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Overview of Village Scale, Renewable Energy Powered Desalination

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Preface

This report reviews commercial and prototype desalination technologies, particularly those technologies appropriate for use in remote villages, and how they can be powered using renewable energy from solar and wind sources. It gives the reader the knowledge to begin selection of an appropriate desalination technology, and shows where more research is needed in using renewable energy for desalination.

There are several thoughts that the reader should keep in mind:

The most important caveat for a water resource planner is that the cheapest, easiest, and most environmentally friendly water supply plan always includes demand management and careful use of naturally available and renewable water resources (rainfall, rivers, and renewable groundwater). A community should resort to desalination only after these options have been exhausted.

It will be helpful for the reader to keep a few numbers in mind. Sea water has total dissolved solids (TDS, a measure of salt concentration) levels of about 35,000 parts per million (ppm), while the salinity of brackish water is typically 3,000 ppm. The World Health Organization recommends that the salinity of drinking water be less than 500 ppm.

All units in this paper are in cubic meters (m^3) of water. A cubic meter of water per day (m^3/day) typically can supply 20 to 50 people in the developing world.

Where production rates for solar thermal processes are given in liters per square meter, these figures reflect an annual average day in a typical (i.e, non-arctic) developing country.

Cost estimates vary widely, because they were obtained from a variety of sources, which described systems in different parts of the world, where labor and material costs vary greatly. In addition, salinity, pretreatment, economies of scale, and the trade-off between higher quality materials and higher maintenance affect costs. The effect of salinity is discussed below. Poor quality feedwater (high in hardness, dissolved metals, or colloids) requires pretreatment systems which can greatly increase the cost and complexity of the system. Where enough data was available in the literature, the effect of economies of scale has been estimated. Higher quality materials result in higher capital costs but lower operations and maintenance costs. Disposal of waste water may prove problematic in inland areas, where the dumping of highly saline water may lead to environmental damage and therefore require costly disposal systems.

Costs fall into two categories: capital cost and lifecycle cost. Capital cost includes only the cost of the desalination system itself, and an effort was made to remove the cost of energy supply or pretreatment from the reported capital costs. Therefore, capital cost does *not* include the cost of PV panels, wind turbines, or site-specific pretreatment systems. Lifecycle costs are taken directly from the literature and include cost of energy, chemicals, and maintenance.

Desalination technologies can be divided into two categories: phase change and membrane separation. Phase change methods change liquid water to water vapor or ice in order to separate it from its solutes. Membrane methods use selective membranes that allow passage of either water or solutes, but not both. The reader should keep in mind some fundamental differences of these two processes.

Distillation produces very pure water (TDS levels of about 4 ppm), which has advantages and disadvantages. The advantages are that the efficiency of the system can be increased by mixing feedwater with product water while still staying below the drinking water standard of 500 ppm, and that very pure water suitable for industrial purposes or discriminating palates is produced. The disadvantages are that people may be so accustomed to salty water that they find the taste of distilled water disagreeable, and that water of high purity has a high ability to dissolve whatever contains it, such as pipes. Calcium carbonate must usually be added to distilled water to prevent pipe corrosion, particularly where lead pipes are used.

The cost, pretreatment requirements, and energy demand of distillation systems are relatively independent of feedwater quality. However, distillation does not remove volatile components from the water, such as volatile organic compounds which are harmful to human health. Some sort of air stripping step must be added if such components are present in the water (e.g., benzene).

Membrane systems are modular and can be designed to meet almost any product water specification. Energy demand and cost is proportional to the salinity of the feedwater. Depending on the quality of the feedwater, extensive pretreatment may be necessary to protect membranes. Product water from membrane processes usually cannot be considered disinfected.

No desalination process provides residual disinfection.

The author would like to acknowledge the help and guidance of David Corbus and Byron Stafford, and also the help of Harry Remmers in reviewing this report.

Several references must be acknowledged for their roles in shaping this report. O.K. Buros's 1980 *Desalination Manual* provided a comprehensive overview of desalination technologies which served as an excellent starting point for this report. The EURORED project team reports on renewable energy-powered desalination experiences in Europe (funded by APAS) were tremendously helpful as a source of information on recent desalination projects and as a point of comparison.

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Summary

An overview of desalination technologies is presented, focusing on those technologies appropriate for use in remote villages, and how they can be powered using renewable energy.

Solar stills are appropriate for very small water demands (one to tens of liters per day) or in areas lacking electricity or skilled technicians. However, they are expensive and require large areas of land. More research is needed to develop rugged multiple effect systems, which, like solar stills, would require no electricity or technical skill, but which would greatly decrease the area of the distiller by reusing the heat of evaporation two to several times. To date, only prototype rugged multiple effect systems have been built.

Currently, the majority of large-scale desalination plants in the world employ Multistage Flash (MSF) or Multiple Effect Distillation (ME) because these desalination technologies were the first to mature and because they have large economies of scale. MSF and ME are most appropriate for large-scale systems where waste heat is available from another process, such as a thermal power plant. Several solar-thermal MSF and ME pilot plants have been constructed. However, given the operational complexity of these systems and the difficulties encountered with the variable nature of solar insolation, solar-powered MSF and ME plants cannot yet be considered appropriate for developing countries.

Three proven technologies require only electrical (no thermal) input: vapor compression (VC), reverse osmosis (RO), and electrodialysis (ED). Which system is most appropriate for a given location depends mostly on the quality of the available feedwater, since the feedwater characteristics determine the pretreatment requirements and energy demands, and therefore cost and complexity, of membrane systems. ED is the most energy-efficient desalination method for brackish water with low non-ionic solute content, while RO can be used for brackish or sea water as long as the water has low potential for fouling the membranes. The popularity of RO has increased greatly during the past decade, and RO is now out-competing MSF in the large- and small-scale desalination markets. VC, while a proven technology, is still maturing, and may become the most energy-efficient method for sea water desalination.

Many successful demonstrations of renewable energy-powered RO have been built. These systems require some degree of technical skill to protect the membranes from fouling and to maintain pumps. The renewable energy systems have included photovoltaic- (PV) and wind-battery-inverter; PV and variable speed wind direct drive using cut-in and cut-out controls; and mechanical wind pump with pressurized water storage. PV-battery-inverter-powered RO and PV-direct drive-RO technologies are commercially available for use in developing countries.

Fewer demonstrations of renewable energy-powered ED systems have been built, and none of VC. The ED systems have included PV-battery-inverter and PV-battery (using all direct current [DC] equipment). The all-DC ED system may soon be commercially available for use in remote communities with brackish water.

Further research is needed in the following areas:

- Demonstration pilot plant of a wind-battery-powered ED

- Development of wind or PV direct-drive ED using cut-in/cut-out power controls

- Demonstration pilot plant of an electrical wind pump-pressurized water storage system to power RO

- Testing of VC using renewable energy sources such as PV-battery-inverter, wind-battery-inverter, hybrid wind/PV/generator/battery, wind-shaft power-direct drive, and wind-electric-direct drive. Testing should include the suitability of VC for use as a deferable load.

- Development of control strategies for hybrid minigrids using modular desalination systems (RO, ED, or VC) as deferable loads for load management and increased renewables penetration.

- Development of designs for rugged ME using solar energy or waste heat from a diesel generator, and testing of these designs to determine appropriateness for use in remote locations

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Nomenclature

CAT	Centre for Appropriate Technology, Alice Springs, Australia
CDC	Centers for Disease Control (U.S.)
CEA	French Atomic Energy Center
CIEA-ITC	Centro de Investigacion en Energia y Agua (Spain)
CIEMAT	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas (Spain)
CRES	Centre for Renewable Energy Sources (Greece)
ECU	European Community Unit
ED	Electrodialysis
EDR	Electrodialysis Reversal
EPA	Environmental Protection Agency
FS	Freeze Separation
FSEC	Florida Solar Energy Center
ITER	Instituto Tecnologico y de Energias Renovables (Spain)
KACST	King Abdulaziz City for Science and Technology (Saudi Arabia)
MD	Membrane Distillation
ME	Multiple Effect Distillation
MSF	Multistage Flash Distillation
NEDO	New Energy and Industrial Technology, Development Organization (Japan)
OSW	Office of Saline Water (U.S)
RO	Reverse Osmosis
SERIWA	Solar Energy Research Institute of Western Australia
TDS	Total Dissolved Solids
US AID	United States Agency for International Development
VC	Vapor Compression
WTTP-	Water Treatment Technology Program (U.S.)

Introduction

As the world's population continues to grow, so will the demand for potable water. However, freshwater resources are scarce. Therefore, alternative means of obtaining fresh water, including desalination, will increasingly be required to meet demand. Indeed, over 19 million cubic meters (m^3) of water are currently desalted daily, primarily to supply municipal water in the Middle East and United States (Rodríguez-Gironés et al, 1996). Desalination's roles in providing potable water for communities in arid or coastal areas, as well as military campaigns and refugee shelters, and in treating waste water are expected to increase greatly in the future.

Currently, most desalination facilities use electricity from the utility grid or diesel minigrids or use heat from fossil fuel combustion. In addition, most desalination facilities are either large-scale plants supplying water to municipalities in developed countries or small systems for vacation homes or boats. However, a growing yet unmet demand for small-scale desalination lies in the many communities of the developing world without access to a utility grid, particularly islands, remote coastal areas, or arid inland areas.

This report describes the cost, energy requirements, and operation and maintenance requirements of the several desalination technologies in commercial and pilot stages of development. The primary focus is on those technologies suitable for use in off-grid areas of developing countries, especially those which could be integrated into a solar PV, solar thermal, or wind renewable energy system.

Solar Stills

The solar still, the simplest desalination technology, consists of a shallow basin with a transparent cover. Water in the basin, heated by the sun, produces vapor which condenses on the cover, releasing its heat to the atmosphere, and runs off the cover into a collecting trough. The temperature difference between the water and the atmosphere needed to produce distillation at a usable rate is about 20° to 30° F. The amount of water desalinated by the solar still depends on the amount of solar insolation, area of the still, ambient air temperature, feedwater temperature, presence of insulation around the sides and bottom of the still, presence of leaks in the still, slope of the cover with respect to the incidence angle of incoming sunlight, and the depth of water in the still. While most solar stills are operated in batch mode, they can also be designed for continuous-flow, gravity-controlled operation.

A primary advantage of solar stills is that they can be constructed from cheap, locally available materials, such as wood, concrete, metal, plastic, or brick. The cover must be transparent to sunlight but trap heat; therefore, glass or plastic is used. A sealant such as silicone prevents leaks. A dark material such as butyl rubber is usually used to line the basin. Sand or sawdust can provide insulation.

Maintenance of the still involves checking for and repairing leaks, periodic flushing to remove salt deposits, and cleaning of debris and dust from the cover. Storms and animals can crack or tear covers. Morse et al. (1970) suggest that 10 to 60 manhours per thousand square feet of still area per year are needed to maintain stills. Several stills have experienced problems with cracks caused by differential settling of soils beneath the still and with heavy storms wetting the insulation, reducing its insulating ability.

The still area required to meet a given water demand will vary depending upon the solar insolation and other factors mentioned above. A widely used rule of thumb is 3 to 4 liters per square meter of still area per day ($l/m^2/day$) (Hasnain, 1995; Buros, 1980; and Hamed et al., 1993). The amount of solar energy used is approximately 640 kilowatt-hours per cubic meter of water (kWh/m^3) (Block, 1989). An analytical method for determining the water production rate from a still is presented in Belessiotis et al. (1995). Eibling et al. (1971) found that within 25% accuracy, the productivity of a still can be predicted by the empirical formula,

$$P = 0.0000689\,(0.1125R)^{1.4}$$

where P is the productivity in m^3 per square meter of still area per day and R is the total solar insolation in kilojoules per square meter per day ($kJ/m^2/day$).

Reported costs for solar stills vary widely, depending on materials used, economies of scale, cost of labor, and other factors. Capital costs reported in the literature range from \$21 to \$150 per m^2 of still area, and lifecycle costs range from \$0.34 to \$50 per m^3 of water (Eibling et al., 1971; Block, 1989; Tiwari, 1991; Ayoup, 1996; Frick and Hirschman, 1973; and Hasnain, 1995). The predominant lifecycle cost is the capital cost, due to the large area of still required per unit output. The higher costs are for stills made in developed countries, using high quality, durable plastics and sealants, while the lower costs are for stills made in developing countries using locally available materials and labor. A good lifecycle cost estimate for a still built locally in a developing country is $12/m^3.

