www.serd.ait.ac.th/reric

Techno-Economic Evaluation of a Salt Gradient Solar Pond: A Potential Energy Source for Seawater Desalination and Power Generation

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

Abstract *- Possible applications of a salt gradient solar pond have been evaluated. The topic is very interesting especially for the countries located within the South Mediterranean belt, generally characterised on one hand by a high availability of solar radiation, on the other by a serious lack of both electric energy and drinking water. Economic factor being one of the main hindrances to the spreading of solar devices so far, an attempt has been made to estimate production cost of both energy and water by using a medium to large-scale solar pond. The influence of plant size, in a range roughly extended from 100,000 to 1,000,000 m*^{2}*, has been considered. In addition, a cost sensitivity analysis for various factors, such like solar pond reliability, price and efficiency, has been performed. Finally the results achieved have been compared to those relevant to fossil fuel based systems and conventional low-temperature solar technology, both from the economic and technical point of view.*

Keywords: **Salt gradient solar pond, Power generation, Seawater desalination, Economic evaluation, Sensitivity analysis, Low-temperature solar technologies**

1. INTRODUCTION

As on today more than 30% of the total world rural population has not any access to the national electric grid. This phenomenon is concentrated in the developing countries (in 1990 rural electrification in Sub-Saharan Africa achieved hardly 8%), where, according to the forecasts, a noteworthy population growth and elevation of standard of living will occur in the next few years, making the situation even more critical. The aforesaid trend explains the increasing interest among the international scientific community on evaluating the possibility of using local renewable resources to integrate or replace the traditional ones. A fair spreading out of this sort of energy could also help in solving problems correlated with fossil fuels reserve shrinking, cost rising and above all negative impacting on the surrounding environment.

Furthermore, owing to the above-mentioned foreseen demographic increase, people living in the developing countries (especially in the Sub-Mediterranean area) will also deal with an ever-growing fresh water shortage. Desalination of brackish or seawater no doubt represents a suitable answer, but the implementation of this tool requests a high energy availability, so water emergency can be perceived as an energy problem once again.

In the vast arid regions of the aforesaid countries, characterised by high values of insolation, solar energy represents a renewable resource with appropriate features in order to face a combined power and water requirement. Nevertheless, the very high production cost by solar thermal or photovoltaic systems (over twice as much as that by conventional fuels ones) has deeply limited the exploitation of these devices so far.

Solar pond constitutes one of the simplest method for thermal conversion of solar energy, to such a point that it can be considered the sole technology able to compete with the aforesaid economic restraints. It is worth to explore the comprehensive conditions under which the adoption of this system is particularly attractive. For medium to large-scale applications the analysis can be restricted to salt gradient solar pond, which is consequently the object of the present study.

A brief description concerning operation fundamentals of the said technology is therefore indispensable, pointing up the literature values of the main techno-economic design parameters. In this framework a primary role is played by the characteristics of the site where the plant is supposed to be located. In addition, the most significant salt gradient solar pond patterns worldwide are reported.

The goal of this paper is however to present an acceptably consistent cost evaluation of a salt-gradient pond outcome. The main possible applications are considered, such like low-temperature process heat supply, power generation and seawater desalination through coupling with both a grid-connected and a stand-alone multiple effect evaporation system (MEE). The chosen size varies, according to the specific case, in the region from 100,000 to 1,000,000 m^2, so examining the scale effect on production cost. Finally, the acquired results are compared to those regarding a plant fed by conventional fuel. Since solar pond running is fuel free, production cost is almost fully determined by the huge initial investment. Thus a sensitivity analysis has been carried out, selecting the following three parameters: depreciation rate, pond overall specific cost and yearly average efficiency, which on one hand strongly influence

---

V. K. Sharma, Visiting Scientist, ENEA Research Centre Trisaia, 75026 Rotondella (MT), Italy (Phone: +0039 0835 974220; Fax: +0039 0835 974210; e-mail: sharma@trisaia.enea.it), corresponding author.

G. Braccio, ENEA Research Centre Trisaia, ENE-BIO Section, 75026 Rotondella (MT), Italy.

G. Fiorenza, ENEA Research Centre Trisaia, ENE-BIO Section, 75026 Rotondella (MT), Italy.

fixed charges, on the other can be predicted with a substantial uncertainty.

After all that, results are matched up to the ones relevant to low-temperature solar collectors, representing the solar technology traditionally employed in similar applications. The comparison is based not only on the economic assessment, which undeniably supports solar pond technology dissemination, but on technical aspects too. The point is to give prominence to the causes justifying the very limited adoption of such systems so far and to draw the conditions under which these barriers can be overcome.

2. RENEWABLE SOURCES MEETING WITH POWER AND WATER NEEDS

At present nearly one third of the worldwide population has weak or no access at all to the electric grid. This negative comprehensive status shows itself even more dramatic, looking at the developing countries only: in South Europe, for instance, the above percentage diminishes up to less than 1%. Considering continuous demographic growth and industrialisation and urbanisation progresses, concentrated in the developing countries too, in these regions situation is destined to become more and more serious in the next few years. On the other hand most of the aforesaid countries, such as those located within the South Mediterranean belt, with vast areas having inadequate power supply, appears to be favourably disposed towards renewable energies. Such sources, able to be employed directly also in remote and isolated zones, could well be exploited to provide low-to-medium scale users.

In addition spreading of sources such like biomass, solar, wind and geothermal energy and so on would attenuate all problems deriving from the intensive use of fossil fuels. In fact, a meaningful contribution from the renewable resources would certainly allow extending the foreseen duration of gas, oil and coal reserves and calming the social negative impacts due to sudden raises in fuel price. Last but most important item, the environment would be safeguarded from further intolerable damages.

In spite of these encouraging aspects, renewable energy role in satisfying world-wide wants, though increasing is still marginal. Leaving aside hydroelectric energy, by now completely exploited and fully competitive, and biomass, mainly employed for low-grade energy production (heating and cooking of the foods), other chief resources (solar, wind, geothermal and tides) all together does not cover even the 1‰ of the global energy production, as shown in Table 1 [1]. This surprisingly scarce diffusion of renewable energy is due to economic restrictions. Cost of kWh by means of main alternative resources in 1997 and future scenarios, according to the U.S. Department Of Energy (DOE) studies, is presented in Figure 1 [2].

As can be observed, as on today, values relevant to the solar energy when compared to the conventional one (0.03 \$/kWh) are very high. It is, however, expected that the cost of the solar-produced kWh will certainly decrease significantly over the next years (up to less than 0.1 \$/kWh before 2010). An opposite trend is estimated as regards the cost of the conventional-produced kWh. This may be attributed to both the foreseen price raise of the fossil fuels and the plausible opening to fiscal penalties for productions causing environmental pollution. Instead both geothermal and wind energy appear competitive under the present-day situation too.

Furthermore it can be proved that water emergency represents a strictly related question. The data show that around 25% of the total world population, residing in more than 80 countries has not access to an adequate fresh water supply both for quality and quantity. This situation is certainly very alarming in the countries located within the South Mediterranean belt, but drought and desertification are getting on significantly, involving wider and wider areas of the planet. Based upon the investigation conducted by the World Health Organisation (WHO), it is to be noted that annual water availability of 1,000 m^3 per capita constitutes the limit, below which it is not possible to guarantee acceptable living standards and less than ever the economic development of a country [3].

