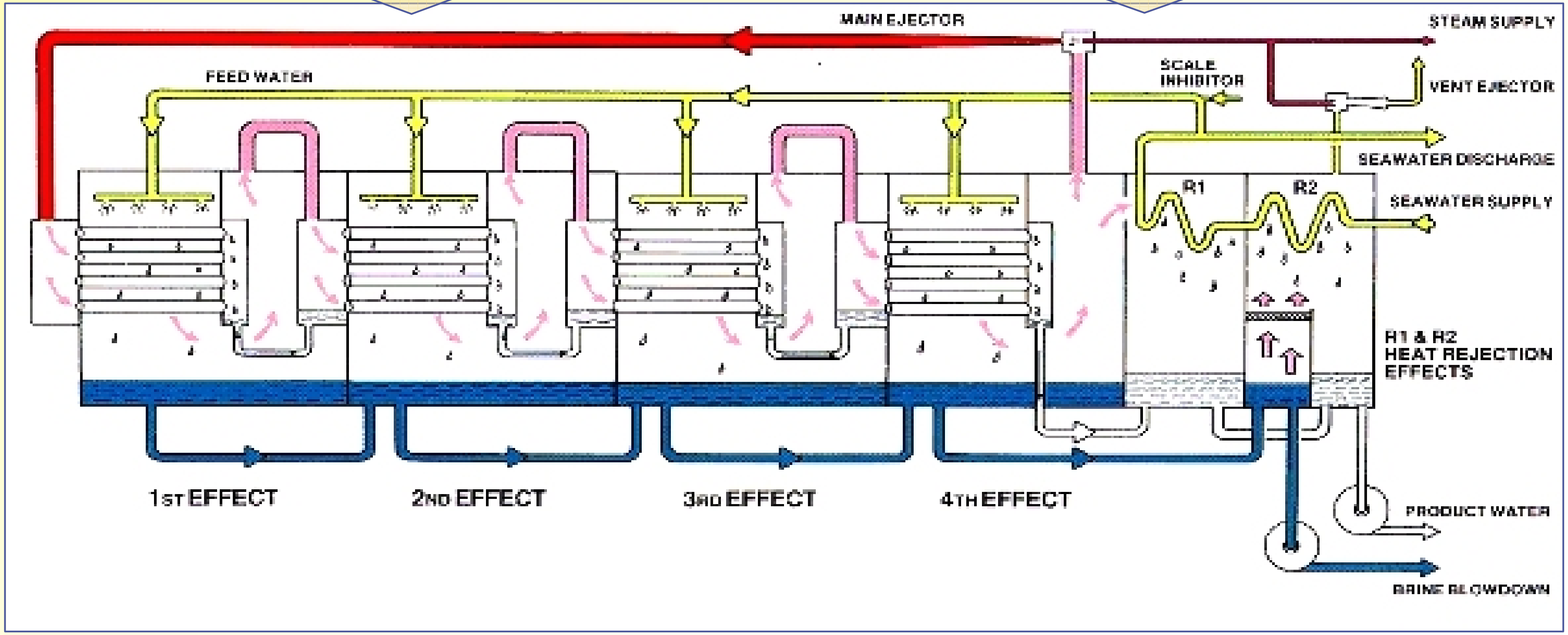


The evaporation in the second effect via the steam provided by the first one requires a lower boiling temperature and hence a minor pressure, so the feed water evaporates in a minor part also by flashing

# Limitations of MEE process

The seawater, after being pre-heated, is either sprayed or otherwise distributed in a thin film over the surface of the evaporator tubes, in order to promote rapid boiling and evaporation

This generates an upper limit for the top brine temperature: in fact precipitation of $CaCO_3$ takes place over 63 °C with scale formation on the tubes and drastic reduction of the heat transfer coefficient



# Efficiency of MEE process

⇒ **heat is entirely transferred from the motive steam to the feed seawater only in an ideal evaporator with an infinite area: in this hypothesis the outlet temperature of produced vapour would be equal to the inlet temperature of steam**

⇒ **during the evaporation, the remaining liquid becomes more and more concentrated: the boiling point rises and the available temperature drop decreases; in addition the viscosity increases too, reducing circulation and the heat transfer coefficient**

**Process economics is characterised by the performance ratio PR:**

$$PR = \frac{\dot m_D}{\dot m_S}$$

$$\dot m_D = \sum_1^N {}_i\dot D_i + \sum_2^N {}_i\dot d_i$$

**mass of vapour formed by boiling/flashing in the i<sup>th</sup> stage depends on previous values and hence on the performance ratio:**

**an iterative algorithm must be used**

**main parameters:**

- **number of effects**
- **temperature of the motive steam**

$$\rightarrow \quad PR = f\left(N, T_S\right)$$

# Equations for the evaluation of PR

**mass balances**

**water**

$$\dot m_F = \dot m_D + \dot m_B$$

distillate is around 40% of feed seawater

**salt**

$$\dot m_F X_F = \dot m_B X_B$$

salt concentration of brine is imposed to 70,000 ppm by scale formation of $CaSO_4$

**energy balance on the 1st effect**

vapour flow rate generated in the 1st effect is about 50÷60% of the motive steam flow rate

$$\dot m_S \lambda_S = \dot m_F c_p (T_S + \Delta T_{BPE} + \Delta T_{loss} - T_1) + \dot D_1 \lambda_1$$

**mass of vapour formed in the ith effect**

**boiling**

$$\dot D_i = \frac{\dot D_{i-1} \lambda_{i-1}}{\lambda_i}$$

almost constant

decreases slightly (10÷20% of the heating steam in the 2nd effect)

**flashing**

$$\dot d_i = \left( \dot m_F - \sum_{1}^{i-1}{}_j \dot D_j - \sum_{2}^{i-1}{}_j \dot d_j \right) c_p \frac{T_{i-1} - \left(T_i + \Delta T_{BPEi}\right)}{\lambda_i}$$

# Calculation of thermal energy need

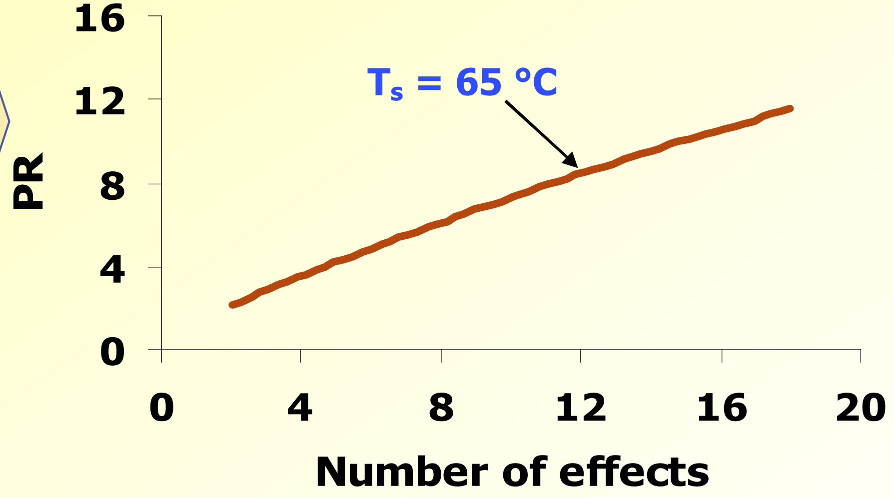
As can be seen form the figure, fFor a given TS, PR is approx. a linear function of N.

$$PR = (0.7 \div 0.8)N$$

In theory a high number of effects may be included, but, the $\Delta T_{tot}$ being limited, this would lead to a drastic reduction in stage $\Delta T$ and consequently to an intolerable growth of heat transfer area:

$$\Delta T_{st} = \frac{\Delta T_{tot}}{N} = \frac{\dot m_S h_v}{U_D A}$$

PR value is drawn from the optimal trade-off point between investment and steam economy



**Example:**

$T_S$ = 65 °C
N = 12
$X_S$ = 42,000 ppm
$X_B$ = 70,000 ppm

$T_1$ = 60 °C
$\Delta T_{BPE}$ = 2 °C
$\Delta T_{loss}$ = 2 °C
$\Delta T_{BPEi}$ = 1 °C