Thousands of stills are in use worldwide. They range in size from a square meter or less as installed by the Brace Research Institute in Botswana and Haiti (Ayoup, 1996), to thousands of square meters as installed by the Solar Energy Research Center of Pakistan (Ali, 1991).

Many variations to improve the simple solar still have been proposed, the most common and effective of which is adding a wick to increase evaporative surface area (Moustafa, 1996). Other proposals include adding dyes to increase light absorption and using fans or compressors (Malik, 1982; and Garstang et al., 1980). One researcher proposes using the steam produced in the still to power a low-pressure steam engine (Stegeman, 1996).

Distillation with Heat Recovery

Simple solar stills are inefficient because they do not reuse the energy absorbed by the evaporating water. Various technologies improve the efficiency of the distillation process by reusing this heat. Among these technologies, the most common are multistage flash distillation (MSF), multiple effect distillation (ME), and vapor compression (VC). Because VC uses electrical energy rather than thermal energy, it is considered in a separate section.

Because efficiency increases with the temperature difference between input water and output water, these plants are usually operated at much higher temperatures (about 90° to 120° C) than solar stills. While these higher temperatures increase the efficiency, they necessitate the use of pretreatment chemicals to prevent scaling and corrosion.

Scaling is the precipitation of carbonate and sulfate salts, whose solubilities decrease with increasing temperature, onto the surfaces of heat exchangers and pipes. Scale decreases the performance of plants with time and is troublesome to remove. Scaling becomes a problem at temperatures above approximately 95° C. To prevent scale, most MSF and ME plant operators add acid or scale inhibitors, such as polyphosphate or Belgard®, to the feedwater. Because acid leads to corrosion within the plant, the modern scale inhibitors are generally preferred for large-scale plants. Both additives require skilled personnel to monitor the pretreatment system. In developing countries, a locally available acid such as vinegar can be the cheapest and easiest way to control scale.

In addition to corrosion caused by acid, corrosion can result from the presence of dissolved oxygen in the feedwater. Therefore, some plants add deaeration systems to reduce corrosion.

The material used to construct MSF and ME systems is decided by balancing the cost of materials against the cost of maintenance to prevent and repair the effects of corrosion. Buros (1980) recommends that developing countries spend the extra money on higher quality materials to avoid the maintenance and repair costs resulting from lower quality metals.

A vast experience with large-scale fossil fuel-powered MSF and ME plants has been accumulated over the past four decades. MSF plants produce 51.5% of the water desalted worldwide, while ME plants produce 4%. Because of this experience, there are many manufacturers of MSF and ME plants, and several produce prefabricated plants requiring minimal on-site construction. Because of the large economies of scale with these distillation plants, most plants built are large-scale (1,000 to 100,000 m^3/day). The large scale nature of MSF facilities is shown in the statistic that only 11.7% of the number of desalination plants worldwide are MSF, while the typically smaller-sized ME plants comprise 6.5%(Wangnick, 1995).

Many papers debating the merits of ME and MSF plants have been written, often with contradictory conclusions regarding relative efficiency, cost, and ease of maintenance (Morin, 1993; Darwish and Al-Najem, 1987; Hasnain, 1995; Buros, 1980; and Wade, 1993). The conclusions that *can* be drawn from this debate are that MSF is by far the more widely used technology, primarily because it was developed before ME; MSF may be easier to maintain because of the on-line ball cleaning system; and MSF can better tolerate fluctuating input conditions. ME has the potential to be cheaper and more energy efficient, and its design minimizes the potential for scaling therefore reducing the frequency of maintenance.

Within the past two decades, a number of solar-thermal MSF and ME plants have been constructed (see Table 1). Solar- powered plants usually use some method of heat storage for continuous operation, such as a solar pond or hot water storage tank. Because ME and MSF reuse the heat of vaporization, much less land area is required than for a simple solar still. To obtain the higher efficiencies that come with higher temperatures, reflectors, lenses, or evacuated tubes are used to concentrate solar energy. To prevent scaling and corrosion in the solar collectors, distilled water or oil is used as the circulating fluid, and the heat is transferred to the saline water in the distillation plant via a heat exchanger.

Table 1. Examples of Solar-Powered Multistage Flash and Multiple Effect Distillation Plants

	Multistage Flash Distillation			Multiple Effect Distillation	
Characteristic	El Paso, Texas	Safat, Kuwait	La Paz, Mexico	Almeria, Spain	Abu Dhabi City, U.A.E.
Year installed	1987	1984	1978	1988	1984
Type of system	24 stage	12 stage	10 stage	14 effect	18 effect
Capacity (m^3/day)	19	10	10	24	100
Energy supply system	3355 m^2 solar pond supplies heat and power	220 m^2 line concentrating collector	194 m^2 flat plate; 160 m^2 parabolic concentrating collector	Parabolic concentrating collector	1862 m^2 evacuated glass tube collectors
Collector area per unit capacity (m^2/m^3/day)	176.6	22	35.4	n/r	18.6
Energy demand (kWh/m^3)	92 to 108	81 to 106	< 144	30 (thermal) 5 (electric)	62
Energy storage	Solar pond	Hot water tank	Hot water tank	Hot oil tank	Hot water tank
Operating conditions	Continuous	Continuous	Continuous	Daytime only	Continuous
Current status	Operating as demonstration	n/r	Shut down 1980 due to operating problems	Shut down 1990 at conclusion of testing	Shut down 1989
Builder	University of Texas at El Paso	Kuwait Institute for Scientific Research	Digaases and Dornier, GmbH	Plataforma Solar de Almeria	Sasakura Engineering Co.
Reference	Manwell and McGowan (1994)	Moustafa et al. (1985)	Manwell and McGowan (1994)	Zarza et al. (1991)	El-Nashar (1990)

Note: n/r means not recorded.

These plants have low electricity requirements (electricity is needed only for low pressure pumps). However, they have high maintenance requirements, primarily because of the pretreatment systems and the need for periodic scale removal. Therefore, these plants have been built in areas, such as the Middle East, which have higher technical skill available than in a typical developing country village (Buros, 1980). In addition, economies of scale generally dictate that these plants be built on a larger scale than is generally needed in remote villages.

Moustafa (1996) comments that solar ME and MSF experiments in Kuwait experienced difficulties operating under the variable conditions of solar insolation. Greater success has been found with self-regulating solar MSF plants than solar ME plants. Solar ME and MSF cannot yet be considered proven technologies.

It is generally concluded that the most rational use of MSF and ME technologies is in "dual purpose" plants, utilizing the waste heat generated by industrial or power-generating processes (Leitner, 1992; and Buros, 1980). While several large-scale dual-purpose plants have been built in the Middle-East, more research is needed on small-scale systems using waste heat from diesel generators or biomass systems. In addition, much more research is needed on small-scale, low-tech systems which are here termed "rugged ME". Under this concept, efficiency (high temperature, large number of effects) is sacrificed for simplicity and ease of maintenance. Rugged ME would be preferred to solar stills, because less land area would be required without an increase in the technical skill level required for maintenance.

In conclusion, MSF and ME plants are best suited for relatively high water demands (2,000 to 10,000 cubic meters per day), for locations with available skilled technicians, for areas where poor quality water (which could foul membranes) rules out the options of reverse osmosis and electrodialysis, and for "dual purpose" operation using waste heat from an industrial process or fossil fuel power plant. Rugged ME could become appropriate for regions lacking electricity and technical skill, as an improvement over solar stills.

Multistage Flash Distillation

In the MSF process, feed water is pressurized and heated to its saturation temperature and then passed through a series of stages. In each stage the pressure is reduced, inducing boiling ("flashing"). The vapor then is passed through a wire mesh to remove any entrained brine droplets. Condensation of the vapor in each stage progressively heats the counter-flowing feedwater. If water that does not vaporize is recycled with feedwater at the end of the cycle, then the plant is termed a "brine recycle" plant. Typical MSF plants have as many as 50 stages. MSF plants can have either long-tube or cross-tube heat exchangers, and can be single deck or two-deck.

MSF plants typically have recovery rates in the range of 25% to 50% (recovery rate is the percent of feedwater that is converted to desalted water). The low recovery rate motivates the interest in brine recycle plants, in order to reduce the quantity of pretreatment chemicals used. However, brine recycle plants are more complex to start up, operate, and maintain than once-through plants.

One advantage of MSF plants over ME is that MSF plants can utilize an "on-line ball cleaning" system to remove scale. The on-line ball cleaning system greatly simplifies maintenance, but still must be supplemented by periodic cleaning to contain scale formation.

Costs reported in the literature show a wide range, depending upon materials used, economies of scale, and cost of steam (which depends on whether the steam is heated by cogeneration, dedicated fossil fuel combustion, or solar energy). Capital costs range from \$800 to \$15,000/m^3/day of capacity, and lifecycle costs range from \$1.21 to \$4.21/m^3 (Sadhukhan, 1994; Al-Ajlan, 1995; Tare, et al, 1991; Talati, 1994; and Wade, 1993). The greatest annual expenses are for steam and pretreatment chemicals.

Efficiencies of installed plants also vary widely. Thermal energy requirements range from 48 to 441 kWh/m^3; the average is 60 to 80 kWh/m^3. Electrical energy requirements for pumping are typically 3 kWh/m^3 (Block, 1989; Al-Ajlan, 1995; Fries et al., 1982; and Talati, 1994). Block (1989) found that solar-powered MSF plants can produce 6 to 60 liters/m^2/day, in comparison with the 3 to 4 liters/m^2/day typical of solar stills. Moustafa et al. (1985) derived an empirical equation for the thermal energy requirements of a solar MSF plant:

$$q = 151.1(T_p - T_i)^{-0.16}$$

where q = thermal energy requirement in kWh/m^3,
T_p = peak temperature achieved in the plant, and
T_i = temperature of the unheated feedwater.

Multiple Effect Distillation

Multiple effect distillation (ME) shares many features with MSF. Both use heat exchangers to recycle the heat of evaporation. While MSF uses counterflow between the feedwater and the evaporating vapor to recycle the heat, ME uses heat exchangers in series. Preheated feedwater entering the first effect is heated to its boiling point. The feedwater is sprayed or otherwise distributed onto the surface of evaporator tubes in a thin film to promote rapid boiling and evaporation. The tubes are heated by condensing steam or hot oil from a boiler or solar collector. That water which is not evaporated is fed to the next effect, which is at lower pressure, and is vaporized by heat from condensing vapor from the previous effect. At each subsequent effect, the difference in temperature between feedwater and heating water becomes smaller. Thus, in each effect steam is condensed on one side of a tube, and the heat of condensation derived therefrom evaporates saline water on the other side of the wall. Typically, there are 8 to 16 effects, with an overall recovery rate of 40% to 65%. Unlike MSF, no brine recycle ME plants have been constructed. Heat can be exchanged through either horizontal or vertical tubes. There has been much discussion of the relative merits of the different configurations (Wade, 1993).

As with MSF plants, skilled labor is required for maintenance of ME pumps and for operation of the pretreatment system, which is required for scale and corrosion control. ME plants are usually operated at lower temperatures than MSF, reducing the incidence of scale, but their heat exchanger configurations make cleaning more complicated.

Capital costs range from \$1,000 to \$12,000/m^3/day, owing primarily to economies of scale, and lifecycle costs range from \$0.70 to \$4.00/m^3 (Talati, 1994; Wade, 1993; Al-Ajlan, 1995; Glueckstern, 1995; Howe and Tleimat, 1974; and Zarza et al., 1991). The cost of steam, which depends on the source of the steam (waste heat, boiler, or solar thermal collectors), is a major factor in the range of lifecycle costs.

