# Using solar energy to desalinate water[1]


Harry Z. Tabor



*One of the world's leading specialists in solar energy discusses the classical, basin-type solar still and the conditions governing its efficiency. Simple and suited to small capacity, this device leads to a high cost of water. For larger yields, conventional desalination processes energized by the sun are more appropriate; their costs are lower by an order of magnitude. Where feasible, they offer a simple technical solution to problems of water supply in the most arid regions of the developing world. Comparative costs are described.*


## Introduction

Considerable areas of the earth's surface are described as 'extremely arid'—where there may not be rain for more than a year—or 'arid'—where rainfall is inferior to the evapotranspiration of the area's water. There are other areas which, although not normally classified as arid, do not have enough fresh water to supply the growing needs of the population. In all such regions, social and economic development will be advanced if additional fresh water is made available. This has led, in the last two decades, to increasing interest in desalination processes.

Assuming that sea water or brackish water is available (or can be piped), the primary conditions for its conversion to fresh water are the availability of investment capital for the necessary plant and a cheap supply of energy. The use of the sun as a source of energy for distillation was, in the early days, mostly a question of local convenience. Today, with the rising cost of fuels, exploitation of this form of energy to augment potable water supplies assumes growing importance.

As one would expect from the notion of aridity, the extremely dry areas are well endowed with sunshine (as well as with large tracts of unutilized land), so that solar desalination would not be limited by the absence of an adequate energy source. This is in contrast to highly populated and developed zones, where solar desalination would not be very practical.

Water consumption varies considerably. In some parts of Africa and Asia it is below 20 litres per capita per day, but 50–150 litres per day is the more usual range [1].[2] These figures include both domestic and agricultural use. By comparison, per capita consumption in cities in the United States can exceed 1,000 litres [2]. A semi-arid country like Israel, doing intensive irrigation used 1,500 litres per capita per day in 1964 [1], four-fifths of this being for agriculture.

1. This article has been adapted from *Desalination with Solar Energy*, a paper presented before the International Symposium on Energy Sources and Development, held in Barcelona, Spain, in October 1977.
2. Figures in brackets correspond to the references at the end of the article.

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### *The realities of solar energy*

The solar energy available in the regions we are discussing varies from about $2 \times 10^6$ kilocalories (kcal) per square metre per year for the sunniest areas (Mauritania, Central India) to about half this amount in the least sunny areas. Central Australia, southern Africa and much of North Africa are near the upper limit; southern Spain is about halfway down the scale, with $1.5 \times 10^6$ kcal/m² per year.

Remembering that 500–600 kcal of heat are needed to vaporize 1 litre of water, for a single-effect distillation process having 40 per cent efficiency and receiving an annual insolation of $1.5 \times 10^6$ kcal/m², the water yield is about 1 cubic metre per square metre of surface, or an average of 3 litres per day. A population with a per capita consumption of 100 litres/day would require about 30 m² of distiller per capita, if all the water came from the solar still. And if the agricultural needs for irrigation water were, say, 7,500 m³ per hectare, about 40 per cent of the land would be covered with solar distillers! Clearly, desalination systems with much higher yields per unit of energy are needed for agricultural use. Some are discussed below.

Desalination is a particularly attractive use for solar energy because, in the case of a simple distilling operation, it is a low-temperature process. Furthermore, the intermittency of sunshine is not a serious impediment since the product, water, is easily stored.

### Early systems

All the early systems were based upon a single-effect distillation process, with the large solar desalination plant at Las Salinas, Chile, being the best known. It went into service in 1872, functioned for about forty years, covered 5,000 m² and had a maximal daily yield of about 19 m³ [3].

The basin-type, single-effect solar still is well known, and its design features can be found in standard references [4]. It comprises a horizontal, black tray with a sloping window above, the recommended minimal slope of which is 10° to prevent the condensate from dripping into the tray. The tray's sides are blocked off so as to enclose the water vapour which, rising from the heated water, condenses on the window's underside and is collected in a transversal drain channel.