PR = 8.7

thermal energy per m$^3$ of water

$$E_{th} = \frac{Q}{\dot V_D} = \frac{\lambda_s \rho_D}{3600\ \ PR}$$

$E_{th} = 2.35\cdot10^3/(3.6\cdot8.7) = 75$ kWh/m$^3$

# Techno-economic characterization

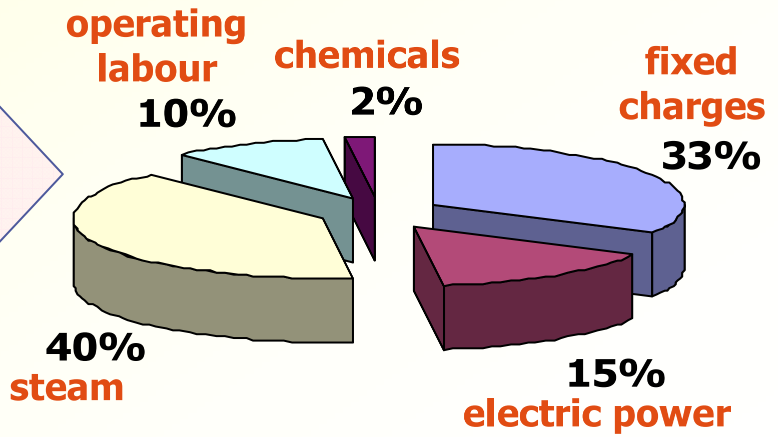
technical features of multiple effects evaporation process

| | |
|---|---|
| Form of energy required | steam |
| Operating temperature | < 70 °C |
| Number of effects | 8 ÷18 |
| Gain Output Ratio | 6.5 ÷14 |
| Thermal energy consumption | 45 ÷90 kWh/$m^3$ |
| Electrical energy consumption | 1 ÷2 kWh/$m^3$ |
| TDS content of feed water | 30,000 ÷100,000 ppm |
| Product water quality | < 10 ppm |
| Single-unit capacity | 500 ÷12,000 $m^3$/d |

economic aspects

- Direct capital cost is around 1,600 \$/($m^3$/d) for a 12,000 $m^3$/d plant
- Cost is strongly sensitive to the system size
- Product water can reach values lower than 1.1 \$/$m^3$

Typical water cost sharing



# Vapour Thermo-Compression in MEE

## Operational principle:

1. a relatively high pressure steam is expanded in an nozzle to high velocity and low pressure thus entraining the vapour generated in the evaporator
2. both streams flows towards the lowest pressure spot and mix together in a violent and rapid manner
3. the mixture flows through the diffuser section, slows down and the discharge pressure rises to a value between motive and suction pressure

$$\dot{m}_D = (N - 1)\dot{m}_{HS} + (\dot{m}_{HS} - \dot{m}_{EV})$$

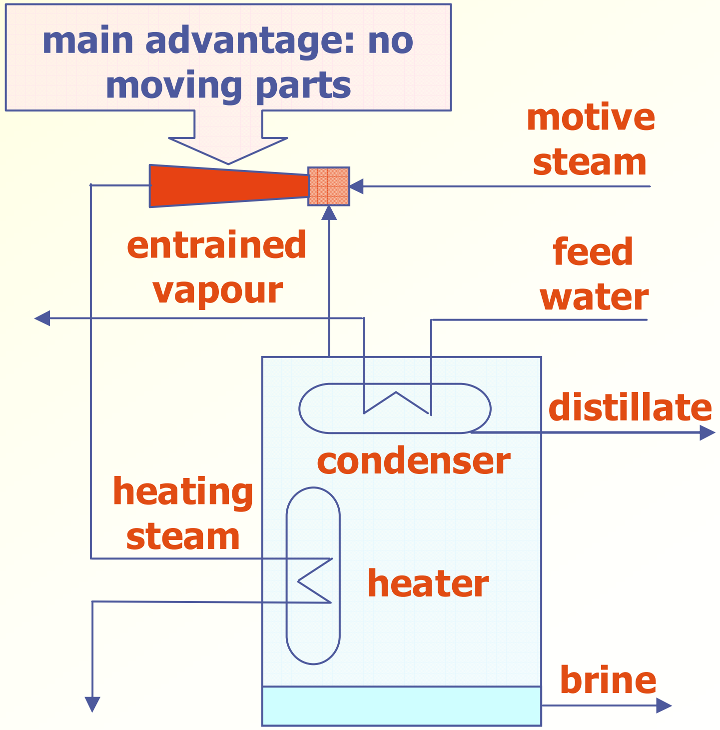
$$PR = N\left(1 + w - \frac{w}{N}\right) \Rightarrow w = \frac{\dot{m}_{EV}}{\dot{m}_{MS}}$$

$$\swarrow$$

depends on the motive steam pressure, evaporator pressure and the discharge pressure (a special diagram is available for the calculation)

**example:** $p_{MS}$ =10 bar, $T_{EV}$ = 50 °C,
$p_{HS}$ = 2 bar, $T_{HS}$ = 70 °C → w = 1.25

N = 4 → PR = 4·(1+1.25-0.31) = 7.8



main advantage: no moving parts

# Example of operative plant

Location: Jebel Dhanna (UAE)

Capacity: 9,000 m³/d

Layout: 2 units of 4 effects each

**Design:**

- thermal vapor compression
- horizontal tube
- once through

Efficiency:

PR = 9

at a top brine temperature of 62 °C

Heat source:

gas fired boiler

# Expected developments

**recent trends**

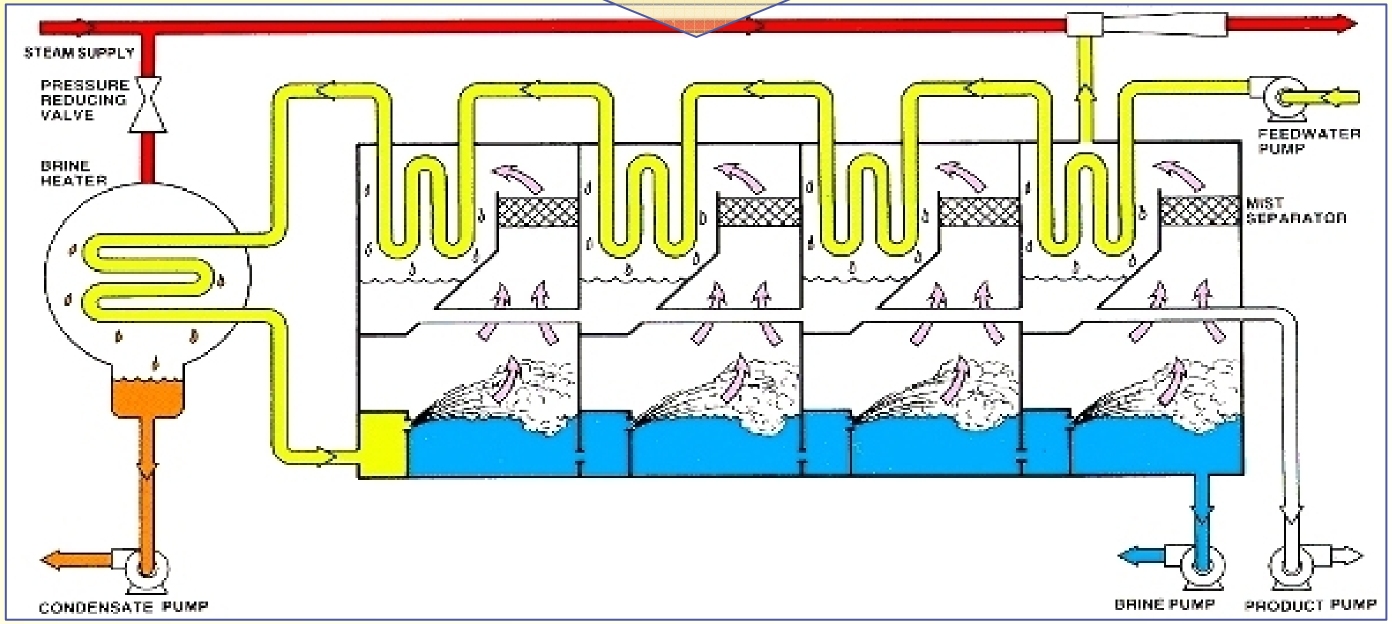
- increase in the unit capacity, by prevailing over technological barriers, such like pumps size limitations, tubes materials and dimensions thus obtaining better process economics
- high corrosion resistance materials for evaporators, such like titanium and aluminum brass, replacing traditional copper/nickel and stainless and carbon steel

**research topics**

- combination with absorption or adsorption heat pumps to boost the gain output ratio
- development of solutions, such like hybrid nanofiltration/MEE system, antiscalant materials, for operating at higher temperature
- reducing the number of pumps, main causes of electric power consumption
- plastic construction materials, with advantages related to cost, lightness, resistance to chemical attack and mechanical erosion, machining, LCA