Energy demands are approximately 30 kWh/m³ for thermal energy and 1 to 5 kWh/m³ for electrical (pumping) energy (Al-Ajlan, 1995; Talati, 1994; and Zarza et al., 1991). Rodríguez-Gironés et al (1996) estimate that 0.7 to 0.85 kg of distillate is produced in each effect for each kg of steam applied to the first effect. Hasnain (1995) describes a solar-powered ME system which produces 9 liters per day per square meter of collector area. El-Nashar (1990) empirically derived equations for energy demand:

$$Qthermal = \frac{(610.74)}{(-0.01875n^2+1.15n-1.625)}, \quad for\ 7<n<13$$

$$Qthermal = \frac{610.74}{(-0.0025n^2+0.625n+2.15)}, \quad for\ 13<n<32$$

$$Qelectric = -0.0000125C^2+0.14C+6.06, \quad for\ C<500$$

$$Qelectric = -0.0000448C^2+0.18C+4.47, \quad for\ 500<C<1000$$

where *Qthermal* = thermal energy requirement in kWh/m³,
Qelectric = electrical (pumping) power requirement in kW,
n = number of effects,
C = capacity of the plant in m³/day, and
610.74 kWh/m³ = latent heat of vaporization of water.

Rugged ME

As mentioned previously, solar stills are widely used throughout the world because they are easy to construct and maintain. However, they require a large land area and large capital expenditure for construction materials because of their inefficient use of solar energy. The large-scale ME and MSF systems described above, which make much more efficient use of energy, are not practical for many areas because of their operational complexity. Therefore, a technology is needed which re-uses heat like ME and MSF, but is easy to build and maintain like a solar still. In this report, such a technology is termed "rugged multiple effect (ME)".

Limited research on such a technology has been conducted to date. Hamed et al. (1993) refer to a prototype of a rugged, six-effect ME system, while Baumgartner et al. (1991) describe testing of a two-effect system. The most extensive research has been conducted by Pierre le Goff of the Laboratory of Chemical Engineering Sciences in France. Constructed of materials commonly available in developing countries, eight prototypes are currently being tested in Morocco, Algeria, Tunisia, Libya, and Benin (le Goff, 1996).

In le Goff's design, sunlight passes through a sheet of transparent ethylene and strikes a movable mirror, which reflects the sunlight onto a vertical aluminum plate. Brine is dripped onto gauze layered on the other side of the plate. The heated plate causes the water to evaporate and move across a narrow space between the first plate and another identical plate. The water condenses onto this second plate, thereby releasing heat to it and heating water dripped onto gauze on the other side of the second plate. The entire system consists of six of these series-connected plates.

le Goff et al. (1991) report that the system can typically reach 94° C on the first plate and 45° C on the last; water production rates are 20 liters per square meter of mirror surface per day. The hand-made prototypes have cost $3,400 each, or about $212,500 per m^3/day of capacity and $116/$m^3$.

Further research on construction techniques and materials is needed to reduce the cost of rugged ME to that of solar stills. Such research should include the use of waste heat from diesel generators, which are commonly used to supply power in remote areas.

Vapor Compression

Vapor compression (VC), like solar stills, MSF, and ME, is a distillation method. In contrast to the other three distillation methods, the primary energy requirement for vapor compression is electrical, not thermal. Some thermal energy is needed for the start up of the vapor compressor. Typically, electrical resistance heating is used. The feedwater is heated, creating vapor. A compressor sucks up this vapor and compresses the vapor, increasing its temperature and pressure. The compressed vapor then passes through a heat exchanger and replaces the start-up heater in the task of heating feedwater. Thus the primary components of a vapor compressor are a compressor and a high quality heat exchanger.

As with the ME and MSF systems, pretreatment requirements include filtration of suspended solids and scale control. One advantage of vapor compression is that the product water is at a higher pressure than the feedwater, reducing the possibility that the product water might become contaminated.

Most vapor compressors built today use mechanical vapor compression. In the past, thermal vapor compression was also considered an option. However, with the improvement of heat exchangers and compressors used in mechanical vapor compression systems, thermal vapor compression has disappeared from the scene.

Operation of vapor compressors is fairly straightforward, and skilled operators are generally not required. Periodic maintenance of compressors and cleaning of heat exchangers requires technical skill.

Several manufacturers build vapor compressors, including Aqua Chem; Mechanical Equipment Co., Inc.; and George Scott International. Vapor compression's share of the desalination market is small, producing about 3.7% of desalted water worldwide and comprising 7.8% of systems (Wangnick, 1995). Vapor compression has historically been used primarily on ships, because it is the most compact of desalination technologies.

Typical electricity requirements in the literature range from 7 to 25 kWh/m^3, with an average of 20 kWh/m^3. Capital costs are reported at $1,100 to $12,000/m^3/day, while lifecycle costs are in the range of $0.50 to $5.00/m^3 (Al-Ajlan, 1995; Buros, 1980; Wade, 1993; and Darwish et al., 1990). Costs generally reflect economies of scale.

One manufacturer of vapor compressors, Superstill Technology, Inc., patented new compressor and heat exchanger designs in 1995. Superstill claims that the new designs greatly increase the energy efficiency, and reports energy demands of 6 to 11 kWh/m^3. These are the lowest energy demands reported of all sea water desalination technologies. Capital costs are listed at $5,200/m^3/day of installed capacity (Sears, 1996).

As with all vapor compression systems, pretreatment requirements include filtration of suspended solids and scale control. Because no distillation process can remove volatile contaminants in the feedwater, Superstill includes a vacuum stripping "degasser" to remove volatile contaminants. Superstills generally have a 40% product water recovery rate.

Superstill vapor compressors can be operated intermittently, and therefore might be suitable for use as a deferable load. Time to start up after shutdown can take between 15 and 60 minutes, depending on how long the machine has been shut down, i.e., how much the system has cooled down. To start up after a shutdown, the compressor is run, gradually removing vapor and adding heat to the system, until it reaches rated capacity.

It is unknown at this time whether VC can operate under variable power. Moreover, although in theory a vapor compression system can be powered directly by any constant shaft power source (such as a constant-speed wind turbine), no such systems are described in the literature (Rodríguez-Gironés et al, 1996). Other questions related to application in developing countries include the frequency of scale control maintenance, ease of maintenance, and the efficiency of the system at different start-up, shutdown cycling patterns.

Historically, vapor compression has been used mostly for desalination on board large ships and in the past has not been considered competitive with reverse osmosis or MSF. However, recent improvements in the energy efficiency of vapor compressors make this technology the most energy efficient of all sea water desalination methods. As energy is often a major cost in desalination, increased energy efficiency greatly increases the economic competitiveness of a desalination technology. More field evaluation is needed to determine whether vapor compression is the least cost option for sea water desalination in developing countries.

Membrane Technologies

The technologies discussed thus far in this report have all been based on distillation. The remaining technologies, with the exception of freeze separation, all rely upon membranes to separate fresh water from brine. While the actual mechanisms of the membranes greatly differ, all membrane processes share certain important characteristics.

The first characteristic is that the energy and pretreatment requirements, and therefore costs, of membrane systems are functions of the characteristics of the feedwater and the desired product water quality. Higher salinity feedwaters require systems using higher pressures or larger membrane areas to achieve a design product water quality. In some cases, the feedwater must be treated through multiple stages in order to achieve a given salinity level.

Membranes are very sensitive to metals, suspended solids, microbes, chlorine and other possible components of the feedwater which might clog or degrade the membranes. Depending on the characteristics of the feedwater, extensive pretreatment systems may be necessary to protect the membranes. Pretreatment systems may become the dominant capital and operational cost. Therefore, the cost of a complete membrane desalination system varies widely from location to location, depending on the particular pretreatment system required by the characteristics of the water source. For this reason, a careful evaluation of available water sources and careful siting of the feedwater intake (e.g., at a coastal well instead of a direct seawater intake) is necessary to minimize cost and system complexity (Rodríguez-Gironés et al, 1996). Table 2 briefly lists the pretreatment options for removing various compounds.

Membrane systems can be designed for a wide range of recovery rates and salt rejection rates. Low recovery-rate systems are generally more appropriate for developing countries, because they require less pretreatment, lower pressures, and less electricity, and because they produce a less-concentrated brine that may be easier to dispose of. High recovery rate systems often involve multiple stages and run the risk of precipitation of salts in the highly concentrated brine. However, high recovery rates may be desired in certain situations, such as joint desalination-salt production facilities or areas with high costs for obtaining the feedwater.

Some people prefer the taste of water with a higher level of dissolved salts than that of distilled water. Membrane systems can be designed to provide any level of total dissolved solids to meet the preferences of the consumers.

One disadvantage of membrane systems compared with distillation systems is that the membranes must be replaced periodically (every 1 to 10 years). Replacement costs add greatly to the lifecycle cost of water produced. Membrane life can be significantly shortened by operator error in situations where pretreatment is critical to maintenance of the membranes. Therefore, some areas may require skilled operators, while others may require little operational oversight.

Membrane systems are modular and can easily be sized to meet any water demand. Their modularity makes them theoretically amenable for use as deferable loads in hybrid power systems. Various researchers have analyzed different module configurations whereby modules are brought on line as power becomes available (Cruz et al., 1996).

Table 2. Pretreatment Options

Feedwater Component	Treatment Option(s)
Suspended solids	5 micron cartridge filtration and/or multimedia filtration
Colloids	Multimedia filtration and/or activated carbon filtration and/or coagulation and flocculation
Organic material	Activated carbon filtration
Hydrogen sulfide	Airtight (anaerobic) feed system or deaeration
Reduced iron or manganese	Airtight (anaerobic) feed system or lime softening or manganese greensand filtration or ion exchange softening
Hardness	Scale inhibitor (e.g., sodium hexametaphosphate or Belgard®) or acid or water softener
Microorganisms	Disinfection (chlorination)
Chlorine*	Dechlorination by adding sodium bisulphite

Dechlorination is necessary only to protect reverse osmosis membranes made from polyamide.

Reverse osmosis (RO) and electrodialysis (ED) are the two proven membrane technologies. Most references state that electrodialysis is the cheaper technology for low-salinity brackish waters, whereas reverse osmosis is the cheaper technology for higher salinity waters (Block, 1989; Buros, 1980).

Reverse Osmosis

Reverse osmosis has been the subject of more papers than any other desalination technology, and it is rapidly supplanting MSF as the most widely used desalination technology. Currently, 32.7% of desalted water worldwide comes from RO plants, which make up 58.8% of all desalination installations (Wangnick, 1995). While RO is certainly a proven technology, it continues to mature as improved membranes and pretreatment systems are developed (Wade, 1993). Numerous renewable energy-powered RO plants, primarily PV-battery systems of small to medium capacity (0.5 to 50 m^3/day), have been built in Florida, Saudi Arabia, Australia, and Qatar (see Table 3). Hundreds more RO systems of similar capacity are powered by diesel generators in Kuwait, India, Mexico, and Brazil.

Reverse osmosis membranes are permeable to water, but not to solutes. The reverse osmosis process uses pumps to force water through the membranes, in the reverse direction of the osmotic gradient. Standard size alternating current (AC) positive displacement or centrifugal pumps are generally used. Therefore, any energy source which can be used to pump water can be used for reverse osmosis, including direct shaft power and electricity. The salts are left behind in the brine stream. The pressure required to overcome the osmotic pressure is proportional to the TDS (total dissolved solids, a measure of the salt content of water) of the feedwater. Pressure requirements range from 6 bar for low salinity brackish water up to 80 bar for sea water (Robinson et al., 1992; and Wade, 1993). Product water flux across the membranes is calculated by the equation,

$$q = \beta_1 (dP_a - dP_0)$$

where q = water produced per unit area of membrane,

dP_a = difference in fluid pressure across the membrane,

dP_o = difference in osmotic pressure across the membrane (For a rough estimate of dP_o, the osmotic pressure of water increases 69 kiloPascals (kPa) per 1000 ppm TDS and dP_o for sea water with 10% recovery rate is about 2700 kPa . See Chapman-Wilbert (1993) for further details.) and

β_1 = coefficient which depends on the membrane type and temperature, and ranges from 0.2 to 3.0, expressed in 10^{-9} m/s-kPa (Chapman-Wilbert, 1993). Temperature dependency is given by the relationship,

$$\beta_1(T) = \beta_1(T_0)\, e^{(C/T - C/T_0)}$$

where C = 2160 Kelvin^{-1}.

Reverse osmosis membranes do not completely exclude all solutes, and some membranes cannot remove certain metals such as mercury or arsenic (Logsdon et al., 1990). The salt flux across the membrane depends upon the type of membrane and is proportional to the difference in salt concentration across the membrane. The salt removal rate is typically 98% to 99%, which is much less than the salt removal rate of distillation systems but is usually sufficient to provide potable water. If not, RO systems can be linked in stages. Large sea water desalination plants often link high- and low-pressure RO units in stages to minimize cost. However, for developing countries most sources recommend using identical RO units if staging is required, thus simplifying maintenance and the number of spare parts which must be kept on hand (Buros, 1980).