Provided care is taken not to allow the brine to become over-concentrated, and thus precipitating salt out, the unit is about as simple and maintenance-free as one could wish. Care must also be taken in choosing its construction materials. If a plastic window is used instead of the more usual glass, its durability must be assured. (The experience with plastics in general has not been encouraging; the large distillation units in the Greek islands seem to have ceased functioning because of the failure of plastic windows.) Frames should not warp and sealing must be durable, as the unit's efficiency drops if there are vapour leaks in the system.

Temperature is a fundamental factor in the performance of solar stills of this type. If the ambient temperature or the water's temperature in the tray is raised, there is an increase in yield—a fact which provides guidelines for design features intended to improve yield.

The heat transferred ($q$) by convection and radiation ($q_r + q_c$) from unit area of the water's surface to the still's cover is nearly proportional to the temperature difference, that is:

$$(q_r + q_c) = C(T_w - T_c)$$

where: $T_w$=water temperature; $T_c$=cover temperature; and $C$ is a 'constant' (value about 1.6) that is only slightly temperature-dependent.

In practical terms, this means that the heat transferred rises markedly once temperatures exceed approximately 17 C.

### *Means of raising efficiency*

To determine actual output, one must allow for the transmission and reflection losses as well as for the loss through the bottom of the still which can be reduced to reasonable proportions by insulating the bottom. In many cases, this insulation is not done because it is difficult to keep the usual insulation materials dry. For a typical case observed over a 24-hour period, the input-output relationship looks like this:

| | | |
|---|---|---|
| Input | 2,555 BTU = 100 | per cent |
| Bottom loss | 572 BTU = 22.4 | per cent |
| Conduction and radiation loss | 396 BTU = 15.5 | per cent |
| Energy transfer ($q_e$) | 829 BTU = 32.4 | per cent |
| Transmission and reflection losses | 758 BTU = 29.7 | per cent |

Both the formula and the table have been calculated on the basis of Imperial (British) measure. Conversion needs to be made in order to express the values in terms of the metric or ISO system. If the condensate is collected, the efficiency is 32.4 per cent based on tray area—and slightly less if expressed in terms of glass area, in that this is usually larger than the tray area. If the bottom loss can be reduced to half, the daily output would be increased by about 30 per cent.

From these observations, we can conclude that: (a) efficiency rises with ambient temperature because a rise in glass temperature induces a nearly equal rise in tray temperature; (b) for the same reason, efficiency increases with reduced wind, though the total effect is not great; (c) higher solar intensities, leading to higher operating temperatures, yield not only increased output but some increase in efficiency; (d) in consequence of (c), the use of stationary booster mirrors providing a modest rise in incident radiation gives a more than proportional increase in output; and (e) high heat capacity, having the effect of extending the hours during which the still operates, causes a small reduction in output since the peak value of $T_w$—with little heat capacity—causes a larger part of the heat transfer by evaporation than the lower, more uniform value of $T_w$ when the heat capacity is high. It is thus preferable to use a small depth of water, provided there is no danger of salt precipitation.

### *Seasonal supply and storage*

At one time it was believed that the natural cooling of the condenser (the window) was a limiting factor. This led to suggestions that the condensing action should not take place within the unit, i.e. the unit should act as a solar collector and producer of water vapour which is then condensed in a separate apparatus. This view is now largely discredited.

For the practical designs one finds described in the literature, annual yield is of the order of 1 m³/m² (about 25 United States gallons per square foot), representing a daily accumulation of a little more than 4 litres/m² in summer and 1 litre/m² or less in winter. Where the still and the spaces between units can be used to collect rain water, the total annual yield will climb, especially in those regions where rainfall occurs mainly during periods of little sunshine. The last factor tends to even the difference between summer and winter yields.

Since demand does not always correspond exactly to supply, storage is needed unless there is to be want at times and waste at others. Short-term storage usually presents no problems, but annual storage (designed to equilibrate the large differences between summer and winter needs) can be expensive. If the storage costs are very high and the still particularly cheap, however, it might pay to use a larger still (in order to meet more of the winter's requirements) and less storage. Optimization studies usually show that it does not pay to make the still too large.