# Multi-Stage Flash operation principle

1. Feed seawater is warmed up by the motive steam in the “brine heater”, then flows through several chambers, where the ambient pressure is so low that it immediately starts to boil, almost “flashing” into steam
2. Generally, only a small percentage of water is converted to steam in a single stage, depending on the pressure, since evaporation will continue only until the water cools down to the boiling point
3. The steam generated by flashing is condensed and thus converted to fresh water through the heat exchange with the incoming feed water going to the brine heater which is consequently pre-heated



# Efficiency of MSF process

→ heat exchanger is not immersed in the brine, therefore no limitation due to CaCO3 precipitation is present

→ heating steam highest temperature (currently up to 120 °C) is imposed by the type of chemical additive used to control scale formation

→ evaporation of water occurs rapidly in non-equilibrium conditions, so additional losses must be taken into account

**Expression of PR for a once-through MSF desalination system:**

$$PR = \frac{N \Delta T_{st} \lambda_s}{(\Delta T_{st} + TTD_{st} + \Delta T_{loss})\bar{\lambda}_v}$$

Conventional MSF is the brine recirculation system, leading to significant reduction in the flow rate of feed water (chemicals consumption and pre-treatment facilities size are cut down)

**Example:**

$T_s$ = 100 °C
$TTD_{bh}$ = 10 °C
$\Delta T_{tot}$ = 50 °C
N = 24
$\Delta T_{st}$ = 2.1 °C
$TTD_{st}$ = 3 °C
$\Delta T_{loss}$ = 2 °C
$\lambda_s = 2.26 \cdot 10^3$ kJ/kg (at 100 °C)
$\bar{\lambda}_v = 2.35 \cdot 10^3$ kJ/kg (at 65 °C)

**PR = 6.8**

**$E_{th}$ = 92 kWh/m$^3$**

# Techno-economic characterization

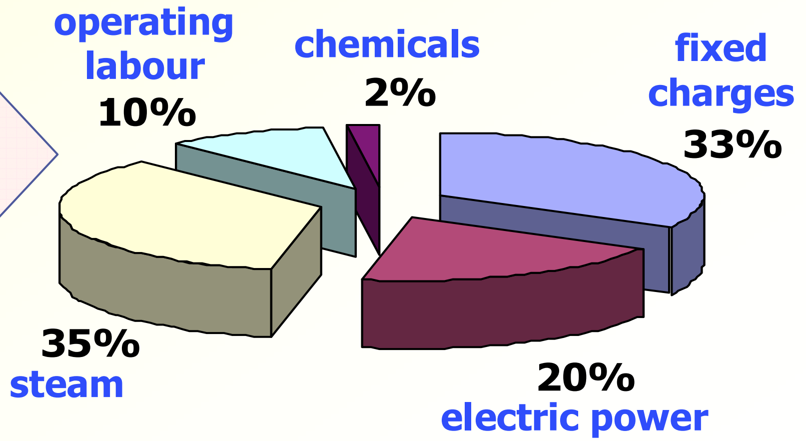
technical features of multi-stage flash process

| | |
|---|---|
| Form of required energy | steam |
| Operating temperature | < 120 °C |
| Number of stages | 20 ÷36 |
| Gain Output Ratio | 6 ÷10 |
| Thermal energy consumption | 60 ÷120 kWh/m³ |
| Electrical energy consumption | 3 ÷4 kWh/m³ |
| TDS content of feed water | 30,000 ÷100,000 ppm |
| Product water quality | < 10 ppm |
| Single-unit capacity | 5,000 ÷60,000 m³/d |

economic aspects

- Direct capital cost is around 1,600 $/(m³/d) for a 60,000 m³/d plant
- Cost is deeply affected by the plant size
- Product water can reach values lower than 1.2 $/m³

Typical water cost sharing



# Example of operative plant

Location: Al Taweelah (UAE)

Capacity: 342,000 m³/d

Layout: 6 units of 20 stages each

Design:

- single tier
- cross tube
- brine recycle

world-largest distiller until 2003

Efficiency:

PR = 8

at a top brine temperature of 100 °C

Heat source:

combined cycle with extraction/ condensing turbine

# Vapour Compression working principle

✓ Vapour Compression is a thermal process where the heat required to evaporate the seawater comes from the compression of vapour instead of the direct exchange with the motive steam

✓ Two primary devices are used to boost the vapour pressure and temperature so as to generate the heat: a mechanical compressor or a steam ejector

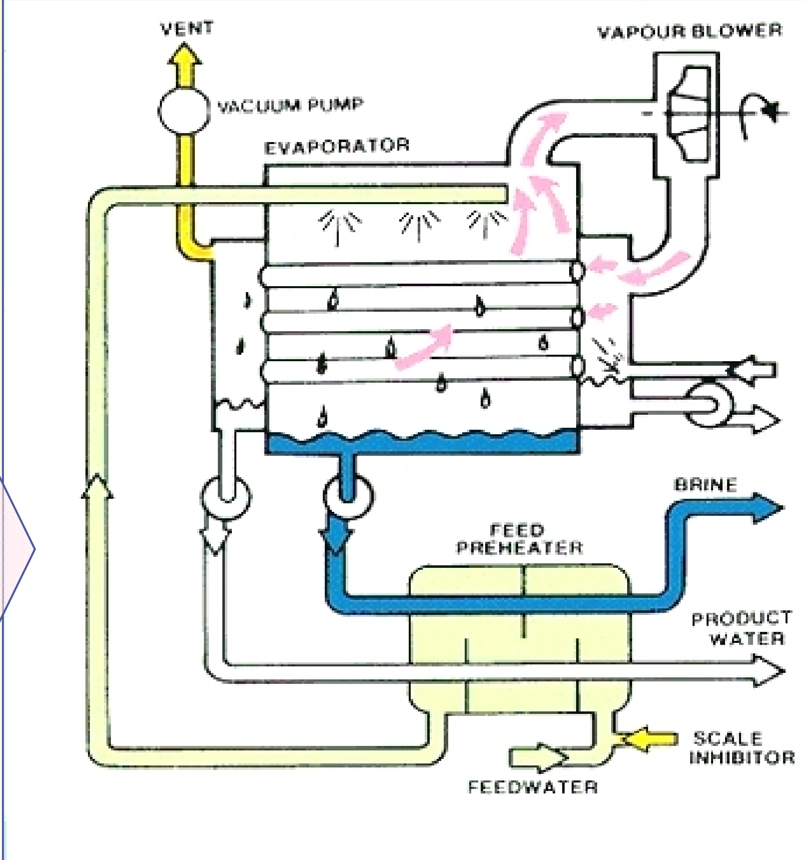
The mechanical compressor is usually electrically driven, thus enabling the sole use of electrical power to produce water by distillation

<u>In a simplified method for MVC:</u>

⇒ the compressor aspirates the vapour from the vessel, compresses and condenses it inside a tube bundle in the same stage

⇒ seawater is sprayed on the outside of the tubes at the point where it boils and partially evaporates

⇒ vapour is condensed via the heat exchange with the incoming feed water which is consequently pre-heated



# Techno-economic characterization

**Example:**

$$\frac{E}{\dot{V}_D} = \frac{\rho_D \left(h_s - h_v\right)}{3600\ \eta_C}$$

- $\Delta h$ is the isoentropic enthalpy drop
- $\eta_C$ the compressor efficiency (0.8)