There are two main membrane types: spiral wound and hollow fine fiber. In the hollow fine fiber type produced by Dow and DuPont, water flowing outside of very small-diameter tubes is forced into the center of the tube. In the spiral wound configuration produced by Desalination Systems, Envirogenics, Fluid Systems, and Hydranautics, long membrane sheets are wrapped into a spiral, forming concentric feedwater and brine streams. Two other types of membranes, plate-and-frame and tubular are no longer used commercially because they are bulkier and more expensive. There are several different polymers used in reverse osmosis membranes. For an in-depth discussion of membranes, see Chapman-Wilbert (1993).

RO systems can be designed for intermittent or continuous operation. Most larger RO systems operate continuously. Systems operating intermittently should include automatic control systems to flush the membranes with desalted water after each shutdown. Fouling of the membranes during shutdown because of microbial growth can present complications which may or may not be preventable (depending upon the quality of the feedwater) with proper disinfection or flushing. While some sources claim that intermittent use wears out the membranes (Buros, 1980; and Abdul-Fattah, 1986), others have experienced no adverse effects of moderate start-up, shutdown cycling (a moderate start-up, shutdown cycle is on the order of 30 minutes to several hours) (McBride et al., 1987; and Robinson et al., 1992). Most systems with intermittent operation have employed computer control systems, batteries, or pressurized water storage to minimize the frequency of cycling and to maintain relatively constant pressure and flow rates during operation. Researchers at the Florida Solar Energy Center (FSEC) have found that RO systems designed for intermittent operation, such as small systems designed for use on boats, often do not perform well under continuous operation, because of overheating of the motor and wear of the pumps (Huggins, 1996).

Maintenance and operational requirements for reverse osmosis systems depend on the quality of the feedwater and the efficiency of the system. The various pretreatments that may be required have already been discussed. Systems requiring much pretreatment also require skilled operators. Therefore, reverse osmosis may not be the appropriate desalination technology in areas with poor quality feedwater supplies and few technically skilled personnel. High-efficiency systems using high pressures and high recovery rates require greater operational oversight and pretreatment than more rugged systems using lower recovery rates.

Post-treatment usually involves pH adjustment, removal of dissolved gases such as carbon dioxide and hydrogen sulfide, and disinfection. Although in theory reverse osmosis should remove all microorganisms, in practice there are often small leaks in the system, making disinfection a

Regular maintenance involves monthly cleaning of the membranes and changing of filters. Performance of the system gradually declines between cleanings as scale and microorganisms foul the membranes. Membranes must be replaced every 2 to 5 years. Operations problems at several reverse osmosis installations have included fouling of membranes by microorganisms, iron deposits, and colloids; improper mixing of pretreatment chemicals; and corrosion of the metal structural and electrical components of the RO control systems due to the high humidity surrounding the RO system. Biofouling in particular has been a major problem where insufficient attention was paid to the training of the system operator (Price, 1996).

The reported price of RO systems varies widely, primarily for two reasons. First, a large number of manufacturers provide RO systems specialized for various applications, including home, boat, industrial, and municipal water supply. Second, the cost of pretreatment varies depending upon the feedwater quality. For developing country applications, a reasonable capital cost estimate is \$1,600 to \$2,000/m^3/day of capacity. Lifecycle costs range from \$0.5 to \$3 per cubic meter, depending on the cost of pretreatment chemicals and on feedwater salinity, which determines the amount of energy needed.

Energy requirements range from 3 kWh/m^3 for brackish water to 17 kWh/m^3 for sea water (Wade, 1993; Block, 1989; Al-Ajlan, 1995; Talati, 1994; and Sadhukhan, 1994). Many reverse osmosis systems now use energy recovery to increase the efficiency of the system. Most of the energy needed for reverse osmosis is for the high pressure pumps. While the product water exits the system at atmospheric pressure, the brine stream remains at high pressure. Energy recovery exploits the energy of this high pressure brine. There are various ways of recovering the energy, including a Pelton turbine, reaction turbine, hydraulic power recovery turbine, or a reverse running centrifugal pump. Of these, the Pelton turbine has been most commonly used (Al-Ajlan, 1995). Systems employing energy recovery turbines generally recover about 30% of the energy put into the system (Wade, 1993). Recently built, large (greater than 20 m^3/day capacity) sea water RO installations employing energy recovery have reported energy demands of 5 to 6 kWh/m^3 (Rodríguez-Gironénes et al, 1996). Energy recovery turbines do not significantly increase the operational complexity of reverse osmosis systems and can be used in installations in developing countries.

Many companies, including Recovery Engineering, Inc., Mobil Corp., Darentek, and Powersurviver, produce small- to medium-capacity PV-battery RO systems. In addition, other renewable energy configurations have been demonstrated. The following section profiles case studies of renewable energy-powered RO systems.

Table 3. Examples of Renewable Energy-Powered Reverse Osmosis Installations

Location and power source	Capacity (m^3/day)	Net Energy Demand (kWh/m^3)	Feedwater TDS (ppm)	Recovery Rate (%)	Energy Storage/ Operating conditions	Builder and year built	Reference
PV							
Concepcion del Oro, Mexico 2.5 kW PV	0.71	6.9	3,000	37	none (direct drive)/ intermittent operation	Digaases and GKSS 1978	Fries et al. (1982)
Jeddah, Saudi Arabia 8 kW PV	3.2	13	42,800	n/r	battery/ daylight operation	Mobil, for SOLERAS 1981	Abdul-Fattah (1986)
Perth, Australia 1.2 kW PV	0.4 to 0.7	4.0 to 5.8	n/r	n/r	battery/ daylight operation	SERIWA 1982	Block (1989)
Vancouver, Canada 0.48 kW PV	0.5 to 1.0	10	n/r	n/r	battery/ n/r	n/r 1984	Block (1989)
Gillen Bore, Australia 4.16 kW PV	1.2	n/r	1,600	n/r	n/r	CAT 1993	Harrison et al. (1996)
Sadous, Saudi Arabia 10.08 kW PV	5.7	<18	5,700	21 to 35	battery/ intermittent operation	KACST 1994	Hasnain (1995)
St. Lucie, Florida 2.7 kW PV	0.64	13	32,000	10	battery/ continuous operation	FSEC 1995	Huggins et al. (1995)
Doha, Qatar 11.2 kW PV	5.7	10.6	35,000	n/r	n/r	Mobil n/r	Block (1989)
Wind-Electric							
Süderoog, North Sea 11 kW Aeroman turbine	4.8	36.3	28,000	25	none/ cut-in, cut-out wind speeds	GKSS 1979/ altered 1985	Petersen (1997)
Planier, France 4 kW Aerowatt turbine	12	7.8 (with 1.2 kW Pelton energy recovery turbine)	n/r	25	none/ cut-in, cut-out wind speeds	CEA 1982	McBride et al. (1987)
Pozo Izquierdo, Spain 2, 200 kW Enercon turbines	8 modules each 25 m^3/day capacity	n/r	38,000	n/r	battery/ modular deferable load	CIEA in progress	Cruz et al (1996a)

Location and power source	Capacity (m^3/day)	Net Energy Demand (kWh/m^3)	Feedwater TDS (ppm)	Recovery Rate (%)	Energy Storage/ Operating conditions	Builder and year built	Reference
Drenec, France 10 kW Aerowatt turbine	water supply for 60 people	n/r	38,000	n/r	battery/ continuous operation	Aerowatt (1990)	Cordis database
Wind-Diesel Hybrid							
Fuerteventura, Canary Islands, Spain 225 kW Vestas V27 turbine, 240 kW diesel	56	7.1	35,000	n/r	minigrid/ deferable load	ITER 1995	Cruz et al. (1996b)
Wind-Mechanical							
Perth, Australia Aermotor wind pump	0.213	5	2,000 to 6,000	6 to 11	pressurized water storage/ intermittent operation	Murdoch University 1990	Robinson et al. (1992)
Solar Thermal- Mechanical							
Cadarache, France 223 m^2 flat plate collector powers heat engine for direct shaft drive	60	n/r, includes energy recovery	2,000	n/r	none/ n/r	CEA 1978	Buros (1980)

Note: n/r means not recorded

GKSS is a German research institution which built two demonstration desalination plants, a PV-powered reverse osmosis plant in Mexico and a wind-powered RO plant, installed in 1979 on Süderoog, an island in the North Sea (McBride et al., 1987; and Fries et al., 1982). The Süderoog plant produced 2.64 m^3/day and consumed 36.3 kWh/m^3 to convert water of 28,000 ppm TDS to less than 500 ppm. Its RO system employed piston pumps to achieve water pressures of 60 bar and a recovery rate of 25%.

Power was supplied by a 6 kW Allgaier-Hütter turbine. In 1985 MAN, another German research institution, replaced this turbine with a two-bladed 11 kW Aeroman 11/11 wind turbine which used automatic pitch control for constant frequency power. A small battery was used for short term power smoothing; otherwise, no energy storage was used. In order to minimize start-up, shutdown cycling, a cut-in criterion was established requiring 20 minutes of wind speed above the cut-in velocity of 6 m/s to start up the RO system. The system was taken out of operation in 1986 because it required too much maintenance for the islanders (GKSS had since ceased its desalination research). The inhabitants of Süderoog reverted to their previous practice of importing fresh water by ship.

Murdoch University installed a wind pump-powered RO plant in Western Australia in 1990. The RO plant produces 0.213 m^3/day. Capital cost of the entire system was $10,000, while operating costs were $250 to $500 per year (Robinson et al., 1992). The system uses a mechanical

Aermotor fan-blade windmill (4 m diameter, 10 m tower, average wind speed 3.2 m/s), to pump brackish groundwater into pressure vessels. Mechanical wind power was selected because the local communities are familiar with this technology and it can easily be serviced locally. A 42 W PV panel connected to a 12 volt deep cycle battery powers the control system. The pressure vessels serve to smooth out the fluctuating output of the windmill. The RO plant can operate within a feedwater pressure range of 6 to 11 bar. When sufficient pressure is reached in the pressure vessel, the RO unit is brought into operation. At high wind speeds, a relief valve prevents overpressuring of the membranes.

The system is designed to be rugged and low maintenance. It has a water recovery rate of 6% to 11% and a salt rejection rate of 83% (RO systems typically have recovery rates of 30% and salt rejection rates of 98%). Because of this design, its only pretreatment requirement is filtration and it can tolerate the fluctuating pressure levels.

Cheap tubing and seals deteriorated and were replaced with UV-resistant tubing and delrin seals. In 13 months of operation, maintenance requirements included one change of filters and one RO membrane servicing, two over-pressure valve servicings, and solar charging system servicings. Membrane performance declined 25% during 13 months.

The researchers offered the following conclusions: (1) optimization of the pressure vessel capacity significantly affects system performance; (2) problems were experienced with wear of the pump seals in the mechanical pump; (3) systems that are the sole source of a community's drinking water should have diesel backups; and (4) this system is cost competitive with water carting in Western Australia only for carting distances greater than about 30 km.

The Canary Technological Institute's Water and Energy Research Center (CIEA-ITC) is currently installing a large-scale desalination complex at Pozo Izquierdo on Gran Canaria Island, Spain, with funding from the APAS project (Cruz et al., 1996). The complex includes a 200 m^3/day, 8 module RO plant, a 50 m^3/day ED plant, and a 20 m^3/day vapor compression plant, and costs 1.5 million ECU ($1.88 million). The entire off-grid facility is powered by two 200 kW variable speed Enercon turbines with battery storage and power conditioning.

Researchers are still in the process of optimizing the system. The system is not designed for continuous operation. Rather, the 8 RO modules will be configured to be individually brought on line as power is available. Researchers are considering whether the optimal configuration might involve using the ED plant as a second stage to the RO plant. Another option being considered is using electrical resistance heating as a dump load to heat feedwater into the RO plant, because of the increase in RO output with temperature.

One concept that has gained much attention recently is the use of a modular desalination system as a deferable load in order to increase the wind penetration potential in a wind-diesel minigrid. The modules of the desalination unit would be brought on-line as power from the wind became available, in order to increase utilization of available wind power, decreasing the amount of excess power which must be "dumped" and reducing the amount of diesel run-time, and to allow the hybrid system to operate a optimal loads. RO is particularly suited for such systems, because RO is a modular technology, with typical installations containing several RO membrane/pump modules.