### Cost of desalinated water

Using basin-type stills, the cost is always high and can be justified only when there are no alternatives. The major reason is that the still is a single-effect machine, so that energy requirements, hence area of collection, are large. This will lead us, a little later, to consider multi-effect systems.

The cost of the water produced is dependent upon a number of factors, the important ones being (a) the annual amortized cost of the still, (b) maintenance and operating costs, (c) solar incidence and (d) distillation efficiency. As regards (a), this is the capital cost, $C$, of the collector multiplied by annual charges, $J$ (expressed as a ratio). $J$ is not only a function of the local interest rate; it is also a function of effective life-time of the still. Thus a well-made still using building materials such as cement, glass and asphalt can be expected to last twenty years, barring accidents. Plastics, given our present knowledge, offer only a few years of life. The consensus amongst users today is in favour of glass stills.

As regards (b), it is almost axiomatic that the still must be designed to be virtually maintenance-free. If leaks or other breakdowns have constantly to be repaired, the cost becomes prohibitive because the cost of labour exceeds other expenses.

The cost of the water produced, $W$, is then:

$$W = \frac{CJf}{QE(1+r)} hu,$$

where: $CJ$ is the annual cost of the still; $f$ a factor allowing for additional costs not detailed ($f > 1$); $Q$ the annual solar incidence; $E$ the mean annual efficiency; $h$ the latent heat of vaporization of water per m³; $u$ the fraction of annual product actually collected; and $r$ the fractional increase in annual yield attributable to rain collection.

$C$ and $Q$ may be expressed per unit area, incidentally, or for the whole area of the still. A typical value for $E$ is 0.3. For a sunny area, $Q \sim 1.5 \times 10^6$ kcal/m²; $h = 580 \times 10^3$ kcal/m³, i.e. $h/Q = 0.387$ m⁻¹; $u \sim 1.0$; $f \sim 1.25$; and $r \sim 0.1$.

The value of $C$, the cost per square metre of the still, would vary greatly from place to place, depending on the availability of materials locally and the cost of labour. In the middle 1960s, the value of $C$ hovered between 10 and 20 United States dollars; today, the figure is probably more than double this. Taking $C$ as \$30/m² and $J$ as 0.15 (8 per cent interest and a ten-year life), we obtain $W = \$6.6/\text{m}^3$, or about \$25 per 1,000 United States gallons. Even if the parameter values chosen were somewhat different, the value of $W$ would remain high unless a radical reduction in the value of $C$ could be achieved.

These high costs suggest that the basin-type still is only suitable to a certain size, beyond which more sophisticated systems—leading to lower water cost—would take over. The cross-over point, from one system to another, depends more on the alternative systems than on the basin still.

### Alternatives to the basin still

If the heat of condensation could be used to evaporate more water, a greater yield per unit area of still would be possible. Several suggestions have been advanced to obtain multi-effect operation in stills substantially of the basin type. In general, however, the extra complication involved has added to the capital, maintenance and operating costs so as to cancel benefits in yield; there are no known commercial systems of this type.

The other approach is to use any known, acceptable desalination process that needs heat as its energy source and to supply this heat from the sun. The viability of the system depends upon whether solar heat is competitive with whatever alternative energy sources are available locally. So we are concerned, in effect, with the techniques and economics of solar heat. But where the desalination plant is sophisticated—and good plant management requires that it be used at close to its rated capacity at all times—then the problem of matching the heat source to the plant becomes important. In this sense, the total system is an exercise in solar distillation. Whilst it is relatively easy to store the 'product water' over long periods, it remains very difficult to store the heat supply through an annual cycle.

It is well known that the collection efficiency of any thermal solar device diminishes with increasing output temperature, so that one has to seek low-temperature desalination processes wherever possible. Until a few years ago, commercial multi-effect desalination plants operated at temperatures well over 100 C, so that focusing-type solar collectors would be needed. In the last decade, low-temperature, multi-effect units have been developed. They have input temperatures of 70–80 C, with an economy ratio (steam input : mass of water output) of 10 : 1. One such process is the aluminium tube multi-effect (ATME), developed by Israel Desalination Engineering Ltd, and already commercially available. Another method under development, the Kogan-Rose process at the Technion in Haifa—using direct-contact condensation—should have similar performance; it is not yet commercially available.