$T_v$ = 55 °C
$h_v$ = 2,601 °C

$T_S$ = 70 °C
$h_S$ = 2,629 °C

E = 28/(3.6·0.8) = 10 kWh/m³

**technical features of mechanical vapour compression process**

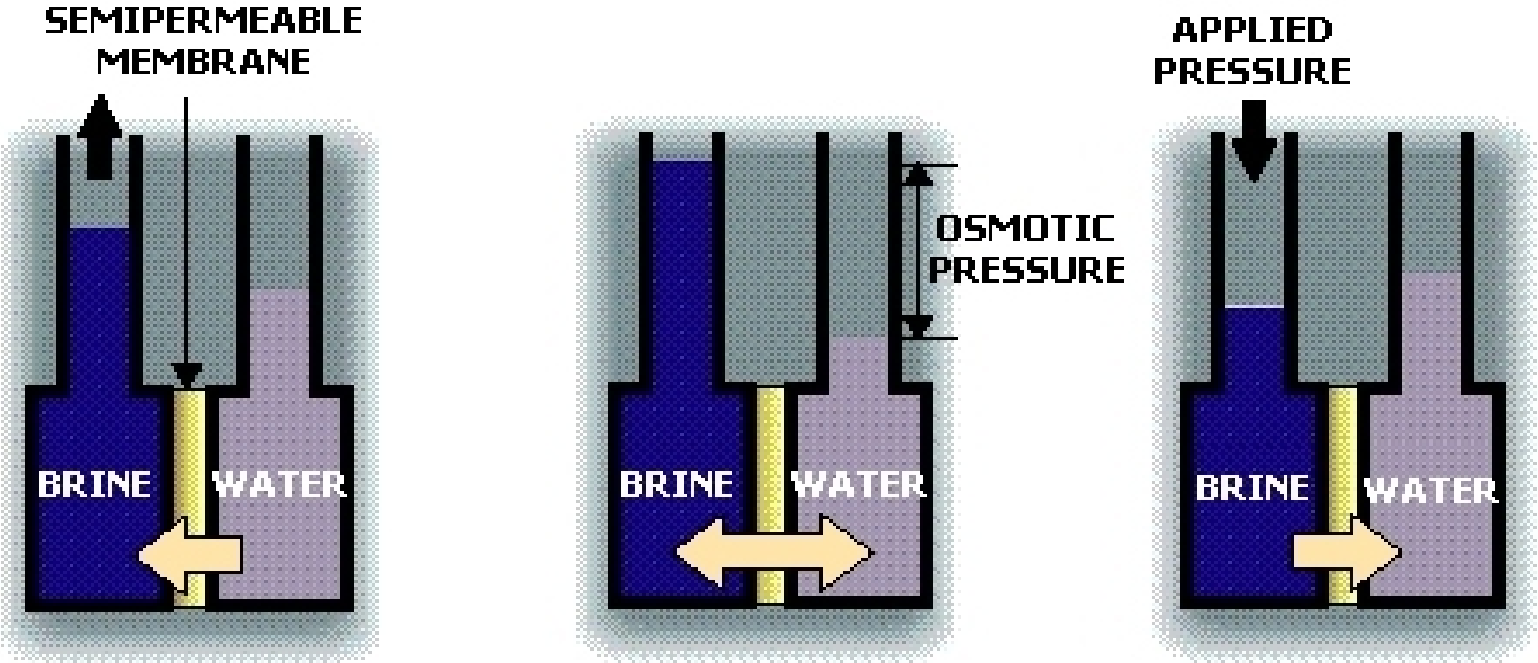
| | |
|---|---|
| Form of required energy | mechanical |
| Operating temperature $^{(*)}$ | < 70 °C |
| Electrical energy consumption | 8 ÷14 kWh/m³ |
| TDS content of feed water | 30,000 ÷50,000 ppm |
| Product water quality | < 10 ppm |
| Single-unit capacity | 10 ÷2,500 m³/d |

(*) in exceptional cases with acid dosing up to 100 °C

**economic aspects**

- Direct capital cost is around 1,000 $/(m³/d) for a 1,000 m³/d plant
- Cost varies considerably due to the wide range of usable capacities
- Product water can reach values lower than 0.9 $/m³

# Reverse Osmosis working principle



**OSMOSIS**

Water flows from lower to higher salt concentration

**EQUILIBRIUM**

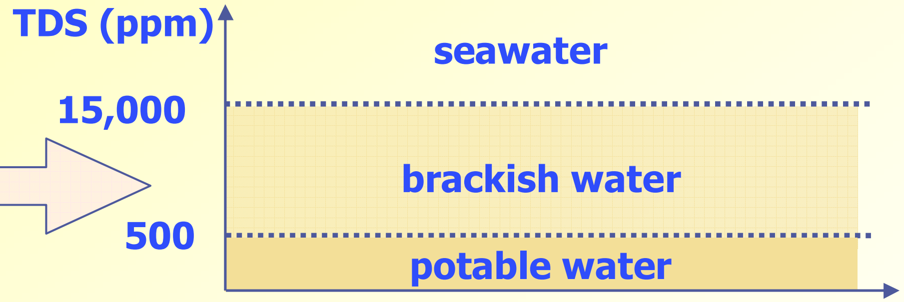
Pressure required to stop water flow reaching equilibrium is defined as *osmotic pressure*

**REVERSE OSMOSIS**

Flow is reversed from higher to lower salt concentration by applying a pressure adequately greater than osmotic pressure

# Water salinity impact on RO

- ⇒ Water is classified according to Total Dissolved Solids content
- ⇒ WHO has fixed an upper limit of 500 ppm for potable water



$$\pi = RT\sum_i X_i$$

$\pi$ = osmotic pressure, kPa

T = temperature, K

$X_i$ = concentration of the single constituent, kgmol/m³

R = universal gas constant, 8.314·kPam³/kgmol·K

**Rough estimation**

**1000 ppm of TDS**

↓

$\pi$ = **0.76 kPa**

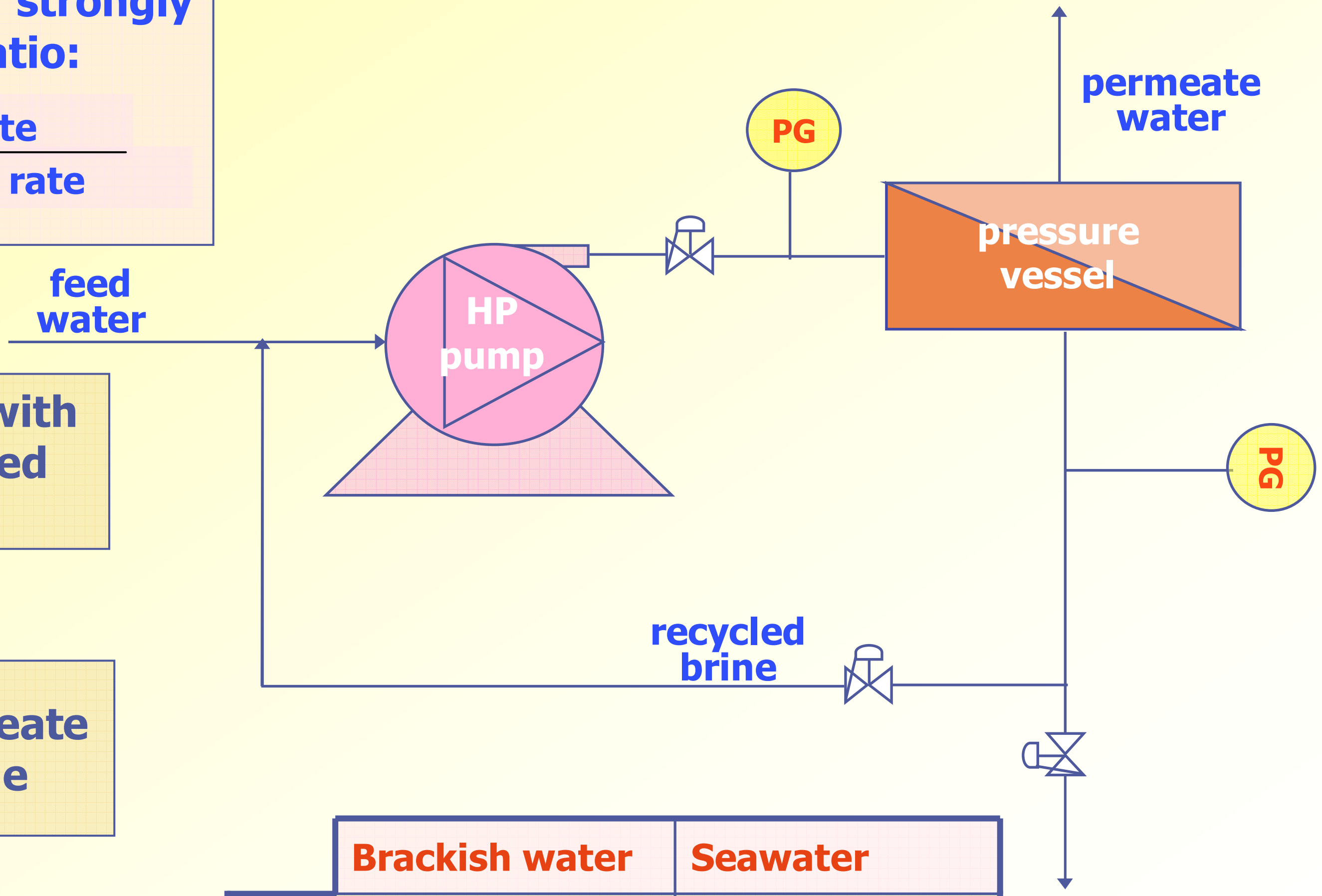
| Sea | TDS | $\pi$ |
|---|---|---|
| Atlantic Ocean | 37,000 | 28 |
| Mediterranean Sea | 41,000 | 31 |
| Arabic Gulf | 47,000 | 36 |