While several modelling studies have been conducted (e.g., Binder et al, 1996; and Warfel et al,

1988) only one operational system could be identified by a literature search. The system, located at Fuerteventura in the Canary Islands, consists of one Vestas V27 225 kW wind turbine and two 160 kW diesel generators, which supply the lighting, refrigeration, sewage treatment, and desalination needs of 300 people. The RO unit requires 16.5 kW and produces 56 m^3/day. Peak load on the minigrid is estimated at 100 kW (Cruz et al, 1996b).

The system is still in the process of being optimized. Problems were experienced with fouling of the RO system and with maintenance of the diesel generators. In order to increase wind penetration, a large (150 kW) dump load was added to stabilize the system at high wind speeds. To date no testing of using the modularity of the RO system to control wind penetration and energy dumped has been conducted,

In Mexico, Digaases (the former Mexican agency for water research and supply) investigated mobile RO trailers, which would include power supply, pretreatment, and an RO unit. The trailers would move from village to village on a weekly schedule, desalinating enough water to last the village until the trailer returns again. The power supply would most likely be diesel. The idea is interesting, because several villages could pool their resources to pay for the system and for a full-time, skilled system operator.

In conjunction with Murdoch University in Western Australia, the RO manufacturer Venco has developed a PV-powered RO unit which can produce up to 400 liters/day from brackish water up to 5000 ppm TDS and is designed for use in remote areas. Several units have been sold. Unlike most PV-powered systems, Venco's uses no batteries. Instead, the 120 peak Watt PV panels, with the aid of a power maximizer, supply power to a DC motor which operates a positive displacement piston pump at variable speed. The system operates therefore with variable flow rates, albeit constant pressure. Recovery rates range from 16% to 25% depending upon salinity and flow rate. The system is designed to operate unattended. In addition, the system is designed so that when maintenance of the membranes or pumps is needed, they can be detached and sent back to the manufacturer for maintenance. A ultraviolet disinfection system can also be added. The capital cost is listed at \$15,000/m^3/day, including the PV system. The unit includes a 25 µm and a 5 µm pre-filter, corrosion-proof cylinder, and energy recovery (Butler, 1997). Although the claimed water production rate may be slightly overstated, the system is of great interest for its efficient use of solar energy and ease of operation in remote locations.

Extensive research has been conducted by the Energy Research Institute of King Abdulaziz City for Science and Technology (KACST) on a PV-battery-inverter RO system in Sadous, Saudi Arabia. Installed in November 1994, the RO system produces on average 5.7 m^3/day, converting brackish water from 5,700 ppm TDS to 170 ppm TDS with an average 30% recovery rate. The entire desalination system consists of pumps (booster, chemical, high-pressure, and distribution), building accessories (ventilation fan, lighting), control system, and a UV sterilization system (Hasnain, 1995; and Smiai and Rafique, 1995).

The system uses a 10.08 kW PV array to charge two 120 volt, 1,101 amp-hour battery banks connected to a 5 kVA inverter. The batteries have a 5-day storage capacity. The RO system is operated intermittently, according to fluctuating demands for water. Typically, the unit goes through six start-up, shutdown cycles each day, staying on for 1 to 4 hours during each cycle. The automatic control system flushes the membranes after each shutdown. Start-up of the RO system creates an approximately 20-second current drain on the inverter of six times more than rated power. The surge distorted the output power wave from the inverter, causing loss of function in the control system. This problem was rectified by adding a 250 volt-amp uninterruptible power supply to maintain power to the control system (Smiai and Rafique, 1995).

The system has tolerated intermittent operation well. Indeed, continuous operation for long periods in hot weather resulted in overheating of the motors. Membrane fouling is an on-going problem, requiring membrane replacement every six months.

The system's recovery rate varies depending on the pressure, age of filter, time elapsed since the membranes were cleaned, and temperature. Recovery rate increased 2.7% for each degree centigrade increase in temperature (Smiai and Rafique, 1995).

The Florida Solar Energy Center (FSEC) installed a PV-powered RO facility at the St. Lucie Inlet State Preserve off the coast of Florida in March, 1995. The island facility uses duplicate RO units produced by Recovery Engineering to desalt 0.64 m^3/day for use by visitors to the nature preserve. The 2.7 kW PV array supplies energy to the 1050 amp-hour battery bank, which powers the supply well pump, the two RO units, chlorine injection pump for disinfection of the desalted water, product water distribution pump, and lighting. The only pretreatment used is filtration. The RO units consume 13 kWh/m^3 and frequently produce more water than is actually needed by the visitors. As originally designed, the excess water was spilled to the ground.

Several challenges were encountered by the designers. The feedwater is very high in reduced iron, which precipitates out, clogging the filters and membranes, if exposed to air. This problem was solved by building an air-tight feedwater intake system. The nature preserve is an environmentally sensitive area, which required the designers to incorporate several features to minimize the impact of the RO facility. Designers chose a low recovery rate (10%) so that the reject brine's concentration would not be significantly higher than the sea water, minimizing the effects of disposal into the ocean.

The RO units were designed for use on vacation boats, and therefore were not designed for continuous operation. Operators experienced frequent problems with continuous operation of the RO units, including overheating of motors, wearing out of the gearbox, and wearing out of the pumps. The system is being redesigned to allow intermittent operation, by alternating operation between the two RO units and/or by installing a float switch on the product water storage tank which would turn the RO units off when the tank was full.

Several questions remain to be answered in regard to renewable energy-powered reverse osmosis systems:

(1) Is the use of electrical resistance heating to heat feedwater to an RO system an efficient dump load? There is some disagreement on this issue. While heating theoretically improves RO output, and the CIEA-ITC project on the Canary Islands is considering it as an option, Robinson et al. (1992) found no statistically significant effect of feedwater temperature on RO output.

(2) A related question is the effect of variable feedwater temperature on the product water quality. Talati (1994) recommends that feedwater temperature be kept constant in order to maintain consistent product water flow and quality.

(3) The possibility of operating the RO system under variable frequency power has not been explored. Exploration of this issue should consider using a wind electric water pump with pressurized water storage in a fashion similar to the wind mechanical pump system installed by Murdoch University.

(4) A potential problem with using variable speed wind power for reverse osmosis, and a problem already experienced by KACST with its battery-inverter power system in Sadous, Saudi Arabia, is the power surge caused when the RO pumps start up. Research is needed into the use of capacitors or other methods for meeting the surge demands of the RO pumps.

(5) One question that has recently gained great interest is whether RO can be used as a deferable load in a wind-hybrid mini-grid to increase the penetration of wind energy (Rodríguez-Gironés, 1996). Many issues regarding optimal control strategies to bring modules on-line have yet to be resolved.

Electrodialysis

Electrodialysis (ED) is unique among all of the desalination processes in that its main power requirement is for DC power (some AC power is needed if AC pumps or reversing controls are used). It differs from RO in principle in that, whereas in RO a pump pushes water through membranes leaving the salts behind, in ED salts are drawn through membranes leaving desalted water behind. Electrodialysis is the most energy efficient method to desalt brackish water less than 5000 ppm TDS.

The basic unit of an ED system consists of four parts: cation-permeable membrane, demineralized feedwater stream, anion-permeable membrane, and concentrate flow stream. About 100 of these units, called cell pairs, are stacked in parallel to form an ED stack. On either side of the stack is an electrode. When an electric current is run through the electrodes, perpendicular to the flow of water, anions are drawn through the anion-permeable membranes by their attraction to the cathode but cannot pass through the cation-permeable membrane (and vice-versa for the cations), resulting in alternating demineralized and concentrated flow streams (see Figure 1). Most ED systems installed today are electrodialysis reversal (EDR) systems, in which the polarity of the electrodes is periodically reversed to clean the electrodes.

Because electrodialysis operates by removing ionic solutes from the feedwater, it has no effect on non-ionic solutes, such as organic matter, silica, and microorganisms. Therefore it cannot disinfect water. For water supplies with high silica levels, pretreatment is necessary to remove the silica. In such cases, RO might be a better choice than ED.

Operation can be in continuous or batch mode; continuous mode is more common. ED systems can be operated intermittently without any significant decrease in membrane life or efficiency, making them suitable for use as a deferable load. Unless DC pumps are used, both an AC and a DC bus are needed to supply ED systems. Ionics, Inc., the primary manufacturer of ED systems, reports that they can also tolerate fluctuating power levels.

Each stage in an ED system has a salt removal rate of about 50%. Therefore several stages are often needed, depending upon the feedwater salinity and the desired product water quality. The same electrodes can be used for a series of stacks, or electrical stages can be used, depending upon the salinity and limiting current of the system (see below). As the cost of the system dramatically increases with the number of stages required, ED systems are most cost-competitive for brackish water desalination.

As mentioned previously, pretreatment depends upon the quality of the feedwater. See Table 2 for a summary of pretreatment options. Post-treatment involves pH adjustment and disinfection. Routine maintenance includes cleaning of membranes to control scale and biofouling, usually by flushing the system with base and then with acid. Membranes must be replaced about every 10 years. Electrodes can degrade over time due to oxidation.

Cost of ED systems increases with increasing number of stages needed (i.e., on the feedwater salinity), and on the pretreatment system required. Ionics, Inc. suggests \$250 per m^3/day of capacity as a rule of thumb for the capital cost of a brackish water ED unit (excluding pretreatment costs). In accordance with these estimates, Ma et al. (1993) report capital costs of \$282 per m^3/day of capacity for a 5,000 cubic meter per day plant in California. Pretreatment equipment, however, added another \$118 per m^3/day of capacity to the total installed capital cost of the system. The lifecycle cost of this system is \$0.48/m^3. Abdul-Fattah (1986) reports lifecycle costs of \$4.50/m^3.

Energy requirements of brackish water ED systems range from 0.8 to 11 kWh/m^3, depending on the feedwater salinity. Of this, approximately 0.5 to 1 kWh/m^3 is for the low pressure (3 to 5 bar) feedwater pumps (Buros, 1980; Block, 1991; and Ionics, Inc., 1996). DC voltages range from 48 to 110 volts. The current needed is calculated from the equation,

$$I = \frac{\mathcal{F} q \Delta N}{\epsilon n}$$

where: I = current required in amps,
$\mathcal{F}$ = Faraday's constant (96,500 amp-seconds per equivalent),
q = flow rate of the demineralized (product) stream in liters per second,
ΔN = desired change in normality (salt concentration), ÷
ϵ = ED unit efficiency (usually 0.88), and
n = number of cell pairs in the ED stack.

This equation allows calculation of the minimum current needed to produce water that meets drinking water standards. The maximum current is limited by the phenomenon of polarization. At high current densities, depending upon the solute concentrations in the water and other factors, electrolysis of water occurs, resulting in loss of efficiency and the production of unwanted, explosive gases. The limiting current can be estimated by the relationship given by Hamada (1992):

$$\log(J_{\mathrm{lim}}) \approx 0.0007 \log(C)$$

where: J_{lim} = limiting (maximum) current density in amperes/square decimeter, and
C = concentration of NaCl in ppm.

Energy supplied to the electrodes is primarily dissipated in resistive losses. Therefore, power requirements to the electrodes can simply be estimated by $P = I^2R$, where R is the resistance of the stack. Less energy is consumed in the actual separation of electrolytes and in redox reactions that occur at the electrodes and form of hydrogen, oxygen, and chlorine gases.

The efficiency of the system increases with feedwater temperature (Hamed et al., 1993). Buros (1980) states that the salt removal rate of an ED system increased 1.8% with each degree C increase in the temperature of the feedwater. Meller (1984) reports that this increase in efficiency is due to a 1.1% decrease in the stack resistance with each degree F increase in temperature. More research is needed to determine whether heating feedwater with excess electricity from renewable energy systems during periods of high wind or insolation is an efficient use of this energy for increasing the output of ED systems.

Electrodialysis is a mature technology that has been in use for almost four decades. It was first developed by Ionics, Inc., a Massachusetts-based company, which still commands nearly 50% of the electrodialysis market worldwide. Other manufacturers include Mitsubishi, Asahi Glass, Tokuyama Soda, and a few English, Dutch, and French companies. The small number of manufacturers contrasts with the large number of RO and MSF manufacturers. Because electrodialysis is only cost effective for brackish water desalination, it accounts for only 5.7% of world desalting capacity and comprises only 12.8% of desalination installations (Wangnick, 1995).