In a number of South Mediterranean countries with wide deserted or semi-deserted areas, water reserve per capita, at the present-day very limited, is destined to reduce further. In Table 2 are quoted the data relevant to population and available water for all uses per capita on the annual basis, during the period from 1960 to 1990. Taking into consideration the forecasts made by Food and Agriculture Organisation (FAO) on the overall increase in the world population [4] and by both the World Resources Institute (WRI) and the World Bank on water stores trend [5], the projections to the year 2020 are also presented. Due to the high population augment in the last three decades, the water resources became strongly shorter. A similar tendency is foreseen over the following thirty years (-48%), thus making water availability in the year 2020 sharply fewer than the minimum recommended by WHO in all of these countries and causing a situation very heavy, with annual availability of less than 200 m^3 per capita, at least in a couple of them.

On the other hand a lot of these areas, especially insular or coastal dry zones, can rather easily access to brackish or sea water. Effectively it is obvious to consider the use of salty water in order to face existing as well as future water shortage problems, since nearly 97.5% of the total water reserve on the planet is of this kind. That's why most of the abovementioned countries have already engaged in desalination technologies, which are now well established and able to yield large amounts of good quality water. Moreover production cost is going to achieve quite competitive standards. The only drawback is represented by the fact that all such processes are energy consuming. Specifically power need to desalt water, using the best available technology in the market, thanks to continuous technological progresses has been drastically reduced in recent times, from values of more than 20 kWh/m^3 during the year 1970 up to current around 5 kWh/m^3, possible with reverse osmosis technology (RO). This value however remains high: it is enough to say that to fulfill the multisettorial water requirements of a 18,000 inhabitans community a 10 MW power station is needed.

As the previous considerations reveal, water emergency is converted into an energetic matter too. In fact, the wide spreading of desalination to get new pure water stores would enhance the power demand, thus making the implementation of alternative resources even more imperative. Moreover, it must be emphasised that nearly 3 kg of CO_2 let in the environment for each m^3 of produced water could be avoided, by replacing the conventional fuel with the renewable one.

In addition, solar energy constitutes a source with many favourable aspects with the purpose of desalting water, such as:

- The natural renewal of water on earth takes place by way of the cycle of evaporation and successive condensation in the form of rain, exactly thanks to solar radiation. Being founded on this principle, seawater was converted into the drinkable on the lifeboats ever since World War II using the so-called solar stills. In such systems salt water is kept in a basin with black bottom and glazing cover: solar heat makes feed water evaporate, vapor is then condensed on the glazed surface and collected in a reservoir through appropriate ducts.
- Most of regions with scarce water resources have abundant solar radiation, as the data in table 3, relevant to South Mediterranean countries, prove. Values have been calculated using the Surface Meteorology and Solar Energy Data (a software made available by NASA). Moreover the water demand certainly augments during the hot season (often owed to the presence of the tourists too), when solar energy availability becomes higher.
- Fresh water could be accumulated in a simple and economic way and successively supplied to the users as and when requested. The present concept will help to realize a useful system for storing solar energy (intrinsically discontinuous), thus resolving one of the main problems of managing this kind of resource.
- Most serious problems of water supply generally occur in the isolated places (far remote areas, rural zones, small islands, big ship, etc.) practically having no access to the electric grid. Under such conditions, solar energy could compete even from the economic point of view with the traditional system (diesel engine powering RO).
- Implementation of small to medium sized plants holds a number of benefits both economic (reduced capital outlay) and technical (minimum construction time, local availability of manpower and raw materials, simple operation and maintenance).

Even though solar energy has been for long time employed to desalt water, having optimal traits for this purpose, the fact remains that its contribution to cover world-wide water needs does not reach a significant figure yet. In effect a large number of solar desalination plants are now working, but for the most part it's a question of solar still very small-scale systems. From the literature survey, it can be drawn that nearly 100 plants (both solar and/or wind powered) are still operational in more than 25 countries with mean capacity of around 20 m^3/d [6]. Since size is too small and above all location is in far remote areas, it happens to be really very difficult to provide complete information. In view of this, it is credible that the data furnished by IDA reports abundantly underestimate current worldwide installations.

In order to reach a substantial exploitation of solar energy, it is crucial to investigate the possibility of powering medium-to-large capacity desalination plants. For this purpose solar technologies can be coupled with desalination processes in various ways:

- Solar thermal collectors and solar pond can obviously feed thermal processes such as multi-stage flash (MSF) or MEE.
- Photovoltaic field can power mechanical vapour compression (MVC), RO or electrodialysis (ED).
- Solar parabolic trough and solar tower producing both electric and eventually thermal energy via a co generation arrangement could drive all the aforesaid desalination processes and, particularly, the hybrid systems (for instance RO plus MSF).

Since high temperature solar devices are still developing technologies, for medium to large-scale applications, which constitute the main goal of the present research work, solar pond no doubt represents the option with the best economic prospects.

3. SOLAR PONDS CLASSIFICATION

Solar ponds can be distinguished in two main categories according to the process taken up to reduce heat losses towards the surrounding environment:

- Convecting ponds using a covered surface in order to avoid water evaporating.
- Non-convecting ponds employing techniques for inhibiting internal convective fluxes.

A convecting pond consists of a pure water mass enclosed in a large thin bag which allows internal convective motion, but prevents evaporation from the top. A plastic or glass double-layer cover reduces heat losses further on. Moreover the container bottom is blackened and insulating from the ground, thus maximising solar radiation absorption and minimising energy waste. Two different storage methods are adopted in relation to pond depth:

- In the shallow pond the water heated during the day is pumped into a large and well insulated external tank, whenever solar radiation is not available, with the purpose of cutting down losses; nevertheless high conveying wastes limit the application of this process to very small users.
- In the deep pond the water amount is fairly large to act as a storage system too; consequently there's no need to pump the liquid in and out of the bag, but nocturnal heat losses are reduced by placing an additional insulating cover on the surface.

A non-convecting pond consists in a water basin, with darkened bottom and insulating walls to support solar energy collection. Two main techniques are put into practice for blocking upward movements, so that hot water remains in the lower zone which acts as a storage system too:

- In the salt gradient pond water salinity increases with depth to the point that the solution placed in the inferior region keeps heavier even when it gets warm, thus slowing down ascensional motion.
- In the membrane pond convection is inhibited by physically separating the water mass into two layers through thin transparent membranes; it is evident that

such a system becomes more and more unstable as pond size increases.

To come to the point salt gradient solar pond represents the sole technology fitting medium to large-scale applications, like those investigated in the present paper. Therefore, from now on the analysis will be focused onto the techno-economic aspects of this system.

4. SALT GRADIENT SOLAR POND FUNDAMENTALS

A salinity gradient solar pond is a basin containing a variably concentrated mixture of salt and water. A dark-coloured material (usually butyl rubber) lines the pond bottom and side walls, pursuing the double aim of enhancing the absorption of solar radiation and preventing the surrounding soil and groundwater from brine contamination. The pond depth hasn't got a prefixed value, but generally never exceeds 4 to5 m.