**Value must be adequately increased to take into account high seawater temperature (up to 35 °C)**

# Energy consumption in reverse osmosis

Process economics is strongly affected by the recovery ratio:

$$\varphi = \frac{\text{feed water flow rate}}{\text{permeate water flow rate}}$$



Recovery ratio increases with permeate salinity and feed pressure

⇓

Excessive salinity of permeate water makes it unusable

⇓

High feed pressure causes a dramatic growth in specific energy consumption

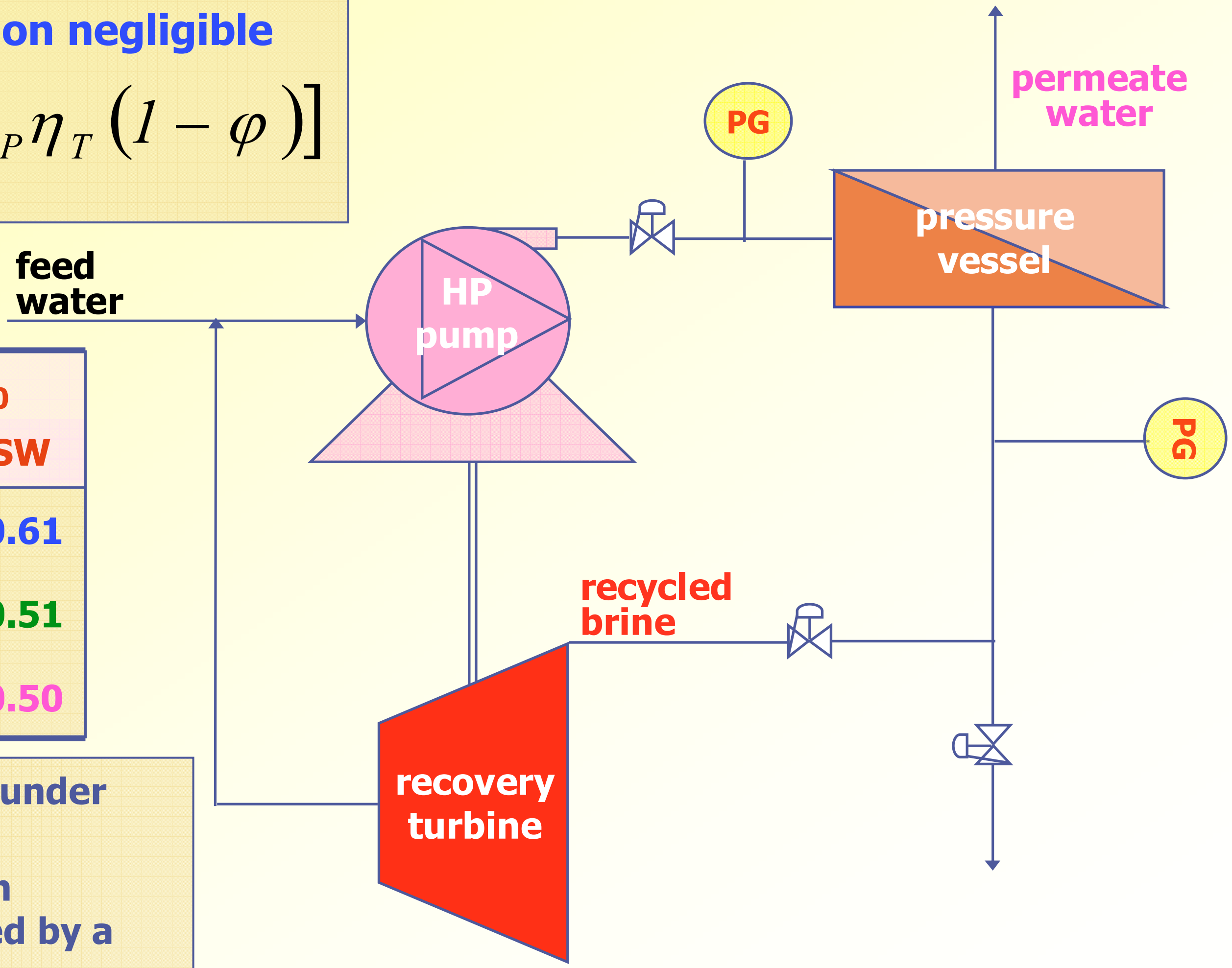
| | Brackish water | Seawater |
|---|---|---|
| $\varphi$ | 0.7 ÷0.8 | 0.3 ÷0.4 |
| p | 5÷30 bar | 60÷90 bar |
| E | 0.5÷3 kWh/$m^3$ | 5÷12 kWh/$m^3$ |

# Energy recovery devices

**Assumption:**
**pressure losses due to friction negligible**

$$\frac{E}{\dot{V}_P} = \frac{\Delta p}{3600\ \eta_P \varphi}\left[1-\eta_P\eta_T\left(1-\varphi\right)\right]$$

| Device | $\eta_P$ | $\eta_T$ | $E/E_0$ | |
|---|---|---|---|---|
| | | | BW | SW |
| Francis Turbine | 0.70 | 0.80 | 0.83 | 0.61 |
| Pelton Wheel | 0.75 | 0.85 | 0.81 | 0.51 |
| Pressure Exchanger | 0.75 | 0.95 | 0.79 | 0.50 |



**Recently developed and currently under application**

**Direct pressure transfer from high pressure brine to low pressure feed by a rotor**

**Pressure difference to correct hydraulic losses supplied by booster pump**

**Reduction in specific energy consumption up to less than 3 kWh/m³**

# Techno-economic characterization

**technical features of reverse osmosis process**

| | |
|---|---|
| Form of required energy | mechanical |
| Electrical energy consumption (*) | 4 ÷7 kWh/$m^3$ |
| TDS content of feed water | 1,000 ÷45,000 ppm |
| Product water quality | < 500 ppm |
| Operating temperature | < 45 °C |
| Single-train capacity (**) | 1 ÷10,000 $m^3$/d |

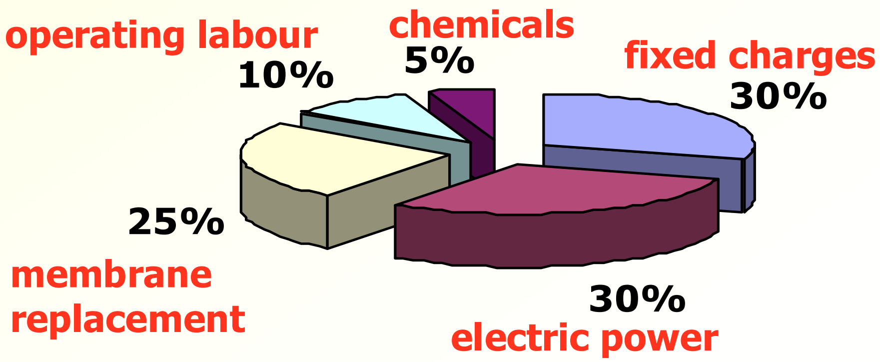
(*) seawater as feed water, lower consumption for brackish water

(**) global capacity far above 100,000 $m^3$/d for multi-trains arrays

**economic aspects**

- Direct capital cost is around 1,000 \$/($m^3$/d) for a 10,000 $m^3$/d plant
- Cost is not much affected by the size thanks to the modular configuration
- Product water can reach values lower than 0.7 \$/$m^3$