The cost of energy is a vital factor in any desalination process. As a consequence, designers of desalination plants (of whatever type) have striven to reduce the energy requirements by further plant refinement, the process being optimized for the total costs of plant and energy. When the energy comes from fixed-price fuel, and when the source temperature may be freely chosen and the regulation of the energy source presents no difficulties, the designer has a relatively easy task.

### *Solar ponds and peak clipping*

When the energy derives from a solar device, the source temperature and the non-uniform character of the output have to be taken into account. One method is to match a multi-flash desalination plant of the ATME type with the thermal output of a solar pond.[1] (A solar pond is a reservoir in which the salty, heaviest layers retain the sun's warmth at the bottom rather than near the surface of the body of water.) Here, a solar pond was chosen because it was considered competitive with fuel as a source of low-temperature heat. If fuel is not available, except at exorbitant prices, and local conditions are unsuitable for a solar pond, then conventional solar collectors can be used. The methodology is essentially the same.

1. Let me describe the multiflash or multi-stage process. When water vapour condenses to water, much heat is released. Under special circumstances, i.e. if the pressure is reduced, this heat can be used to evaporate more water, and the process is repeated. Thus in, say, a ten-age system, nearly ten times as much distillate can be produced for a given input of heat as in a single-stage distillation. The plant is, of course, much more expensive, and the optimal number of stages used depends upon the cost of energy.

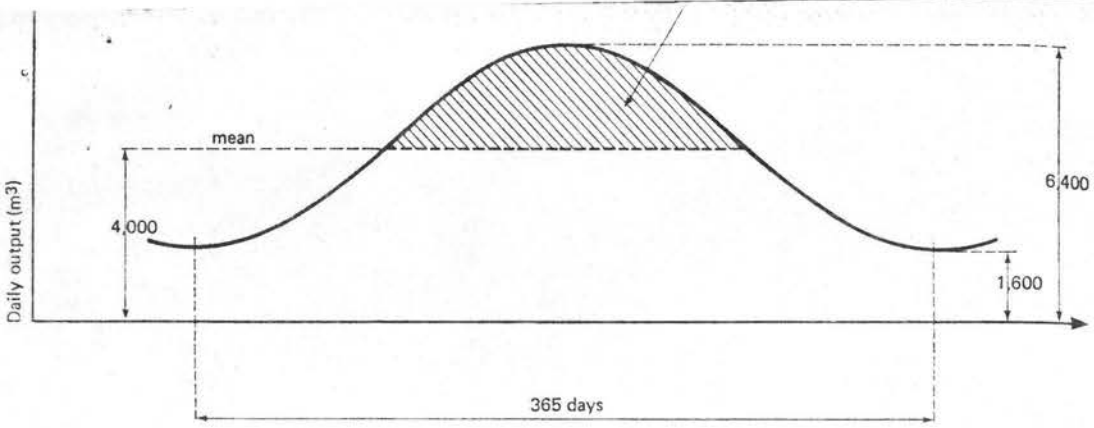


FIG. 1. Annual output of solar pond, when summer production is four times that in winter.

The method is based on 'peak clipping'—making the collector somewhat larger than necessary in order to provide the mean annual requirement, and rejecting surplus energy during the summer months. Seemingly wasteful, the process allows the expensive plant to be used at much nearer its rated value, thereby reducing its capital cost for a given total annual yield. Figure 1 shows the output of a solar pond when the summer peak is about four times the winter trough. Daily variations are smoothed out because of the system's heat capacity. The size of the pond required for such an operation, based on the efficiency indicated, would be about 0.23 km² (about 0.085 mi²).