Although no work on wind-powered ED systems has been published, several PV-powered pilot plants have been built, two of which are described below. All of the installations have used batteries to supply constant power. Further research is needed into direct-drive systems which could significantly reduce the cost of the energy supply system.

The Bureau of Reclamation is currently applying for patents on a small-scale (0.18 m^3/day) 2.3 kW PV-battery brackish water EDR desalination system that can operate unattended. The system, which uses entirely DC power, is designed for use in remote areas with little technical skill. A pilot plant provides water to 200 Navajo Indian families in New Mexico. The system uses 100 watts to convert feedwater at 900 ppm to 280 ppm, and consumes 0.8 kWh/m^3 of product water. A 600 amp-hour battery bank allows continuous operation. The control system shuts down the EDR unit in the case of low battery voltage or loss of water pressure indicating failure somewhere in the system. A service technician cleans filters weekly and replaces filters monthly (Lichtwardt and Remmers, 1996). The system has operated successfully since installation.

Ishimaru (1994) describes a PV-battery ED unit demonstration built in Fukue City, Japan, in 1988. The system is notable for the very low salinity of the feedwater (700 ppm), resulting in very low energy demands. A 65 kW PV array supplies enough energy to produce an average of 200 m^3/day of potable water. Battery storage of 1,200 amp-hours (10 hours of storage) provides constant power. A 30 kVA inverter supplies AC power to the pumps, while the electrodes are powered by a DC bus. Due to natural fluctuations in feedwater salinity and temperature, the water production rate and energy requirements fluctuated between 130 and 370 m^3/day and 0.6 and 1.0 kWh/m^3, respectively.

Electrodialysis is frequently compared with reverse osmosis, its rival membrane desalination technology. The advantages of ED are that it can operate at higher levels of solute supersaturation and therefore can have higher water recovery rates, minimizing the amount of brine which must be disposed of or enabling the joint production of salt; it operates under low pressures, reducing the operational hazard of high-pressure systems; unlike RO, the product water stream is under slightly higher pressure than the concentrate stream, reducing the chance of contamination; flushing the membranes with desalted water after each shut-down is not necessary; and its membranes have a lifetime more than twice that of RO membranes. The disadvantages of ED compared with RO are that ED cannot remove non-ionic solutes such as microorganisms and silica; ED systems take up more space than RO; and ED becomes significantly more expensive at

Membrane Distillation

Membrane distillation is still in the prototype phase of development. However, the technology shows great promise, because it combines the advantages of membrane separation and distillation, and it may begin to compete with more proven technologies in the near future.

In membrane distillation, a membrane permeable to vapor but impermeable to liquid water separates a heated feedwater stream from a cooler product water stream. Water vapor from the heated stream passes through the membrane due to the gradient in vapor pressure and condenses in the product stream. A heat exchanger recovers some of the heat. The advantages of the system are that it operates at relatively low pressures and temperatures, requires only filtration for pretreatment, and, like any distillation process, its energy requirement and product water quality are independent of feedwater quality. Because it operates at low temperatures (50° to 90° C), the feedwater can be heated by solar-thermal collectors. The primary energy requirement is thermal, although some electrical energy is required to pump the water through the system.

Membrane distillation can readily tolerate fluctuating and intermittent operating conditions. In addition, maintenance requirements are low.

At least three demonstration projects using solar-thermal membrane distillation have been built. Hogan et al. (1991), at the University of New South Wales in Australia, describe a 0.05 m^3/day system using 3 m^2 of solar collectors. The calculated efficiency of 17 liters per day per square meter of collector area compares favorably with solar MSF and ME plants. The researchers calculate that the process requires 55.6 kWh/m^3 (thermal and electric). Capital cost estimates range from $60,000 to $80,000 per m^3/day of capacity; the primary costs are the solar collectors, heat exchangers, and membranes.

The Water Re-use Promotion Center in Tokyo, Japan, installed a demonstration solar-powered membrane distillation plant in 1994 that produces 40 liters per hour. Automatic controls start up the desalination system whenever sufficient sunlight is present to provide hot water and electricity for pumping from the solar collectors and PV panels.

A solar-powered membrane distillation system was installed in the Canary Islands in 1988. The system produced 14.5 liters per day per square meter of collector area, and operated intermittently according to the availability of sunlight.

Freeze Separation

When salt water freezes, pure ice crystals rise to float above the denser salt brine. The ice can then be scraped off and melted to produce desalted water. While freeze separation has been proposed as a method for desalination for several decades, only demonstration projects have been built to date. The concept is appealing in theory because less energy is needed to convert ambient temperature water to ice than to steam, because of the smaller change in temperature and because the enthalpy of fusion is less than the enthalpy of vaporization (335 kJ/kg compared to 2250 kJ/kg). Plants built in the 1960s reported energy demands of 6 to 108 kWh/m^3, which compare favorably with ME and MSF plants. In addition, the use of low temperatures removes the risk of scaling or corrosion, so that the only pretreatment requirement is deaeration.

In practice, however, the complexity of designing systems to remove the ice from the brine and wash entrapped brine from the ice crystals has discouraged many engineers. The necessity of washing the ice with desalted water also reduces the efficiency of the process. Freeze separation has not proved to be a cost-effective method of desalination. Many plants proposed in the 1970s were abandoned because of these technical obstacles (Buros, 1980).

Future research may discover solutions to these problems. In the near future, however, proven distillation methods such as vapor compression are preferable to freeze separation.

There are as many designs of freeze separation processes as there are methods of refrigeration. Four of the most commonly used methods are described briefly below.

Vacuum-freezing vapor compression. Feedwater, entering a chamber, is subject to the vacuum created by a compressor, which brings the feedwater to its triple point. Some water vaporizes, cooling the water around it. The resulting ice is removed and washed. The vapor enters the compressor and is then mixed with the washed ice, melting the ice. The brine is drained and used to precool the feedwater. The process requires a large, low-pressure compressor. Colt Industries developed such a compressor for a 379 m^3/day plant and built a 454 m^3/day plant in Wrightsville Beach, North Carolina in the 1960s that required 11.9 kWh/m^3. Other pilot plants have had trouble with inadequate heat removal systems (Buros, 1980).

Vacuum-freezing ejector-absorption. This process is similar to that of vacuum freezing vapor compression, except that the vapor compressor is replaced with a steam ejector and absorber system. The steam ejector has fewer moving parts than a compressor, but it needs steam and a caustic absorption solution to absorb vapor.

Refrigeration freezing. A standard refrigeration cycle is used to cool the product water stream until ice forms. The ice is scraped off and melted. The most widely cited demonstration project of this type is the solar-powered plant in Yanbu, Saudi Arabia, built by Chicago Bridge and Iron, Inc. as part of the SOLERAS program, a joint venture between the United States and Saudi Arabia. The system at Yanbu was highly inefficient. It used point-focused solar collectors to heat oil, which heated salt, which acted as a storage medium for continuous operation, to heat water, to produce steam, to produce shaft power for the condenser of the refrigeration cycle. The Florida Solar Energy Center (FSEC) (Block, 1989) calculates that the system uses 108 kWh/m^3. A 43,800 m^2 collector area was required for the plant, which produced between 48 and 178 m^3/day. The salt provided enough heat storage for 10 days of operation (Hasnain, 1995; and Al-

Ajlan, 1995). The plant was shut down in 1989 because it was not economically viable.

Secondary refrigerant. An immiscible liquid refrigerant, e.g., butane, is mixed with seawater, which then enters a chamber maintained at a pressure below the boiling pressure of the refrigerant but above that of water. The refrigerant (butane) evaporates, cooling the water. A compressor creates the vacuum and compresses the butane, which is then condensed on the ice in the melter. The ice-butane mixture is then separated. Less of a vacuum is required, and less vapor is produced so that a smaller compressor is required. However, stripping is required to recover refrigerant from brine and product, and butane is explosive. A pilot plant built in Israel in the early 1960s experienced problems with the design of the washer. Several companies have built pilot plants, including North American Aviation Co., Struthers Scientific and International Corp., Israel Desalination Engineering, Koppers Co., AVCO Corp., UK Atomic Energy Authority, and Misui Shipbuilding and Drydock Co. (Buros, 1980).

Past and Present Research Efforts

Research has been conducted on desalination at numerous research institutions during the past forty years. The following is a brief listing of some of these research efforts on small-scale, renewable energy-powered desalination systems. It should not be considered a complete listing.

From 1952 to 1970, the U.S. Department of Interior administered an Office of Saline Water (OSW), which looked primarily at solar stills and MSF technologies. Research was conducted at Daytona Beach, Florida, and in conjunction with the University of California at Berkeley's Sea Water Conversion Laboratory. The results of the OSW's research are summarized in OSW's *Manual on Solar Distillation of Saline Water* (1970) and in *Fresh Water from the Sun* (1978), published by US AID.

The OSW was replaced in 1992 by the Bureau of Reclamation's Water Treatment Technology Program (WTTP). Among other things, the Bureau is aiding in the establishment of a Middle East Desalination Research Center in Oman. In addition to the Middle Eastern countries, Japan, Israel, Korea, and the European Union are participating in the research initiative. The WTTP has also established the Interagency Consortium for Desalination and Membrane Research to coordinate research conducted by member agencies, which include the Bureau of Reclamation, Environmental Protection Agency, Centers for Disease Control, Army, and Navy. WTTP is in the process of establishing a system of National Centers for Water Treatment Technologies, in order to coordinate the various research being done around the country.

The Florida Solar Energy Center (FSEC) has extensively researched solar stills and PV-powered RO systems, with a focus on meeting Florida's water needs. It has installed a small-scale PV-powered RO system at St. Lucie.

The University of Massachusetts, Amherst has studied the technical issues of wind-driven reverse osmosis since the 1980s.

The Solar Energy Laboratory of the Federico Santa Maria Technical University (Chile) researched solar stills in the 1960s and 1970s.

The Brace Research Institute (Quebec) has researched solar stills since the 1960s. It has installed many solar stills in developing countries, including Haiti, Argentina, and Botswana. Recently the Institute has begun research on solar thermal membrane distillation.

Researchers at Murdoch University in Western Australia have installed several demonstration wind-powered reverse osmosis systems, including grid-connected systems and off-grid mechanically powered systems. Murdoch is also testing membrane distillation systems.

SOLERAS was a joint research agreement between Saudi Arabia and the United States to cooperate in developing solar energy technology and to facilitate technology transfer. Implemented by the National Renewable Energy Laboratory (then called SERI), the program lasted from 1977 until the late 1980s. Several prototype plants, including a PV-powered electrodialysis plant, a PV-powered RO plant in Jeddah, a solar-thermal MSF plant in Mexico, and the Yanbu freeze separation plant, were built as part of the SOLERAS program.

Following the closure of SOLERAS, solar energy research was transferred to the King Abdulaziz City for Science and Technology in Riyadh, Saudi Arabia. Research has continued on using solar thermal and photovoltaic energy to supply water to remote communities in Saudi Arabia.

The Laboratory of Testing and Development of Solar and Other Energy Systems at the National Center for Scientific Research in Athens, Greece, has done substantial work on solar stills, including developing models to predict still output. In addition, the Laboratory has published an international desalination directory.

The Centre for Renewable Energy Sources (CRES), located in Pikermi, Greece, has funded several demonstration projects to desalinate water for Greek islands. These systems have tended to be rather large (several hundred cubic meters per day) and have been powered by hybrid wind-diesel minigrids.

APAS is a fund for energy research sponsored by the European Union which has funded several projects by CRES, ITER, and CIEMAT to build demonstration desalination projects powered by renewable energy. Several other Greek organizations and universities have participated in APAS projects. APAS funded the creation of a database of renewable energy-powered desalination installations and of European organizations and individuals involved with desalination. In addition, APAS funded the creation of the CORDIS database of research and development projects.

The Instituto Tecnologico y de Energias Renovables (ITER), in conjunction with the University of Gran Canaria, has evaluated large-scale hybrid-powered desalination systems for the Canary Islands. ITER has done much work on how desalination can be integrated into a load-management scheme for hybrid minigrids. PRODESAL is a program sponsored by ITER to develop large-scale renewable energy-powered desalination facilities.

Plataforma Solar de Almeria is a Spanish solar energy research center which has built and analyzed prototype solar thermal ME and MSF systems.