As shown in figure 2, three distinct layers can be schematically singled out, in relation to the salt concentration and the corresponding function:

- a thin (0,3-0,6 m) shallow layer of almost pure water, through which heat passes in the environment owing mainly to evaporation and convection;
- an intermediate layer having a depth variable between 0,8-1,5 m (optimal value is around 1 m), in which a tending to be linear salt gradient is realised, such as to strongly lessen heat transfer toward the surface, thus acting like a thermal insulator;
- a lower layer with very high salt concentration (practically saturated) in which solar energy is trapped.

Precise values of the different zones thickness can not be settled on due to seasonal fluctuations: in fact the extent of the two extreme layers reduces during the cold period, when internal convective flow slows down and consequently diffusion process prevails, enlarging the salt gradient region.

As solar radiation is most of all absorbed by the lining, the temperature of the water located near the pond bottom raises, but thanks to its high salt contents the solution keeps denser than the layers above and as a result does not move upward. Therefore solar heating process of the lower layer continues up to relatively high temperatures (a typical hot season value is approximately 90 °C).

Thermal energy is then removed from the pond bottom and sent to the end user by means of an integrated or external heat exchanger. The second solution is preferable since the pumping related consumption are largely compensated by the reduction of cost (a higher heat transfer coefficient and a resulting superior compactness is attainable) and technical difficulties (maintenance is easier for an outer apparatus in comparison to a submerged one).

Considering typical depth values, the achievement of a temperature close to 90 °C in the storage zone exposes the pond to a strong thermal gradient, mostly concentrated in the insulating layer. Significant differences in temperature tend to perturb this zone, thus a high salt concentration is required, according to the dynamic stability criterion introduced by Weinberger [7]:

$$\frac{d\rho}{dz} = \frac{\partial\rho}{\partial C}\frac{dC}{dz} + \frac{\partial\rho}{\partial T}\frac{dT}{dz} \geq 0$$

where z is the pond height, and r, C, T are the solution density, concentration, and temperature respectively.

As a result, the salinity have to pass from nearly 0% at the top to over 20% by weight at the bottom. For a 4 m deep pond, such concentration corresponds to an average gradient of about 0.05 g/cm³ for each meter of height; obviously, since actually the salinity varies just in the insulating layer, as schematically shown in figure 3, the slope in this zone is much higher (> 0.1 g/cm³ for each meter). Owing to the aforesaid ratio, a typically sized solar pond needs a large amount of salt (over 500 kg per m² of basin area) in the setting up stage.

The following key features are taken into consideration, while selecting the type of salt to be used:

- Sufficient solubility with an increasing trend when temperature grows.
- High boiling point of the resulting solution.
- Inexpensive and easy availability.
- Moderate impact on the environment.

The common sodium chloride (NaCl) properly meets the above listed qualities; in few specific applications, a mixture with magnesium chloride ($MgCl_2$) is also employed.

The salt gradient preservation all over the plant running is an extremely critical issue; in fact the convective flux through the intermediate layer is practically blocked, but the salt migrates toward the upper zone via diffusion. This phenomenon, even if very slowly, tends to make uniform the concentration in the whole pond. Therefore, the periodical addition of highly concentrated solution to the insulating layer base and the simultaneous washing of the open surface with fresh water are necessary. The diluted solution, discharged from the top, can be re-concentrated by evaporation and then put in the working cycle again.

The diffusion of salt occurs at a theoretical rate of 60 to 80 g/m²d only, but values up to 200 g/m²d have also been recorded. On the other hand, even considering the minimum value, the maintenance of the designed salinity gradient implies an annual consumption of salt extremely high (over 20 kg per m²). Besides an amount of chemicals is required, however modest it is, in order to keep under control the growth of algae in the pond.

Due to its high thermal inertia and the effectiveness of the measures taken on to minimise convective flow, a well insulated pond does not represent simply a solar energy collecting device, but also a long term storage system. In fact, even if solar radiation is absent, typically it takes some weeks before the temperature of the lower zone diminishes significantly (10 to 15 °C less). Hence pond performance is relatively independent of alternating of seasons: as illustrated in figure 3 again, the storage temperature recorded in April, after the whole cold period, still reaches an exploitable value (over 50 °C).

Obviously, to hit this target appropriate steps must be taken to mitigate the impact of all potential causes of gradient instability (disturbances due to the wind or other external agents generally of meteorological type) and to limit losses as much as possible. In this respect thermal exchange coefficients should not exceed the typical very low values quoted in Table 4 [8].

On such conditions, solar pond converts an intermittent source, as solar energy is by nature, into one able to supply at length and with continuity the users. This specific feature provides one of the principle advantages in comparison to the other solar energy conversion systems (for example a set of conventional solar collectors), which need an additional storage device.

5. STATE OF THE ART OF THE SOLAR POND TECHNOLOGY

The properties of a salinity gradient solar pond were discovered on the beginning of the last century in Transylvania, when it was noticed that in a really salty lake the water temperature rose to about 70 °C, during the summer, at a depth of little more than one meter. Since the efficiency of a natural pond is extremely low, such a technology can't be exploited for commercial purpose; for that reason a further investigation was left out till the Fifties, when the early attempts to carry out an artificial pond were made in Israel and in Australia [9]. The capital required to build up the plant proved to be huge, in a situation still based upon fossil fuels low price, so the testing were dropped very soon. Only in the late 1972, after the first oil crisis took place, salt gradient pond gained a renewed and constant interest, but even under the current conventional fuels value, in most cases this source does not turn out competitive from the economic point of view.

Due to the aforesaid drawback, the number of solar ponds operating worldwide up to today is still very limited and their size never attains really significant values, as it can be observed in table 5. The crucial features of each plant are also listed, the data being drawn from various references [9, 10]. A great quantity of small-scale ponds (100 to 500 m^2), targeted fundamentally on research and development, exists indeed. Nevertheless it must be stressed that two large plants are at present under construction in Truscott (USA) and Dead Sea (Israel), having a planned area in the order of 50,000 m^2 and 250,000 m^2, respectively. In addition, an enormous pond (it is expected to achieve one million m^2) is in design at Salton Sea (USA) [9].

In some particular circumstances, however, solar pond can prove to be the most cost-effective approach; the indispensable bases for the attainment of such goal are a plant significant size and a site abundant insolation. For instance, the low-grade thermal energy requirements of rural or somehow remote areas, located in North Africa, could be fulfilled in the cheapest way by means of the installation of a 50,000 to 100,000 m^2 pond.

In any case, the surcharge of the generated energy is quite limited in comparison with typical values relevant to the diverse solar technologies, capable of large-scale applications. In addition, such system seems to be preferable with reference to the following fundamental aspects:

- reliability on a long period running (at least up to 25 years), in critical ambient conditions;
- continuity of the energy supply, in spite of the fluctuating nature of the source;
- containment of expenses involved in the energy conversion system comprehensive of storage;
- moderate maintenance requirements;
- fully automatic working, included start and stop manoeuvres;
- ease of installation, operation and maintenance, practicable applying to local technical skills and spare parts.