In Figure 2 we see the effect of increasing the size of the pond by a factor of 1.37, to 0.31 km², rejecting 27 per cent of the summer yield. The rated plant capacity is now reduced to 4,700 m³, and the storage capacity—for equal demand through the year—is lowered by almost half. The results summarized in Table 1 show that the

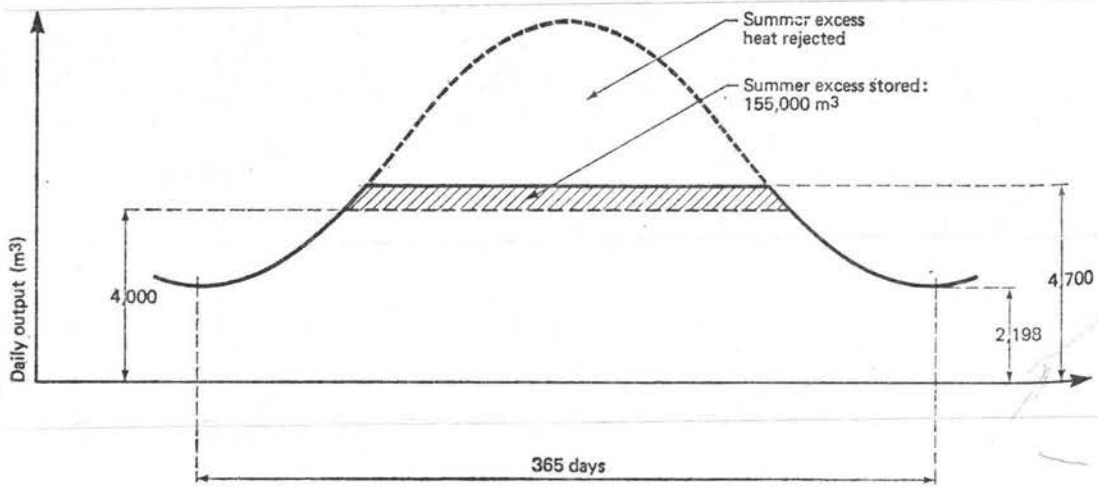


FIG. 2. Result of increasing the size of solar pond by approximately one-third.



| Production element | Without peak clipping | Optimized peak clipping |
|---|---|---|
| Pond size (km²) | 0.226 | 0.31 |
| Plant size (rating), i.e. peak summer output (m³/day) | 6,400 | 4,700 |
| Winter trough output (m³/day) | 1,600 | 2,198 |
| Storage capacity (for equal demand, year-round) (m³) | 279,000 | 155,000 |
| Annual cost of pond ($)[a] | 237,000 | 325,000 |
| Annual cost of plant ($)[b] | 892,000 | 655,000 |
| Total annual capital charges ($) | 1,129,000 | 980,000 |
| Capital charges component in cost of 1 m³ of water (cents) | 77.3 | 67.1 |
| Energy component (pond) (cents)[c] | 16.2 | 22.2 |
| Plant component (cents) | 61.1 | 44.9 |

a. Assumed cost of pond: $7 per m²; annual charges of 15 per cent.
b. Plant cost $700 per m³/day (in 1974 costs); annual charges of 20 per cent.
c. Does not include power for pumps.

optimized system (excluding any saving in the expense of storage) costs about 13 per cent less and produces a much more uniform output.

*Flat-plate maintenance is costly*

As can be seen from Table 1, the cost of desalinated water produced by such a system is about one-tenth that obtained from the basin-type still. This is attributable to the higher energy efficiency of the sophisticated plant and the fact that the 'collector' was assumed to cost $7 per square metre compared with $30 for the basin still.

If flat-plate collectors are used in place of a solar pond, then, assuming the collectors to cost about $100 per square metre (installed), these are 1.5 times as efficient as a solar pond. The capital charges for collectors and plant come to a little under $2 per cubic metre; this is still about one-third the cost when the basin-type is used. Because of the much higher cost of the collectors, optimization would show much less peak clipping.

So it is clear that basin-type distillers should be used only for small installations, where more elaborate plants are inappropriate. Where the latter can be used, the cost of product water would be an order of magnitude lower if a solar pond were feasible, and half an order of magnitude if metal collectors were used. In the last case, however, no allowance is made for the formidable problem of maintaining and cleaning very large areas of flat-plate collectors and for the associated plumbing problems.