**Typical water cost sharing**



# Example of operative plant

**Location: Al Jubail (Saudi Arabia)**

**Capacity: 90,920 $m^3/d$**

**Layout: 15 parallel trains of 205 modules each**

**Design:**

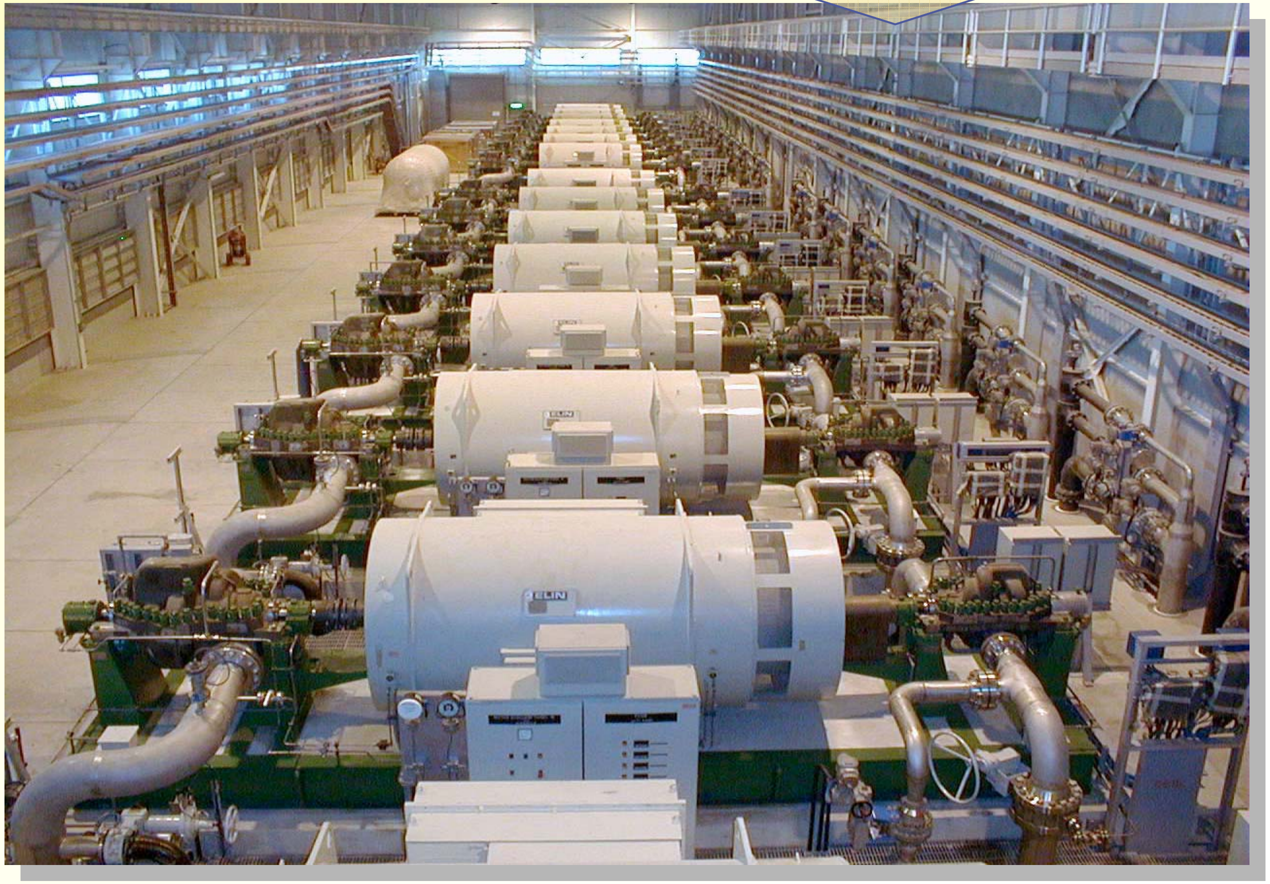
- single pass
- hollow fiber membranes
- energy recovery: Francis Turbine

**Operational parameters:**

- $\varphi = 35\%$
- $p_{max} = 82$ bar
- T = 25 °C
- TDS< 450 mg/l
- $Cl^- < 250$ mg/l

**Specific energy consumption:**

**5 $kWh/m^3$**



# Expected developments

**recent trends**

- continuous increase in the total plant capacity, by augmenting the number of vessels per bank and the number of parallel banks, to meet larger demands with economies of scale
- development of a new generation of membranes having higher salt rejection, recovery rate, mechanical strength, and chemical resistance

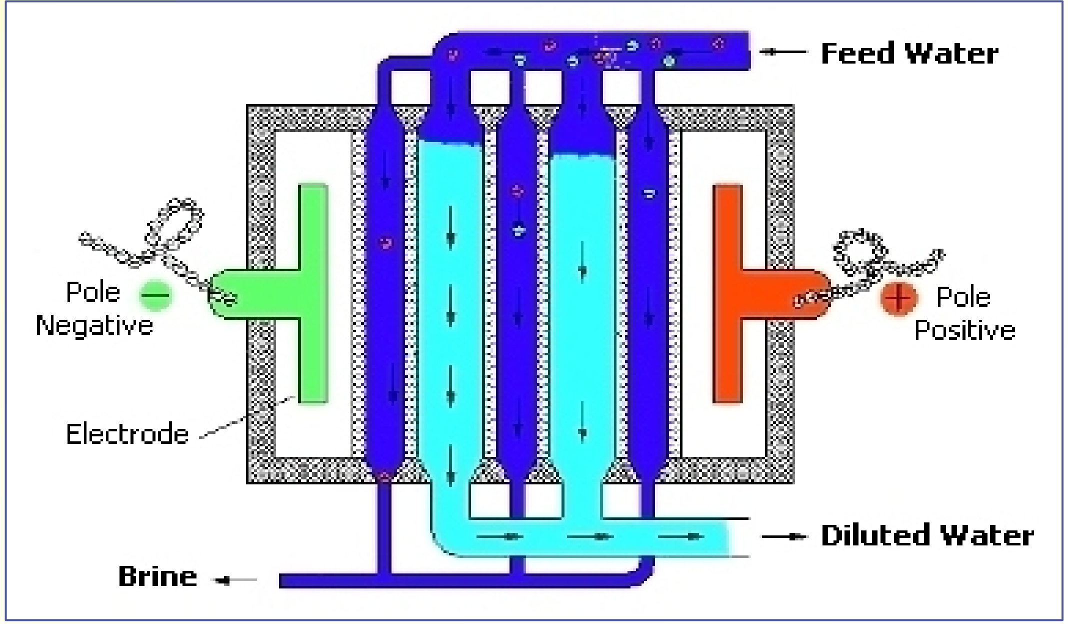
**research topics**

- innovative composite materials for the achievement of low fouling membranes
- on line regenerating membranes for the pretreatment of raw water
- advanced energy recovery devices matching high efficiency and low cost

# Electrodialysis operation principle

1. The dissolved ionic constituents in a saline solution ($Na^+$, $Cl^-$, $Ca^{++}$, $CO_3^{--}$) are dispersed in water, effectively neutralising their individual charges
2. When electric current is carried through the solution by means of a source of direct current, the ions tend to migrate to the electrode with the opposite charge
3. Water desalination is obtained by placement of membranes between a pair of electrodes that will allow either cations or anions (but not both) to pass

- Membranes are arranged alternatively (anion-selective followed by cation-selective) so as to create concentrated and diluted solutions in the spaces between (cells)
- A cell pair consists of the dilute cell from which the ions migrate and the concentrate cell in which the ions are trapped



# Techno-economic characterization

$$E = E_{ion} + E_{pump}$$

$$\frac{E_{ion}}{\dot{V}_D} = \frac{RI^2}{\dot{V}_D}$$

$$I = \frac{\mathbf{F}\,\dot{m}_D\,\Delta X}{MW\,\varepsilon N}$$

- F is the Faraday constant (96,480 C/mol)
- molecular weight can be assumed as for the sole NaCl (58.4 g/mol)
- efficiency of the ED unit is typically 0.8 ÷0.9
- N is the number of cell pairs in the stack

- contribution of pumping is generally modest
- power consumption is on average 1 kWh at 1,500 ppm TDS
- energy need is roughly a quadratic function of salt concentration
- use of ED becomes too energy consuming over 5,000 ppm

technical features of electrodialysis process

| | |
|---|---|
| Form of required energy | electrical |
| Electrical energy consumption (*) | 0.8 ÷10 kWh/$m^3$ |
| TDS content of feed water | 100 ÷5,000 ppm |
| Product water quality | < 500 ppm |
| Operating temperature | < 45 °C |
| Single-train capacity | 1 ÷12,000 $m^3$/d |
| (*) strongly depending on salt content in raw water | |