The site constitutes a primary factor for the overall success of the installation, owing to several reasons, which can be assembled into four main categories [11]:

- climatic conditions;
- soil characteristics;
- water and salt reserves;
- energy market status.

Clearly, a high yearly average value of solar radiation increases the amount of the thermal energy generated by a given area pond. In addition, losses are minimised in presence of more favourable ambient conditions.

Windiness represents a further remarkable climatic factor: in fact, a recurrent excessive wind velocity causes the formation of superficial waves, which can disturb the designed temperature gradient, up to its complete annulment. However, wave motion can be moderated by use of nets.

Finally, the site should be sufficiently rainy to compensate the evaporation, thus preserving the required water level in the basin, but not to the point to excessively dilute the solution or even to make it overflow from the banks.

A crucial site-related factor is the availability at a low price of a vast area, which first of all has to be as much flat as possible in order to drastically cut the installation cost. Furthermore the soil must possess adequate mechanical and thermal properties, i.e.:

- high cohesion to ensure the necessary structural stability to the works for the containment of an enormous liquid mass;
- low permeability to limit the brine leakage, thus avoiding environmental damages, energy losses and the addition of further salt;
- moderate thermal conductivity to reduce heat losses through the bottom as well as the sidewalls.

It is evident that the most profitable compromise amongst the wanted characteristics has to be made, since a ground can't turn out to be so dry to minimise heat transfer, and simultaneously highly hardwearing and waterproof.

While selecting the region in which the pond has to be set up, the local positioning of water resources must be taken into account too. In fact, on the one hand an easy access to large volumes both of salt and pure water is required to fulfil the needs of the periodic restoration of the salinity profile, in opposition to diffusive phenomena; on the other hand the presence of shallow aquifers in the neighbourhood is unwelcome, since contamination processes can occur.

In addition, availability of abundant and cheap salt stocks is also suitable for the initial formation of the gradient and his preservation throughout the plant working.

A further condition promoting the pond technology is the presence in the area of a substantial energy demand, accompanied by no or very expensive access to conventional fuels.

Since the production cost is affected for the most part by the initial investment, the financial parameters, which also vary on a local scale, constitute an additional decisive factor. For example the prospect of counting on a low discount rate or on funds meant for the diffusion of renewable sources surely encourages the building of a solar system.

Like for any other energy conversion device, a primary element for evaluating the techno-economic feasibility of a solar pond is the efficiency, defined as the ratio between the thermal energy made available by the system and the radiative one incident on its surface. Such a parameter can reach a peak value around 30%, but the annual average usually does not exceed 20%, being mainly influenced by the site climatic conditions and the following factors to set in the planning stage [11]:

- **transmittance of the saline solution and absorbance of the pond bottom and sidewalls**: the product between such coefficients must be 0,45 at least, in order to achieve an adequately efficient system [10];
- **thickness of the intermediate layer**: such quantity must be adequately high to provide an optimal thermal insulation to the storage layer;
- **difference in temperature between bottom and top of the pond**: an excessive heating of the storage zone turns out to be counterproductive, since it makes the salinity gradient unstable, so reducing its insulating capability;
- **thickness of the storage layer**: a huge liquid mass is characterised by a temperature more constant during the year, so favouring the system efficiency, but the inertia, and hence the time required to reach steady conditions, grows too;
- **size of the pond**: increasing the basin surface, losses from both bottom and sidewalls influences less the system global efficiency in proportion and the performance of the auxiliary devices improves as well.

An efficacious description of the losses sharing within a solar pond is the energy balance shown in figure 4. It can be observed that over 80% of the incident energy is dispersed in the atmosphere due to convection, evaporation and reflection, and below 5% in the ground via conduction. In spite of its thinness, the most critical layer is the upper one, since nearly 50% of the energy does not succeed in getting over this barrier. The heat losses in the intermediate layer are remarkable too (approximately 30%), so only less than 25% reaches the pond storage zone.

To carry out a complete feasibility study, the efficiency of the investigated technology must be correlated to its setting up and running charges.

Obviously the initial investment is a function of the pond area: in fact the unit cost appreciably decreases for a large sized plant. In this regard values included between 20 and 15 \$/m^2 for a 10^6 and 10^7 m^2 system respectively, are typically adopted while performing cost-effectiveness analysis [12]. These figures are supported by the data collected in the field and available in the literature, which indicate costs of 20 and 10 \$/m^2 for a $0.25 \cdot 10^6$ and 10^6 m^2 pond respectively [13] and even 15 \$/m^2 for a $6 \cdot 10^3$ m^2 pond [10].

Considering that land is mostly obtainable free of charge or in any case very cheaply, the remaining items that mainly affect the required investment are:

- excavation and execution of walls for containment of the water mass;
- lining of bottom and sidewalls of the basin with impermeable and insulating material;
- salt required to achieve the pre-set gradient of concentration;
- instrumentation for monitoring and controlling the plant;
- system for heat extraction from the storage layer;
- design and preliminary simulation;
- piping, pumping and other accessories (diffusers, devices for wave control, etc.).

Figure 5 illustrates the contribution to the overall fixed cost of the aforesaid factors. The extrapolation is based upon data relevant to small to medium scale applications [9, 14].

As for any other renewable source, initial investment is very high, but no fuel is needed during the plant running. Therefore operating cost, due essentially to manpower and maintenance, is a fairly small fraction of capital recovery (25% or less). Further significant items are electricity used up by auxiliary and control systems and salt necessary to gradient preservation [14]. According to the actual situation, the last factor can have either a strong or a negligible impact on operating cost. In some conditions it can even be converted into an income [15], for example if the region, in which the pond is to be located, is characterised by the need of removing large amounts of salt or if the pond is coupled with a desalination plant, so that the expense due to the disposal of the discharged brine is avoided.

6. SOLAR POND COUPLING WITH DESALINATION SYSTEMS

The peculiar traits of the energy stored in a solar pond make it clearly fit for supplying all those processes, weather industrial or agricultural, which require low-grade steam. Furthermore numerous alternative applications are possible, among which the most widespread are:

- heating and air-conditioning of the environment;
- sea or brackish water desalination;
- heating of the greenhouses;
- power generation;
- manufacture of refined salt.

Considering the imperative need to find new water reserves, a specific attention must be paid to the coupling with desalination plants. On the other hand solar pond is properly suitable for such application, given that:

- Heat is provided within a temperature range especially appropriate for the needs of certain thermal desalination process.
- The highly concentrated solution, discharged by the plant, can be recycled to preserve the salt gradient, thus simultaneously avoiding the additional cost relevant to the supplement of salt and contributing to the brine disposal, which represents one of the major ecological issues of a desalination process.
- The opportunity of fulfilling both thermal and power requirements set the desalination plant free from the grid, making easier its installation in the remote areas. In theory, a solar pond could feed all main processes of desalination: MSF, MEE, MVC, RO.

Nevertheless, the coupling with electricity driven processes, such like MVC and RO, seems to be barely attractive. In fact, the efficiency of a low temperature Rankine cycle is really scarce, thus the generated power will be too expensive with respect to the market price; furthermore, construction and management of the plant will prove to be more complex, in consequence of the insertion of a steam turbine into it.