**Non-distillation processes**

In distillation, we remove water from brine. As a consequence, the process is hardly affected by salt concentration. There are some processes, however, in which salt is removed from its solution by ion transport. In these processes, the energy requirement increases with salt concentration—so that the processes are thus possibly suitable for brackish waters but generally prohibitive for sea water. Nevertheless, the Japanese have recently put into service an electrodialysis plant to desalinate sea water.

Resins have been developed that absorb ions at ambient temperature and reject them at higher temperatures (80–90 C). There is no change of phase involved and the thermodynamic energy required to remove ions at low salt concentrations is extremely small; the process requires, in principle, almost no energy since the hot brine can be cooled by heat exchangers in order to reheat incoming brine.

A case-study for water with 2,100 parts per million of dissolved salts (reduced by the process to 500 ppm) indicated a cost of about 47 cents per cubic metre based on the original costs in Israel—in addition to an energy equivalent to 24.4 kWh of heat for the same volume.

For heat derived from fuel oil, the cost is about 1 cent per $kWh_t$[1] when the local cost of fuel is $100 per tonne. The total treatment costs (excluding delivery of raw water, rejection of waste, and cost of facility) come to about 71 cents/m³. Heat from a solar pond, based on the figures already cited, comes to 0.23 cents per $kWh_t$. Therefore, the 24.4 $kWh_t$ needed for this process cost 5.6 cents and the water treatment costs 52.6 cents/m³. This is lower than the computation for the multiflash process energized by a solar pond. Note, however, that the multiflash plant is usable with sea water whereas the resin system is not.

*Electrodialysis*

This is a process intended primarily for brackish water and requires electricity as its energy source. Thus, where solar energy is considered, it must be in electrical form which (if derived from heat) is far more expensive per kWh. Only if the process as a whole is very cheap could solar electrodialysis be considered as an alternative to a thermal process.

Some success has been reported in the case of the Japanese plant already mentioned: 230 yen/m³, of which 150 yen was spent for electricity. Capital charges at 15 per cent added 163 yen, making a total of 393 yen/m³. If a comparable plant were used for brackish water, the requirement for electricity would be halved. Assuming that 250 yen equal $1, the cost of this water treatment exceeds 90 cents/m³ besides the respective quantities of electricity needed to treat either brackish or sea water.

The electricity could be obtained from a solar pond, the thermal energy cost in the case already noted being 0.23 cents/kWh. At 90 C, the conversion efficiency to power is approximately 10 per cent; but, to allow for auxiliaries, we assume only 8 per cent (at an energy cost of about 2.875 cents per $kWh_e$—the subscript 'e' standing for 'electrical'). Allowing, again, for the machinery involved (turbo-generators, condensors, and the like), the cost of electricity derived from a solar pond would come to 4–5 cents per $kWh_e$. The cost of processing water by electrodialysis with solar energy thus becomes about $1.50/m³ for sea water and $1.20/m³ for brackish water.

Note that the requirements for electricity (which represent a sizeable part of the total cost) may be reduced by heating the feed water. A reduction of about 2 per cent in cost can be expected for each degree of rise in temperature. Solar energy has been of no help at all—apart from complicating the process.

1. Until the introduction of the ISO system in many parts of the world, there was rarely confusion concerning the term kWh: it nearly always referred to electrical energy. Today, however, kWh is used universally as a measure of both heat and electricity. Because 1 kWh of electrical energy involves about 3 kWh of primary energy (from oil, coal or gas) at a power station having 33 per cent efficiency, it is customary to distinguish carefully between them. For electrical energy, we refer to $kWh_e$; for thermal energy, we allude to $kWh_t$. This is essential in all discussions on solar energy where the conversion of heat to electricity may be at efficiencies much lower than 33 per cent.