economic aspects

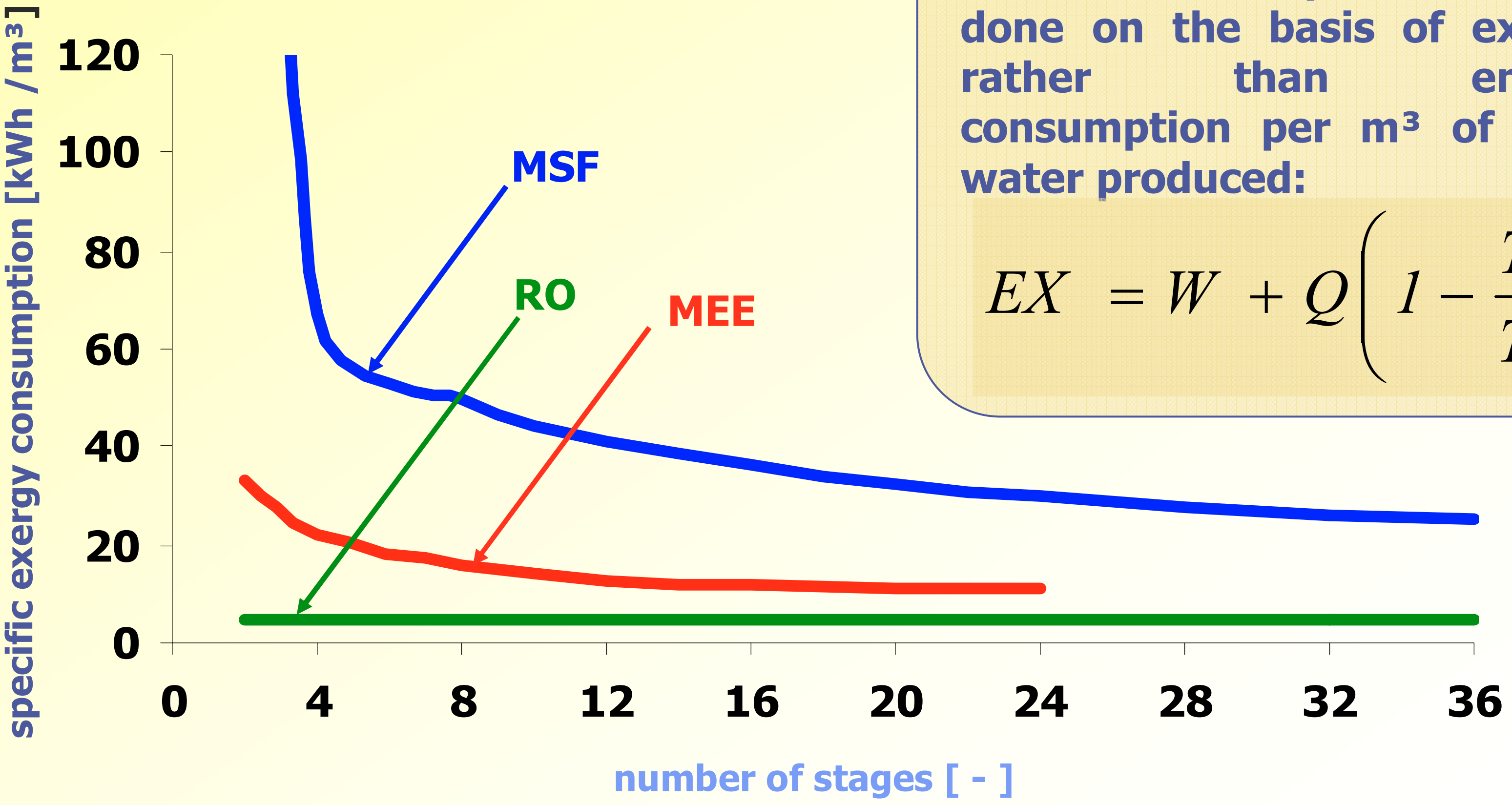
- Direct capital cost is around 250 \$/($m^3$/d) for a 5,000 $m^3$/d plant
- Cost is not much affected by the size despite of its ample range of variation
- Product water can reach values lower than 0.5 \$/$m^3$

# Specific exergy consumption

- RO makes use of a different form of energy with respect to MSF and MEE
- MSF and MEE operate at appreciably different temperature levels

a coherent comparison can be done on the basis of exergy, rather than energy, consumption per m³ of fresh water produced:

$$EX = W + Q\left(1 - \frac{T_a}{T_S}\right)$$



# Comparison between MSF and RO

## Multi-Stage Flash

### ADVANTAGES

- ✓ reliable, robust process
- ✓ more than 30 years of experience
- ✓ not sensitive to feed water quality
- ✓ long service life time
- ✓ significant cost savings due to the possible manufacturing in the client country

### DISADVANTAGES

- ✓ higher specific investment cost
- ✓ higher specific exergy consumption
- ✓ limited to high capacities

## Reverse Osmosis

### ADVANTAGES

- ✓ lower specific investment cost
- ✓ lower specific exergy consumption
- ✓ any capacity possible

### DISADVANTAGES

- ✓ sensitive to feed water quality, danger of biofouling
- ✓ strong dependence on membrane/module manufacturer
- ✓ highly qualified manpower needed for operation and maintenance
- ✓ high consumption of chemicals

# Key issues for MEE process

**Multiple Effect Evaporation process has many attractive characteristics in comparison with Multi-Stage Flash**

- approximately the same performance ratio with fewer than half of number of effects
- higher thermal efficiency using a lower temperature heating steam
- lower power consumption for pumping
- possibility of simple modification in the process configuration
- higher operating flexibility with a shorter start-up period
- stable operation over a load range of 30 ÷120% versus 70 ÷110%
- reliable capability of combination with both thermal and mechanical vapour compression
- lower specific capital cost
- lower maintenance and operating expenses

Main reasons of the enormous diffusion of MSF in MENA countries are:

- ✓ reliability
- ✓ long-time experience
- ✓ high capacity
- ✓ scarce importance of energy saving

# Solar desalination

**possible benefits**

- countries with fresh water shortage can generally rely on high values of solar irradiance
- solar energy availability is maximum in the hot season when fresh water demand increases and resources are reduced
- water constitutes a medium which allows to store for a long time possible energy surplus, economically and without significant losses
- lack of water usually takes place in isolated areas, like rural regions or small islands, where the soil occupation is not critical and the cost of traditional means of supply may dramatically rise

additional remarks for small scale applications

⬇

capacity up to 1,000 m³/d
[domestic water needs of a community of more than 5,000 people]

- ✓ low capital cost
- ✓ reduced construction time
- ✓ utilisation of local manpower and materials
- ✓ simple management

# Coupling options

in general solar energy can feed any desalination process

| | DESALINATION PROCESS | | | |
|---|---|---|---|---|
| **SOLAR TECHNOLOGY** | **MSF** | **MEE** | **MVC** | **RO** |
| Concentrating Parabolic Collectors (Solar thermoelectric station producing both electricity and eventually heat through a cogeneration arrangement) | ● | ● | ● | ● |
| Flat Plate/Evacuated Tubular Collectors | ● | ● | | |
| Salt Gradient Solar Pond | ● | ● | | |
| Photovoltaic | | | ● | ● |

**Options**

MEE driven by low temperature solar thermal collectors, both flat plate and evacuated tubular

systems for the generation of high temperature heat (linear parabolic collectors, solar towers)

- ⇒ larger capacities are requested
- ⇒ a combined demand of power must be present
- ⇒ economic feasibility is still too far

**alternative systems**

- ⇒ RO coupled with photovoltaic panels
- ⇒ MEE coupled with salt gradient solar pond

# Assumptions made for the estimation

**main parameters**

| | |
|---|---|
| Capacity of the plant | 1,000 $m^3/d$ |
| Annual solar irradiance | 2,000 $kWh/m^2$ |
| Heating temperature | 65 °C |
| Number of effects | 14 |
| Performance Ratio | 10 |
| Thermal energy consumption | 65 $kWh/m^3$ |
| Electric energy consumption | 1.5 $kWh/m^3$ |
| Specific cost of desalination process | 2,600 $\$/(m^3/d)$ |

**flat plate collectors**

⇒ efficiency curve:
- intercept 0.78
- slope 4.4 $W/m^2{}^\circ C$

⇒ specific cost 200 $\$/m^2$

**evacuated tubular collectors**

⇒ efficiency curve:
- intercept 0.7
- slope 1.8 $W/m^2{}^\circ C$

⇒ specific cost 300 $\$/m^2$

the remaining parameters, such as amortization factor, cost of electricity, chemicals, operating labour, are set to the typical values

# Results

⇒ Tool: *f-chart* software

⇒ Criterion: to accomplish the nominal load in the hottest period

**FPC**

| | |
|---|---|
| Average covering of the load | 73% |
| Minimum covering of the load | 50% |
| Efficiency | 29% |
| Specific area | 30 m²/(m³/d) |
| Specific direct capital cost | 8,600 $/(m³/d) |
| Water production cost | 2.5 $/m³ |

**ETC**

| | |
|---|---|
| Average covering of the load | 74% |
| Minimum covering of the load | 60% |
| Efficiency | 44% |
| Specific area | 20 m²/(m³/d) |
| Specific direct capital cost | 8,600 $/(m³/d) |
| Water production cost | 2.5 $/m³ |

configuration for remote areas

**Stand-alone system with flat plate collectors driving an ORC to generate the required power**

- Specific area
  40 m²/(m³/d)
- Specific direct capital cost
  107,000 $/(m³/d)
- Water production cost
  3 $/m³