Likewise, the coupling with MSF systems, even though rather frequent, offers some critical aspects:

- The steam is provided to the process with an average temperature below the normal working values (90 to 112 °C), thus producing an exponential augmentation of the required heat exchange area.
- The intermittent nature of the energy source brings considerably down the performance of the MSF plant, which needs a steady and close to nominal values feeding.
- The reduction in storage temperature, which takes place in the cold periods, implies a significant increase of the re-circulation flow rate and, consequently, of the pump size, and electricity consumption.

A promising answer to the above-mentioned problems can be given by the so called auto-flash process [16]. Thanks to an interstage control system that auto-regulates the pressure at each passage of the fluid, the plant is highly flexible with regard to the fluctuations in heat source and can run all over a wide range of feeding vapour temperature (30 to 95 °C), without drastic reductions in efficiency. The same measure makes possible to adjust the system capacity so as to meet the user's need or maximise the solar pond yield.

Obviously, such technology still being relatively new, only small scale devices have been tested so far and the resulting water production cost is remarkably elevated.

On the contrary, a MEE system represents a reliable large scale option, since pond storage temperature fully meets the process needs (60 to 75 °C) and the plant is highly flexible, being able to work stable and effectively, even if load or supply conditions markedly fluctuate.

It is however to be noted that, if electricity can be provisioned at a low price, a hybrid desalination plant (RO/MEE) may bear a better economic outcome. In such a configuration, in fact, a higher salinity of the water coming out from the membranes is acceptable, since subsequently it can be blended with the distillate drawn from the MEE device to get the purity requisite limit. This is the central reason why the power consumption, and accordingly the water production cost, of the RO process are drastically cut down.

Nevertheless this technological option is not suitable for remote areas, since to feed the RO process the grid-connection is required. In addition, energy needs are only partially covered by the solar source, thus environmental benefits are strongly reduced. For such reasons a hybrid scheme will be not examined in the present paper.

7. COMPARISON BETWEEN SOLAR POND AND SOLAR THERMAL COLLECTORS

Since the high cost represents the main hindrance to the spreading of solar devices so far, it is undoubtedly interesting to investigate the feasibility of the solar pond technology, which, as it will be shown afterward, offers the very best economic result. Nevertheless, an accurate assessment must comprise technical factors too. Such a comparison can be set out consistently only with medium temperature solar thermal collectors, which represent a technology with both an identical target (production of heat at an average temperature of about 90 °C) and level of maturity.

Other systems, such as solar photovoltaic or thermal concentrators, will not be considered, given that they are essentially directed to power generation. In any case, at the current status salt gradient pond proves the most cost effective solar device even for the production of electricity. Actually, in spite of its scarce efficiency in solar-to-electrical energy conversion (about 2%), due to the low temperature of the stored heat, the generation cost is expected to stand below 0,10 €/kWh, as it will be shown in the next section. It is to be emphasised that, unlike solar pond, these technologies (particularly solar thermal ones) promise to be capable of great developments in the medium term. Nevertheless, salt gradient pond should continue to be more appropriate than the competing solar systems for the application in developing countries, because of its ease of setting up and running.

For an overall economic estimation of solar pond and thermal collectors, it is necessary to compare not the mere cost per unit area, but the ratio between cost and thermal efficiency. This parameter for a pond stands roughly at 170 \$/m². Whereas, a conventional solar collector, with an efficiency ranging from 50 to 60% and a price of about 150 to 200 \$/m² [17], is characterised at best by a value of 250 \$/kWh, more than the 50% higher. To come to the point, solar pond technology presents the most excellent economic performance both per unit surface area and useful thermal energy available.

A further remarkable advantage of a solar pond, in comparison with a collector field, is the absence of piping for gathering and transporting heat over long distances, thus avoiding expenses for installation and insulation of additional components and waste of energy via heat losses and pumping. Management problems owing to high thermal inertia of the system are also reduced. Finally maintenance operations are simplified, since there is no necessity of removing dust deposit from the surface.

The key penalising factor for solar pond technology is the noteworthy ground requirement. For example, using thermal energy for desalting seawater in a stand-alone configuration, a surface area of more than 90 m² is needed to produce 1 m³/d of fresh water. This value is 3-4 times higher than the one typically assigned to a collector field, under the same conditions, thus making very problematic the adoption of such technology, especially in urban areas. Quite the opposite, solar pond appears to be competitive to provide heat for agricultural or industrial use or water desalination in the far remote and isolated areas, where shortage of space is not a relevant difficulty. In Table 6, main advantages and drawbacks of salt gradient solar pond technology are summarised.

8. PRELIMINARY ECONOMIC ANALYSIS

As previously shown, salt gradient pond is currently the most cost-effective solar technology for generating thermal or electrical energy. Nevertheless normally the production cost is markedly higher than conventional systems one: this is the main reason why the number of ponds operating on large scale worldwide is still very limited.

It is, therefore, necessary to investigate about the subsistence of particular conditions, under which solar pond may compete, from the economic point of view, with traditional systems too.

This aim will be pursued assuming the following suppositions in order to fix the base values of parameters concerning solar pond technology:

- typical insolation of Sub-Mediterranean region;
- trend of cost with size extrapolated from the limited experiential data available in the literature;
- average level of efficiency affecting significantly sized plants;
- characteristic interest rate for an innovative production process suffering from a high risk;
- enough prudential estimation of plant life;
- absence of financing depending upon site and period of installation and thus case related;
- annual maintenance and operational expenses equal to a percentage of elevated initial investment, such as to cover auxiliary energy consumption and salt restoration too.

These figures are recapitulated in table 7. Likewise, the values adopted for parameters relevant to desalination and power generation are reported in table 8 [18].

The calculations have been performed for the following four key applications, considering medium to high plant capacity:

1. direct thermal energy production;
2. power generation via feeding an organic Rankine cycle (ORC);
3. seawater desalination by coupling with a MEE unit and drawing electricity from the grid;
4. stand-alone seawater desalination plant including both a MEE device and an ORC engine.

In each case the maximum size has been chosen so as to obtain an overall solar pond area of the order of 10^6 m^2. The calculated trend of the production cost for the aforesaid applications is illustrated in figure 6, whereas indicative values relevant to the corresponding traditional methods are reported in table 9 [18]. Comparing these results, it is possible to draw the following chief conclusions which roughly match with the information obtainable from the literature survey [12, 19]:

- production of thermal energy proves to be cost effective, if both the supply is required at an average temperature no higher than 80 °C and waste heat from industrial processes is not easily accessible;
- power generation cost appears to be very high (more than three times as much as the conventional one), essentially, due to the low temperature of the feeding heat that prevents the ORC to attain reasonable efficiency values;
- a grid connected plant can yield fresh water at a cost quite close (only about 20% more) to conventional systems one, thanks to the very appropriate characteristics of solar pond technology for its coupling with a MEE plant;
- the gap is limited further (up to nearly 15%) when a stand alone configuration is adopted, since the\ electricity needs are quite limited (little more than 1.5 MW for a 20,000 m^3/d plant) and can be fulfilled in a more economical way by the pond itself (the required increase in the overall area reduces the unit cost) rather than by a diesel powered generator, affected by additional charges owing to transportation and storage of the fuel.