*Reverse osmosis*

There is another process for brackish water, one which appears to be displacing electrodialysis. Like the latter, reverse osmosis needs mechanical (electrical) energy, not heat. Considerable development of the process can be expected in the next few years, and there are proposals to adapt the process to sea water. The essence of the method is to force brine through a selective membrane that is permeable to water molecules and substantially impermeable to salt molecules. Very high pressures are needed—several hundred atmospheres—to overcome the osmotic pressure that develops across the membrane. This is where most of the energy goes. The system is inherently suitable for both small and large plants, in contrast to multiflash processes that are not really suited to small units.

A preliminary 'paper study' for a plant with a capacity of 5 million cubic metres per year showed a cost of about 29 cents per cubic metre, excluding energy, with capital charges taken as 15 per cent per annum. The energy requirement is of the order of 2 $kWh_e$ per cubic metre.

As already indicated, electricity from a solar pond might be obtained at a cost of 4–5 cents per kWh, leading to a water treatment cost of under 40 cents per cubic metre. But even if solar electricity were to cost twice as much or more than estimated here, the very low energy requirement for reverse osmosis would still lead to probably the lowest water cost for any of the systems discussed.

*Conclusions*

For small communities, a simple solar still, preferably one equipped with glass window material, is a practical and simple device—particularly in areas remote from the electrical grid. Its product water is expensive, however: about $6 per cubic metre.

Larger installations can take the form of sophisticated, conventional desalination plants, with the sun providing the energy. These processes can be divided into those using low-temperature heat, e.g. multiflash distillation and thermally regenerated resins, and those needing electrical or mechanical energy, i.e. electrodialysis or reverse osmosis. (I have omitted mention of the vapour compression method because of the high cost of the electrical requirements.) Of the thermal systems, the thermally regenerated resin system requires far less energy and looks more attractive than the multiflash process. The latter is a well-tried process, whereas experience with the former is very limited. The resin system is, however, not applicable to sea water.

Of the electrical systems, the newer reverse osmosis process appears the more attractive because of its lower energy requirements. If electricity can be produced from the sun at reasonable cost, reverse osmosis will yield cheaper desalinated water than the best thermal process. The system seems proven for brackish water. Work is progressing in order to adapt it to sea water.

Because costs of capital, materials and labour vary considerably from country to country, the choice between alternative possibilities requires that each system be examined in the light of local conditions. □

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# Local innovation: a neglected source of economic self-sufficiency

James E. Clayson

*Here are examined some of the hidden, but real, causes of indigenous economic g*
*Several examples are advanced to describe how success at the micro-economic le*
*developing countries can have a multiplier effect upon the macro-economy of the n*

Technological innovation is generally regarded as the major stimulant to economic growth in the industrialized world—a stimulant that is proving statistically to be more important even than increasing the supplies of capital and labour. But the realization that growth may be the quantitative consequence of technical innovation says nothing about the nature of innovation, or where innovation comes from.

A good starting-point is to appreciate that innovation is not limited to the technological. Innovation includes not only the development and introduction on the market of new products and processes (along with their supporting machinery and manufacturing techniques); innovation also includes whatever improvements in the organization, training and motivation schemes of workers lead to higher productivity and job satisfaction. So innovation implies management, personnel and marketing techniques as well as improved product design and engineering. Innovation is therefore a highly complex matter, but one which is essential to understand if we are ever to come to grips with the problem of how best to encourage economic growth.

Economists have investigated the various faces of innovation, but usually only within the context of the developed world. Almost no work has been done on the po
importance of indigenous innovation
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encouraging local economic advance. F
the literature of development contin
emphasize technology transfer as a
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potential for innovation already inher
local enterprise. Even the recent con
appropriate technology has been disap
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that the only truly suitable technology
that is self-generated and self-gene
Appropriate technology fails to compr
a major lesson of 'Western' develop
since a causal relationship seems to
between a nation's capacity to innova
its rate of economic growth, then the d
economic expansion comes about only
local innovation is encouraged.

### Small enterprises as social institutions

I suspect that the reason why industri
societies seem more innovative than
is because their institutions systema
support and encourage individual a
creativity to a degree that the others d
It is important, therefore, to see how
institutions operate in developed socie