Risø National Laboratory in Denmark has studied hybrid wind-diesel desalination systems, including ME, RO, and vapor compression. Research has focused on robust systems suitable for use in developing countries, and has included analysis of hybrid power issues.

Conclusion

Determining the appropriate desalination technology for a community depends primarily on the availability of technical skill, the size of the water demand, the quality of the feedwater, the community's ability to pay, and the source(s) of energy available. Figure 2 shows how to begin selection of the appropriate desalination technology, based on these factors.

The economies of scale (and therefore the water demand at which the various technologies are economically competitive) of five technologies are graphed in Figure 3, which was extrapolated from a least-squares regression analysis of capital costs available in the literature (where capital cost includes cost of the desalination installation only, and excludes cost of energy and pretreatment). Insufficient data were available for VC to estimate its economy of scale.

Figure 4 shows how energy demand is proportional to feedwater quality for membrane systems, but independent of feedwater quality for distillation systems. Figure 5 divides this energy demand into its thermal and electrical components for specific desalination systems.

Finally, Table 4 summarizes all of these factors for the different desalination technologies. Note that the column labeled Vapor Compression in Table 4 does not include Superstill's characteristics, which are described in the section on vapor compression. From the comparison in Table 4, several general conclusions can be drawn.

Solar stills are the most widely used technology in developing countries, because they are easy to build and maintain. However, they are the most expensive technology. Solar stills are most appropriate for communities with very little technical skill and low water demands.

ME and MSF are appropriate for large water demands in areas with available technical skill and available waste heat from another process such as a thermal power plant.

RO, VC, and ED are the lowest-cost choices where electricity and trained maintenance technicians are available. ED is most energy-efficient method for desalination of brackish water with low non-ionic solute content. RO is suitable for brackish or sea water with low potential for membrane fouling. As it continues to develop, VC amy the most energy efficient method of sea water desalination.

Every desalination technology is capable of tolerating intermittent operation, given proper design and maintenance. In addition, all are capable of being powered by renewable energy. See Table 5 for a summary of the status of development of renewable energy-powered desalination.

Solar-powered operation of ME and MSF is still in the development stage, and past demonstration plants have experienced operational difficulties. ED and RO demonstration plants using PV or wind power have operated successfully using various methods to accomodate variable power, including battery storage with an inverter to supply AC power to pumps; battery storage with an all-DC ED system; cut-in/ cut-out power controls for both PV and wind operation, with a battery to supply uninterruptible power to the control system; and, for RO, pressurized water storage. Both battery-inverter and direct drive designs for PV-powered RO are essentially commercial, while PV-powered ED may soon be commercial.

Further research should be directed towards testing a wind-powered ED system using cut-in cut-out power criteria or wind-battery, and towards testing an electrical wind pump-pressurized water storage RO system. Development of a direct drive PV-ED system may significantly reduce the cost of this near-commercial combination. In addition, testing of VC using battery-inverter power systems and variable speed power is needed. Further modelling and design work is needed to develop optimal control strategies for a modular desalination system used as a deferable load for a hybrid mini-grid. Solar thermal research should focus on easily operated systems such as the rugged ME concept proposed here, rather than the more complex ME and MSF. Rugged ME systems could also be designed to utilize waste heat from diesel generators in diesel-hybrid minigrids. Finally, much research is needed to determine the competitiveness of freeze separation and membrane distillation with the more proven desalination technologies.

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Table 5: Development status of renewable energy-powered desalination

(Italic text indicates research areas of greatest interest for near-term commercialization. Blank cells represent renewable energy-desalination combinations which have not been tested. n/a means that the particular technology cannot be powered with this form of energy.)

Renewable Energy Source	Desalination Technology				
	Multiple Effect Distillation	Multistage Flash Distillation	Vapor Compression	Reverse Osmosis	Electrodialysis
Solar thermal	pilot plants (Spain, 1988; U.A.E., 1984) *Rugged ME*	pilot plants (Kuwait, 1984; Mexico, 1978)	n/a	n/a	n/a
Solar thermal-electric or mechanical		pilot plant thermal plus stirling engine (Texas, 1987)		pilot plant mechanical direct drive (France, 1978)	
PV-battery-inverter	n/a	n/a		commercial	pilot plant (Japan, 1988)
PV, no inverter	n/a	n/a		commercial direct drive (Australia, 1996)	commercial prototype battery/all-DC (New Mexico, 1995) *PV-direct drive*
Wind-battery	n/a	n/a	pilot plant (Spain, in progress) *Wind-battery-inverter*	pilot plants (France, 1990; Spain, in progress) *Wind-battery-inverter*	pilot plant (Spain, in progress) *Wind-battery*
Wind-diesel			*Wind-diesel-load management*	pilot plants in progress (Spain, Greece) *Wind-diesel-load management*	
Wind-mechanical	n/a	n/a		pressurized water storage pilot plant (Australia, 1990)	n/a
Wind-electric direct drive	n/a	n/a		cut in/cut out control pilot plants (Germany, 1979; France, 1987) *Pressurized water storage*	

Table 4: Summary of Desalination Options

Technology	Solar Still	Multiple Effect	Multiple Stage Flash	Vapor Compression	Reverse Osmosis	Electrodialysis	Membrane Distillation	Freeze Separation
Proven technology?	yes	yes	yes	yes	yes	yes	no	no
Energy needs	thermal	thermal and electric	thermal and electric	mechanical or electric	mechanical or electric	electric	thermal and electric	thermal and/or electric
Factors affecting power demand	ambient temp., wind, insulation	ambient and feedwater temp.	ambient and feedwater temp.	heat exchanger efficiency	feedwater salinity, energy recovery	feedwater salinity	n/d	ambient temp.
Energy consumption (kWh/m^3)	642	32 (thermal) 1 to 2.5 (electric)	48 to 441 (thermal) 3 (electric)	11 to 25	4 to 17	0.8 to 11	56	6 to 108
Capital cost ($/m^3/day)	9,000 to 66,000	1,000 to 12,000	800 to 15,000	1,100 to 4,200	1,600 to 2,000	280 (brackish)	80,000	2,400
Estimated lifecycle cost ($/m^3)	3.4 to 50	0.7 to 4	1.2 to 4.2	0.5 to 5	0.5 to 3	0.5 to 3 (brackish)	n/d	n/d
Typical Size of Installation (m^3/day)	0.005 to 5	1,000 to 10,000	1,000 to 100,000	2 to 1,000	0.01 to 10,000	0.1 to 200	n/d	n/d
Pretreatment requirements	none	Filtration, scale control, deaeration	Filtration, scale control, deaeration	Filtration, scale control	Filtration, other (depends on feedwater)	Filtration, other (depends on feedwater)	Filtration	n/d
Maintenance requirements	Inspection and repair of leaks; dust and salt removal	Scale and corrosion control, pump maintenance	Scale and corrosion control, pump maintenance	Scale and corrosion control, pump maintenance	Replace filters, clean mem-branes, pump and corrosion maintenance	Replace filters, clean mem-branes, pump maintenance	n/d	n/d
Operational complexity	Low	High	High	High	Depends on recovery rate and pretreatment	Depends on recovery rate and pretreatment	n/d	High (separation of ice)
Replacement requirements	none	Filter	Filter	Filter	Filter (monthly), Membranes (2 to 5 years)	Filter (monthly), Membranes (10 years)	Membrane lifetime unknown	none

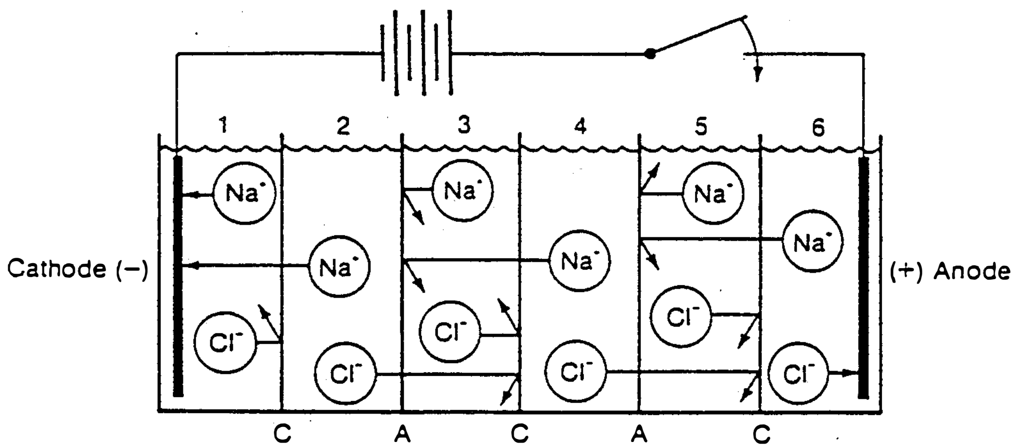
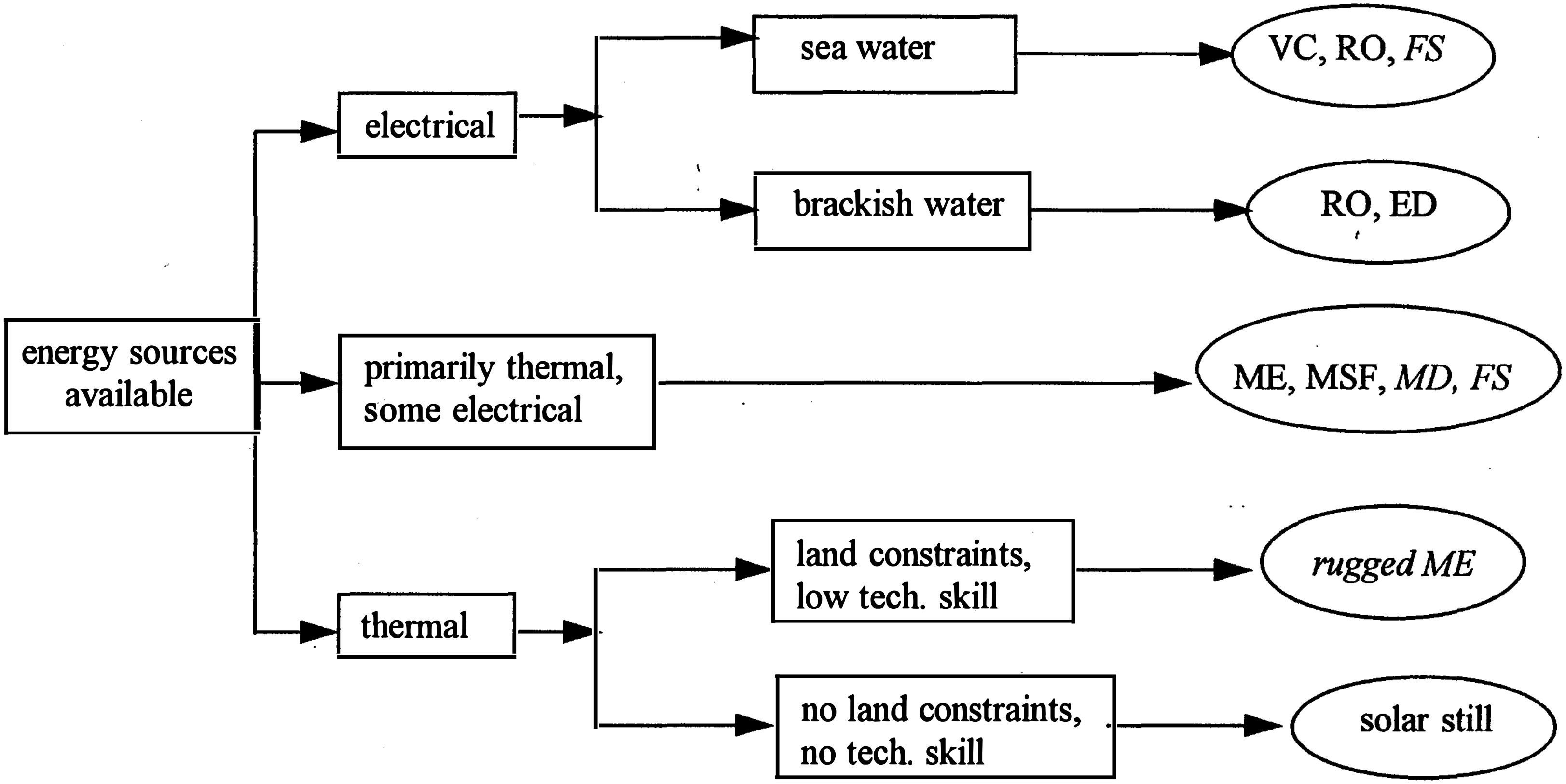


Figure 1: Schematic of electrodialysis

Shown are two cell pairs. "C" represents a cation-permeable membrane, "A" represents an anion-permeable membrane. Streams 2 and 4 are being demineralized, streams 3 and 5 are becoming concentrated, and streams 1 and 6 flush salts away from the electrodes. (From Ionics, Inc.)