It is necessary to reaffirm that these results must be considered simply as a preliminary assessment, given that large sized operating plants do not reach a significant figure yet and crucial factors both technical and economic are site related. For that reason, it seems opportune to perform a sensitivity analysis for the production cost varying such input parameters, i.e. depreciation rate, pond unit price and efficiency, that on one hand mostly contribute to final value, and on the other are affected by an elevated uncertainty. The range of variation for each factor has been selected in order to meet most of the conditions that could occur for real plants having a significant capacity.

Moreover the analysis has been restricted to power generation and off-grid water desalination, which represent the most interesting applications. Actually for the former it is fundamental to investigate the existence of conditions under which the economic gap in comparison with conventional systems is reduced to an acceptable level, whereas the latter, as well as being closer to the traditional alternative in terms of costs than a grid connected system, represents the most fitting solution for remote areas users, characterised by lack or limited availability of both power and water supplying.

The sensitivity of final result with respect to plant cost per unit area is shown in figure 7. It can be observed that assuming the parameter lowest value (15 \$/m^2), the price of generated electricity, no doubt, diminishes significantly (up to approximately 0.06 \$/kWh for a 10 MW plant), but it still remains over twice as much as the one coming from the use of fossil fuels. Under the identical conditions, the production cost of fresh water by an off-grid desalination plant (less than 0.9 \$/m^3 for a capacity of 20,000 m^3/d) appears acceptable compared to the conventional one. In addition, it is to be noted that, for a plant of maximum size, a cut in the technology cost of 10% reduces power and fresh water price by 8 and 6% respectively.

Similarly, the graphs obtained from the variation in plant efficiency, reported in figure 8, show that even assuming an ideal value of 20% the cost of generated electricity becomes a little more than 0.08 \$/kWh for a 10 MW sized plant, which is still equal to nearly three times as much as the conventional price. In the same hypothesis fresh water is produced at a cost of nearly 0.9 \$/m^3 by an off-grid desalination system provided with a capacity of 20,000 m^3/d, again proving to be competitive with conventional technologies. As for efficiency too, an increase of 10% implies a cost reduction approximately of 7 and 5%

for power generation and desalination respectively, considering the greatest sizes of the investigated range.

Finally, the production cost sensitivity to depreciation rate is presented in figure 9. In this case also, under optimal conditions (an interest rate at 5% coupled with a plant life of 30 years) the generation cost of electrical energy by a 10 MW plant takes a value (about 0.07 \$/kWh) more than twice as much as the conventional one. On the contrary, cost of fresh water by a 20,000 m^3/d off-grid plant is nearly 0.8 \$/m^3 absolutely acceptable in comparison with the ordinary price. It is to be noticed that, with respect to the highest capacities under examination, an increase of 10% in that factor makes production cost diminish by about 7% for both electric energy and fresh water. Moreover, it can be observed that between the two terms which contribute to depreciation, the interest rate affects more the final cost than the life of the plant.

In addition, calculations have been made to find out the values which the considered parameters must assume in order to break even with the conventional production cost for both electricity and fresh water. The results relevant to a 10 MW solar pond powered thermoelectric plant are reported in table 10. Supposing in all cases a very low installation cost (10 \$/m^2), even under advantageous depreciation values (Case 1), a high efficiency is required so that the plant may be competitive with traditional systems. On the other hand if the aforesaid conditions are not so encouraging (Cases 3 and 4), the needed efficiency values grow to be intolerably elevated. Obviously, in remote areas, the situation may drastically change till it can be in favour of the technology under investigation, provided that an enough significant energy demand to justify such an investment subsists.

Correspondingly the results pertinent to a solar pond coupled with a stand alone MEE plant having a capacity of 20,000 m^3/d are reported in table 11. It is easy to realize that the conclusions are very different with respect to the previous case. In fact, under normal depreciation rate (Case 3), the balance in cost with conventional systems certainly requires a high efficiency (over 20%) but accompanied by an ordinary value of the installation charges; vice versa, assuming a standard energy yield, a basically low but still realistic (nearly 18 \$/m^2) solar pond cost is sufficient. Under more favourable conditions about financing and plant life (Case 1), economic competitiveness can be achieved even with either a relatively high cost (around 28 \$/m^2) accompanied by the typical productivity, or a quite low efficiency (nearly 13%) in combination with the usual investment expenses.

9. FIGURES AND TABLES

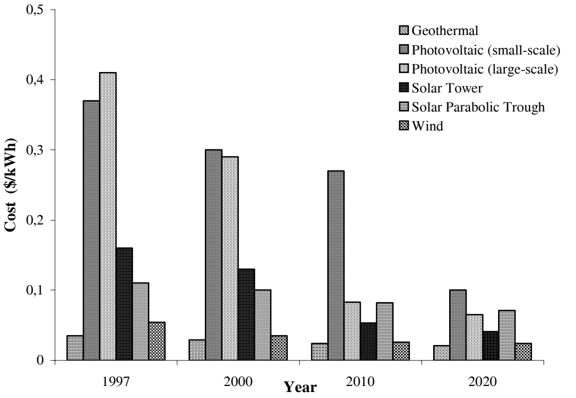

Fig. 1. Production cost of electrical energy by using renewable sources: present values and short to medium term forecasts.

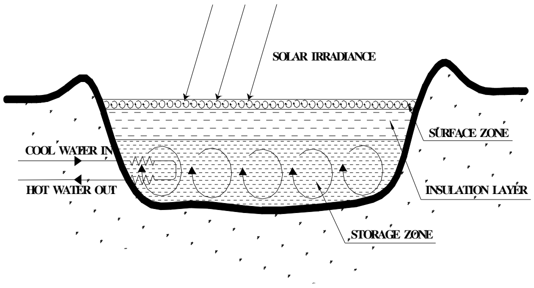

Fig. 2. Schematic of a salt gradient solar pond.

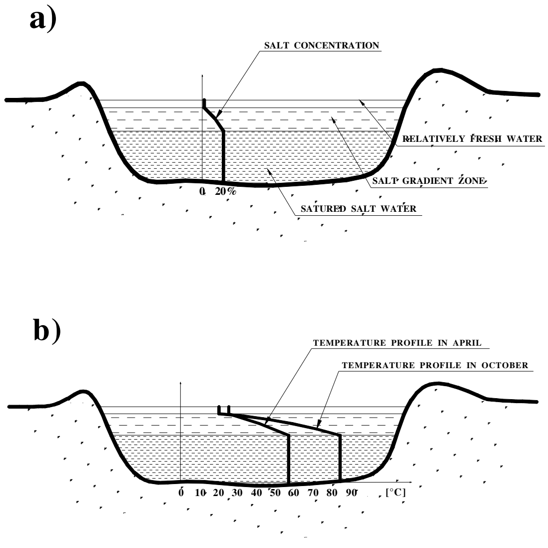

Fig. 3. Typical salinity distribution (a) and temperature profiles after winter and summer season (b) for a salt gradient solar pond located in the South Mediterranean belt.