# Alternative options

**CONVENTIONAL**

reference value for the water production cost can be assumed equal to 1 $/m³ in case of medium to small size desalination processes connected to the electric grid

desalination system typically used in stand-alone configuration is a reverse osmosis process coupled with a diesel powered generator; due to the additional charges for transporting and fuel storage, water production cost can rise up to 1.5 $/m³

**SOLAR**

**RO/PV**

| | |
|---|---|
| ⇒ Specific capital cost | 4,200 $/(m³/d) |
| ⇒ Water production cost | 2 $/m³ |
| ⇒ Specific area | 10 m²/(m³/d) |

**MEE/SGSP**

| | |
|---|---|
| ⇒ Specific area | 70 m²/(m³/d) |
| ⇒ Specific capital cost | 3,700 $/(m³/d) |
| ⇒ Water production cost | 1.5 $/m³ |

# Comparison between solar options

## RO coupled with Photovoltaic

| ADVANTAGES | DRAWBACKS |
|---|---|
| ✓ lowest specific soil occupation<br>✓ ideal for stand-alone configuration<br>✓ any capacity possible with no dramatic rise in cost<br>✓ best potential towards further cost reduction | ✓ sensitive to feed water quality<br>✓ advanced materials required<br>✓ complexity of design and management<br>✓ most costly operation due to membrane and battery replacement |

## MEE coupled with Salt Gradient Solar Pond

| ADVANTAGES | DRAWBACKS |
|---|---|
| ✓ competitive water production cost<br>✓ lowest investment<br>✓ simplified operation due to limited piping and absence of coverings<br>✓ use of discharged brine for salt gradient preservation | ✓ availability of a huge area<br>✓ adequate mechanical and thermal characteristics of the ground<br>✓ long time for design, simulation, construction and fully operating<br>✓ difficulty in reliable predictions |

# SOLAR DESALINATION
## (Conclusion)

- Compared to conventional processes, water cost using solar desalination for plants of capacity 1000– 5000 m3/day, is still quite expensive.
- For remote areas with no access to electricity conventional systems water cost rises up to 1.5 \$/m³
- Cost is 0.6 \$ lower for the PV/RO system in comparison with ST/MEE system
- Also, solar field area in case of PV/RO system is small (nearly 8 m2 compared to little less than 20 m2 per m3/day of installed capacity).
- ST/MEE is more sensitive to scale effect: doubling capacity MEE and RO cost falls down over 20% and less than 10% respectively
- Hybrid system i.e. ST/MEE with auxiliary fossil fuel boiler allows quite a large cost reduction, because solar source exploitation can be optimised and consequently solar field cut down

# Conclusions (in general)

- Seawater desalination has already confirmed its potentiality to resolve the fresh water problems in numerous countries. It is, however, to be noted that in spite of the good reliability and favourable economic aspects of desalination processes, the problem of high energy consumption till remains to be resolved.

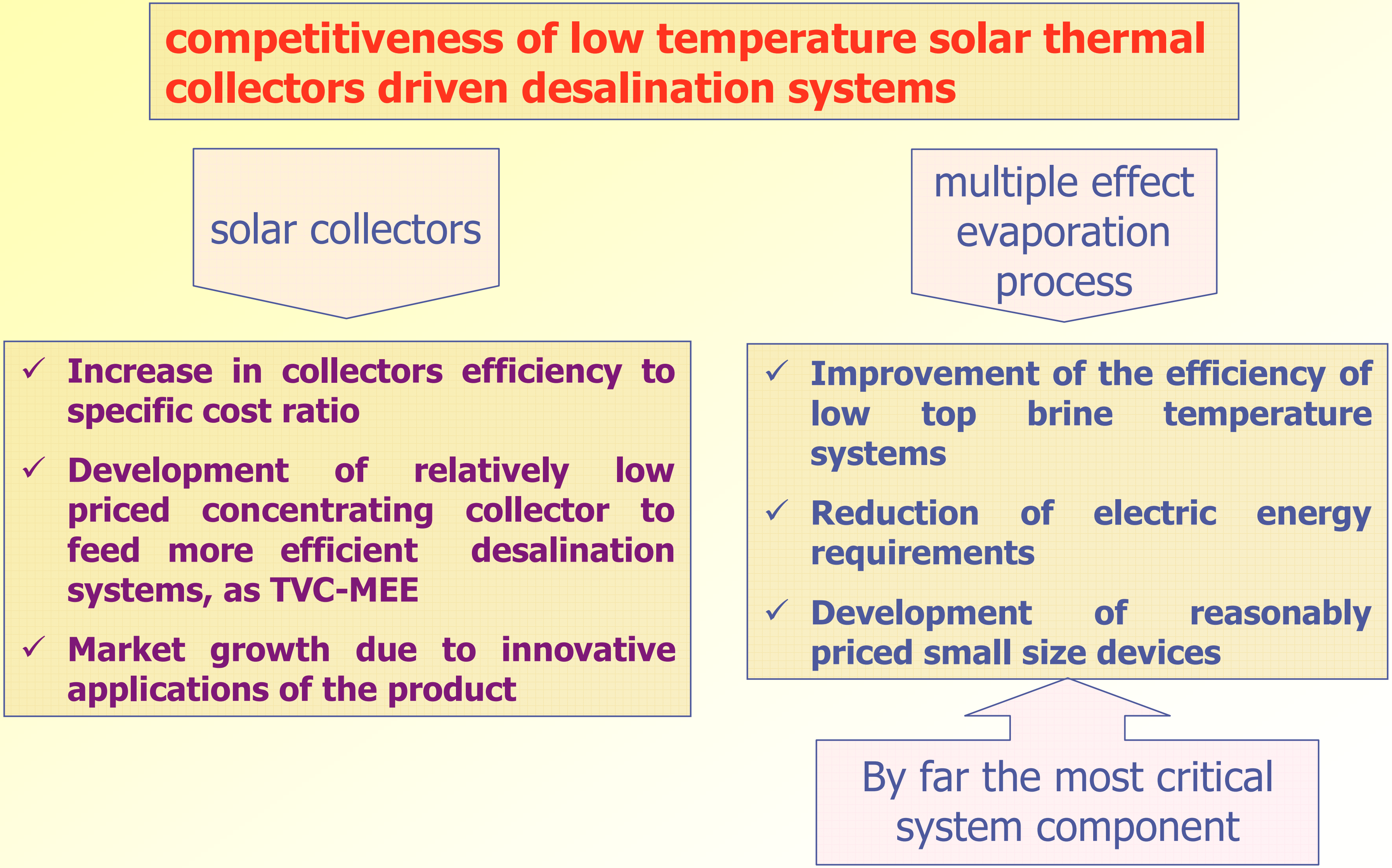
- In particular, advantages of photovoltaic become decisive for stand-alone configurations and smaller sized systems (approx. 1000 m3/day). In addition, ground requirements are less than half with better expectations of cost reduction.

- On the other hand photovoltaic coupled with reverse osmosis is not suitable for severe operational conditions regarding the feed water. Also, the technology may become too onerous under specific circumstances, for example if know how and materials are not locally available

- For large scale plants coupling of desalination processes with high temperature solar technologies needs to be investigated thoroughly.

- In case of extraordinarily costly traditional means of water supply and availability of possible financing at low interest rates for renewable sources, solar desalination can be a viable option.

# Perspectives



**competitiveness of low temperature solar thermal collectors driven desalination systems**

solar collectors

- ✓ **Increase in collectors efficiency to specific cost ratio**
- ✓ **Development of relatively low priced concentrating collector to feed more efficient desalination systems, as TVC-MEE**
- ✓ **Market growth due to innovative applications of the product**

multiple effect evaporation process

- ✓ **Improvement of the efficiency of low top brine temperature systems**
- ✓ **Reduction of electric energy requirements**
- ✓ **Development of reasonably priced small size devices**

By far the most critical system component

# Solar Laboratory activities

⇒ R&D activities on desalination have been undertaken during the recent years with the main purpose of extending the field of solar energy application

⇒ In the past, a solar still was designed, installed and experimented

⇒ Photovoltaic driven desalination plant has been designed

**New Generation of Solar Thermal Systems**

18 organisations out of 14 different European countries

**Main targets of ENEA:**

- pre-normative work collaborating with Demokritos
- identification and characterization of the most suitable technologies in collaboration with main South European Institutions
- development of simplified tools for designing and performance assessment with support from Polytechnic of Milan.

# Acknowledgements

- My special thanks are due to Prof. G. Furlan for his valuable guidance and moral support
- Ing. Domenico MARANO
- Dr. Vincenzo SABATELLI
- Dr Vincenzina SARNO
- Dr. Isabella DE BARI

Last but not the least my thanks are due to all the participants.