KEY

Proven Technologies		Experimental Technologies	
RO	reverse osmosis	*FS*	*freeze separation*
ED	electrodialysis	*MD*	*membrane distillation*
VC	mechanical vapor compression	*rugged ME*	*rugged multiple effect*
ME	multiple effect distillation		
MSF	multistage flash distillation		

Figure 2: Choosing the Appropriate Desalination Technology

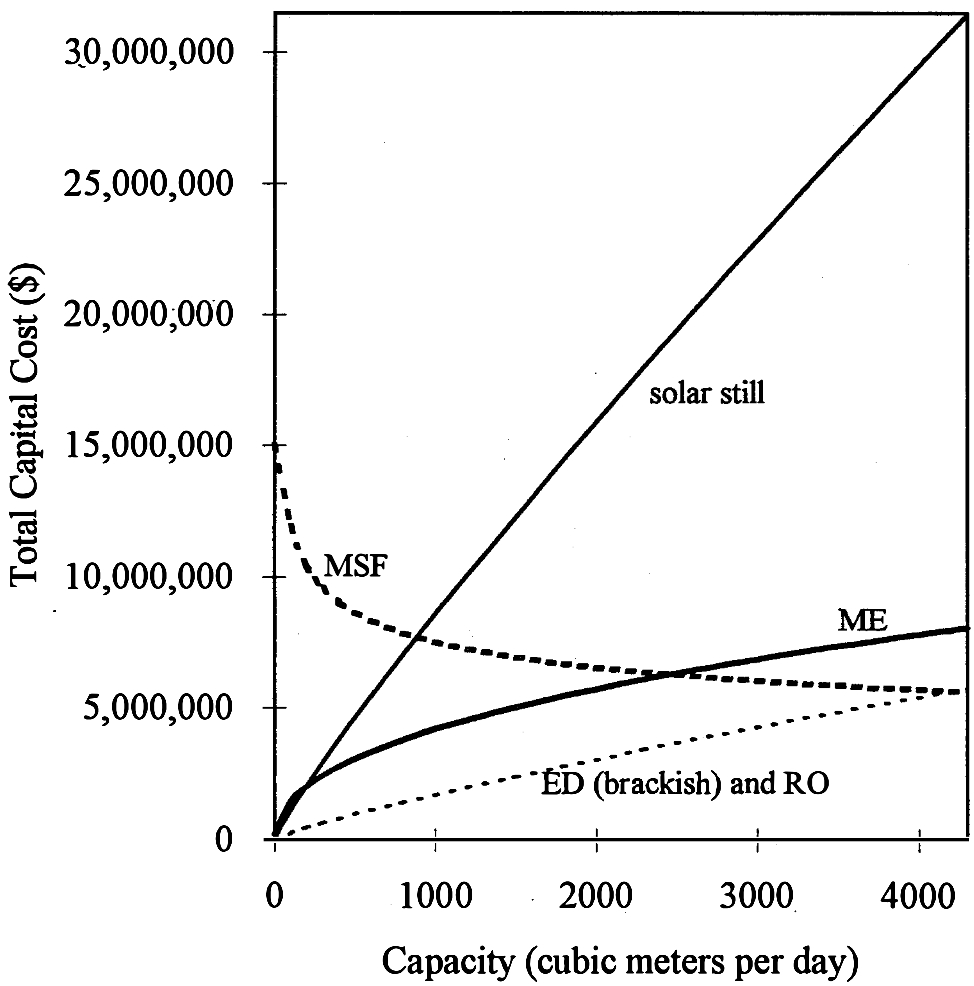


Figure 3: Relative Economies of Scale of Different Desalination Technologies

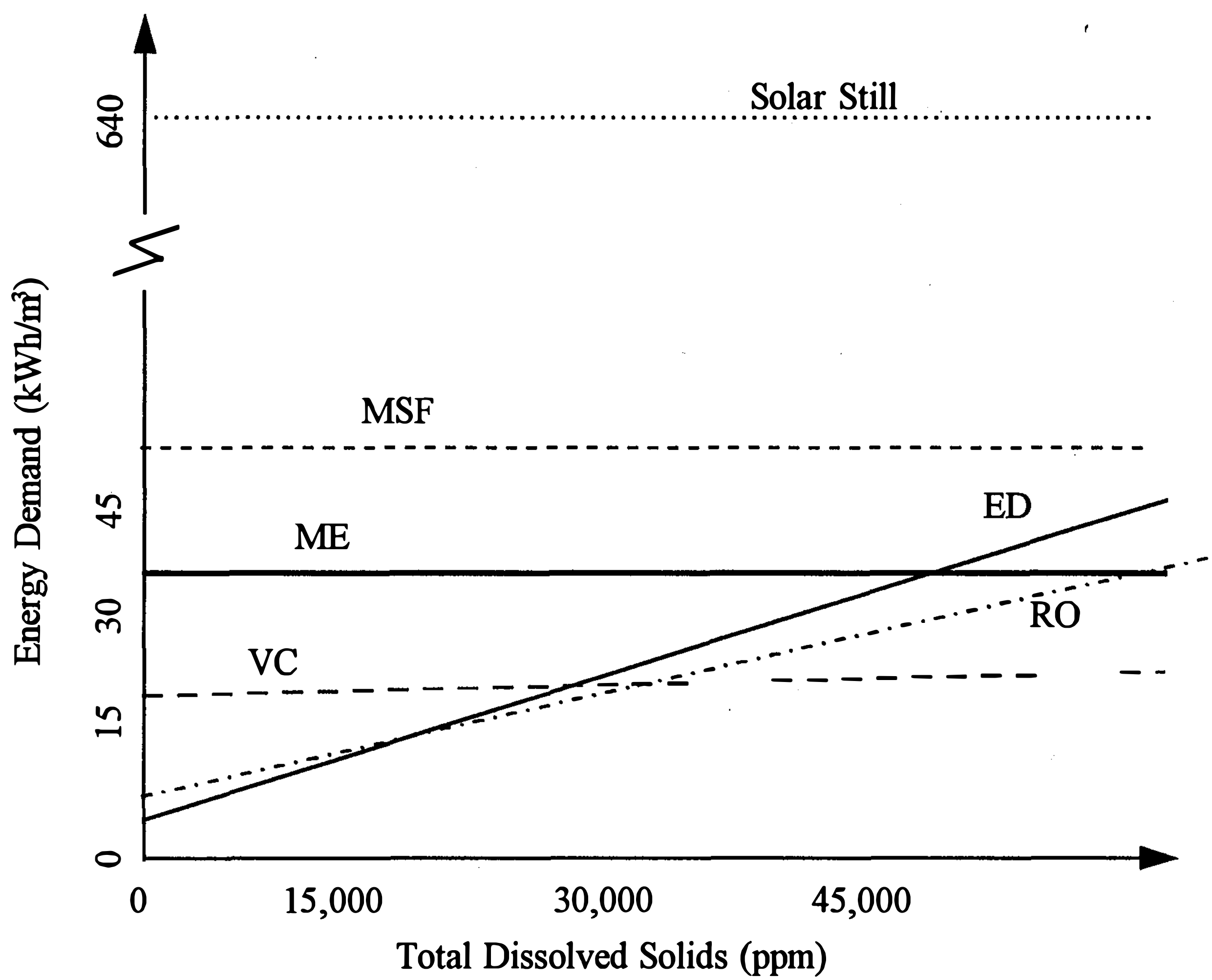


Figure 4: Effect of Feedwater Salinity on Energy Demand

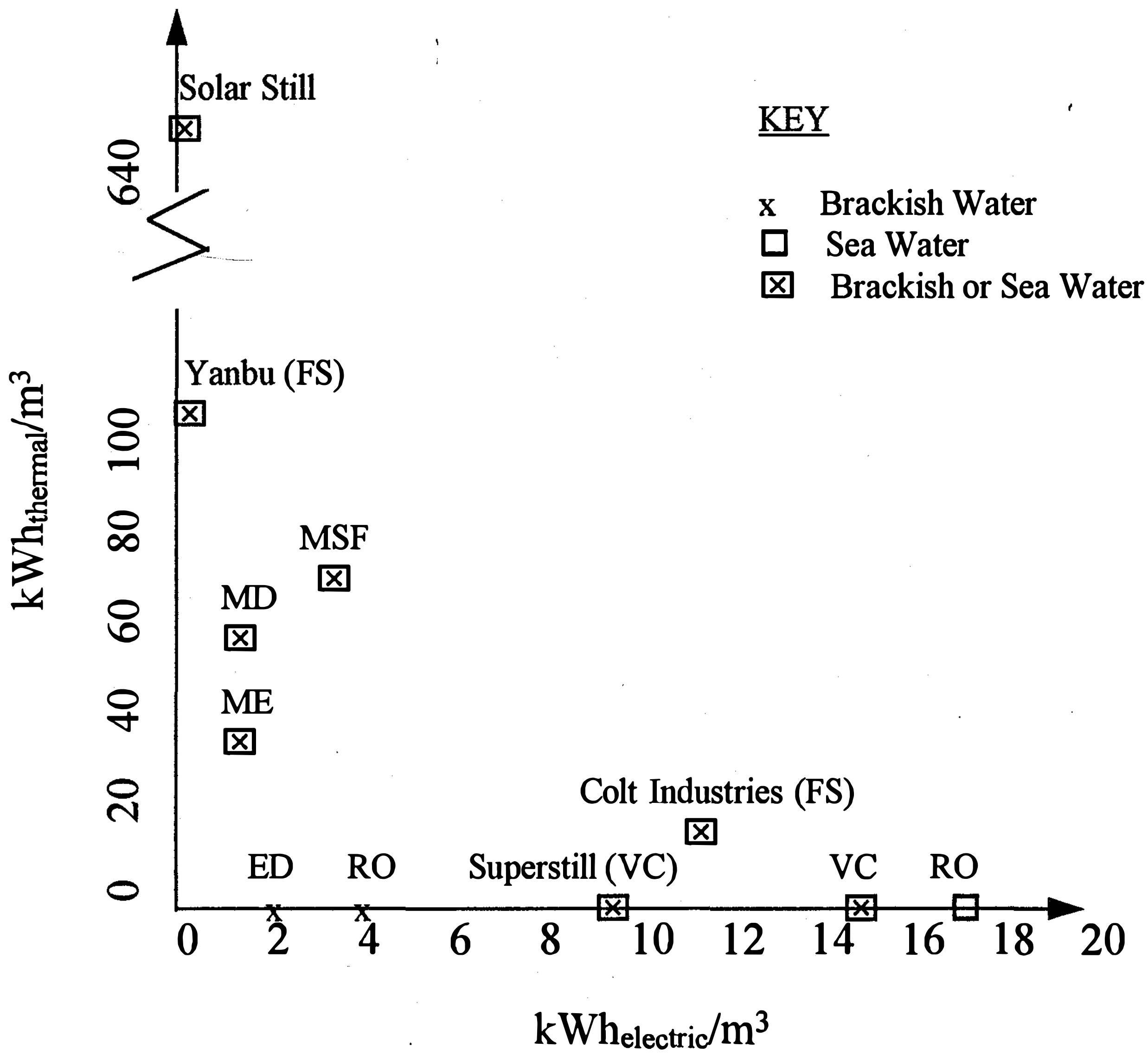


Figure 5: Thermal vs. Electrical Energy Demands

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13. ABSTRACT *(Maximum 200 words)*
An overview of desalination technologies is presented, focusing on those technologies appropriate for use in remote villages, and how they can be powered using renewable energy. Technologies are compared on the basis of capital cost, lifecycle cost, operations and maintenance complexity, and energy requirements. Conclusions on the appropriateness of different technologies are drawn, and recommendations for future research are given.

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