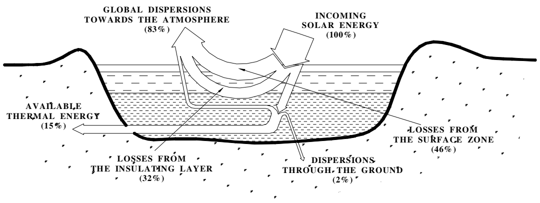

Fig. 4. Indicative energy balance of a salt gradient solar pond.

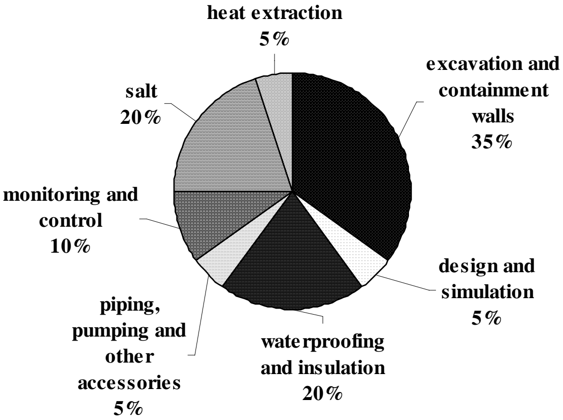

Fig. 5. Plant cost sharing relevant to a salt gradient solar pond.

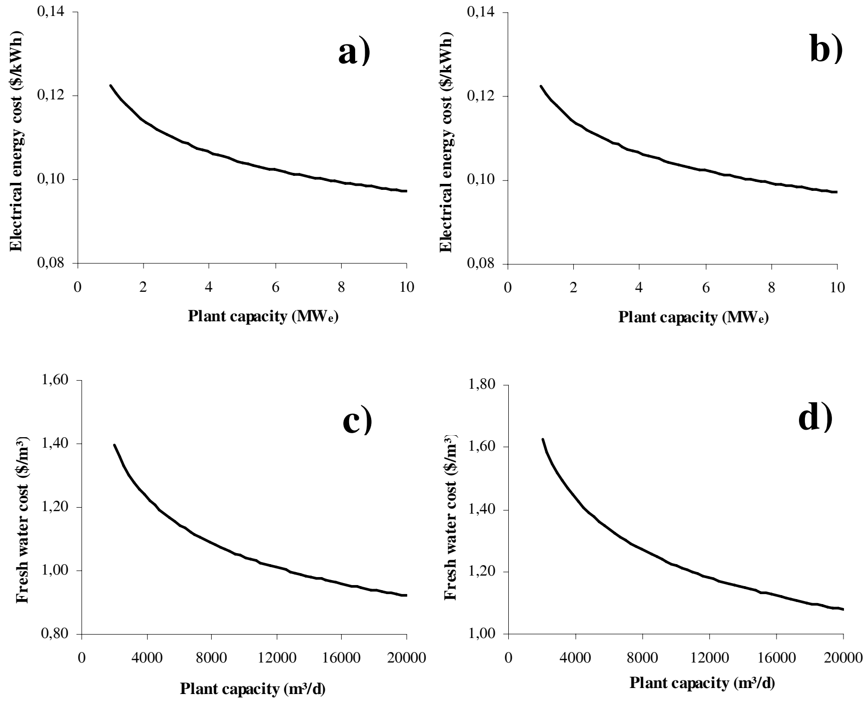

Fig. 6. Final cost trend with capacity for a solar pond powered plant in case of direct thermal energy production (a), electricity generation (b), seawater desalination by a grid connected (c) and by a stand alone (d) system.

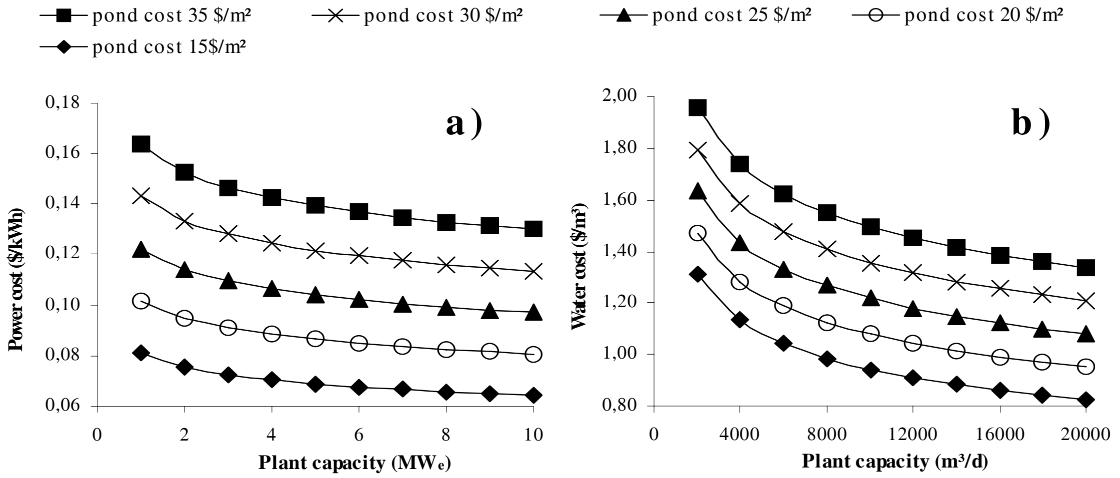

Fig. 7. sensitivity of the final cost with respect to the solar pond unit cost in case of power generation (a) and sea-water desalination by a stand alone system (b).

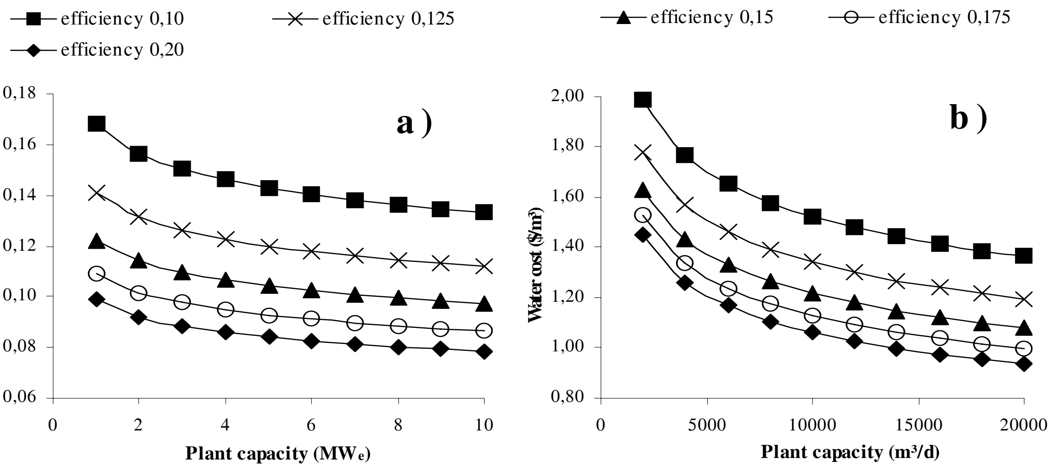

Fig. 8. Sensitivity of the final cost with respect to the solar pond efficiency in case of power generation (a) and seawater desalination by a stand alone system (b).

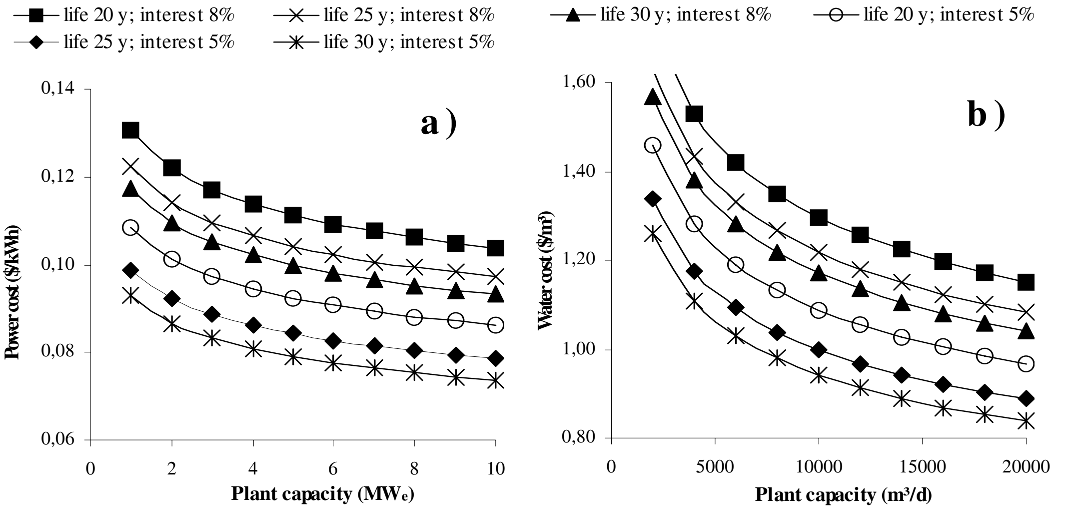

Fig. 9. Sensitivity of the final cost with respect to the depreciation rate in case of power generation (a) and seawater desalination by a stand alone system (b).

Table 1. Annual World-Wide Energy Production and Impact on Global Value by Most Important Renewable Sources

Renewable source	Annual production (TJ)	Energy global production ratio (‰)
Solar Thermal	228,720	0.523
Solar Thermal (electric)	1,200	0.003
Photovoltaic	630	0.001
Geothermal	128,060	0.292
Geothermal (electric)	151,390	0.345
Wind	35,760	0.082
Tides	2,160	0.005

Table 2. Trend of Population and Yearly Water Availability per Capita in the South Mediterranean Countries

Country	Population (10^3 of inhabitants)			Water availability (m^3 per capita)		
	1960	1990	2020	1960	1990	2020
Saudi Arabia	4,075	16,045	36,424	537	156	54
Libya	1,349	4,416	8,103	538	154	59
Malta	312	354	427	100	75	76
Yemen	5,247	11,590	34,190	481	214	82
Jordan	763	3,306	8,204	529	224	100
United Arab Emirates	90	1,921	3,170	3,000	189	117
Syria	4,561	12,386	24,555	1,196	439	172
Israel	2,114	4,660	7,952	1,024	467	324
Tunisia	4,221	8,156	12,254	1,036	532	334
Algeria	10,800	24,936	43,853	1,704	737	376
Oman	558	1,785	4,719	4,000	1,333	477
Egypt	27,840	56,333	90,491	2,251	1,112	682
Morocco	11,626	23,931	36,742	2,650	1,185	685

Table 3. Annual Solar Energy Available on a Horizontal Surface and Relative Peak Value in the South Mediterranean Countries

Country	Annual solar energy (kWh/m²)	Peak radiation (W/m²)
Yemen	2170	940
Saudi Arabia	2160	940
Oman	2140	930
Egypt	2050	1030
Jordan	2050	1020
Libya	2010	1040
United Arab Emirates	1980	910
Israel	1930	1010
Syria	1910	1040
Malta	1900	1040
Morocco	1860	960
Algeria	1840	950
Tunisia	1750	980

Table 4. Typical Heat Transfer Coefficients Value for an Adequately Insulated Solar Pond

Surface overall heat loss factor	0.4 W/m² K
Bottom thermal conductivity	0.1 W/m² K
Side walls thermal conductivity	2.2 W/m² K

Table 7. Values of the techno-economical parameters relevant to the salt gradient solar pond assumed in the calculations

Annual solar energy (kWh/ m²)	2,000
Utilization coefficient	0.9
Thermal conversion efficiency (%)	15
Unit cost for a 100,000 m² pond ($/m²)	25
Scale factor	0.9
System life (years)	25
Interest rate (%)	8
Maintenance and operational annual cost (% of plant total cost)	2

Table 5. Main Features of the Important Salt Gradient Solar Ponds Operating World-Wide

Location	Year	Area (m²)	Depth (m)	T_{max} (°C)	Capacity (kW_{th})	Efficiency (%)	Application
Ein Bokek (Israel)	1979	7,500	2.6	92	150-170	15-19.4	Electricity
Bhuj (India)	1987	6,000	4	88	150	-	Process heat
El Paso (USA)	1984	3,360	3	87	100	-	Electricity/desalination
Alice Springs (Australia)	1981	2,100	2.3	82	20	-	Electricity
Miamisburg (USA)	1978	2,020	3.5	66	-	15	Swimming pool heating
Yavne (Israel)	1977	1,500	-	90	40	-	Electricity
Dead Sea (Israel)	1975	1,100	-	103	-	15	Heat
Argonne (USA)	1980	1,080	-	-	-	4.3	Electricity
Montreal	1981	700	2	70	10	-	Environmental heating

Table 6. Strong and Weak Key Points Regarding Salt Gradient Solar Pond Technology

Advantages	Drawbacks
• low installation cost • simple and economical storage of the heat embodied within the collecting system • exploitation of diffused radiation too • low cost for piping, pumping and insulating • absence of maintenance owing to dust deposition. • possibility of recycling waste brain discharged by a desalination plant	• very low conversion efficiency • peak temperature of the supplied thermal energy not higher than 90 °C • economic feasibility only for large size plants in sites provided with appropriate characteristics • long times for installation and start-up • unsteadiness of the salt gradient due to adverse weather conditions • application limited to areas having access to large amounts of saline water or salt

Table 8. Values of the Techno-Economical Parameters Pertinent to the ORC Power Generation System and the MEE Desalter Adopted in the Analysis

ORC power generation system parameters	
Turbine isentropic efficiency	0.85
Average inlet temperature (°C)	75
Unit cost for a 10 MW turbo-generator ($/kW)	1,000
Scale factor	0.9
Additional maintenance and Operational annual cost (% of plant total cost)	0.5
MEE desalter parameters	
Thermal energy requirements (kWh/m³)	60
Power requirements (kWh/m³)	2
Unit cost for a 20,000 m³/d desalter ($/(m³/d))	1,000
Scale factor	0.7
Additional maintenance and Operational annual cost (% of plant total cost)	0.5
Water pre-treatment cost ($/m³)	0.025
Power cost ($/kWh)	0.04

Table 11. Sets of Values Assigned to the Parameters in order to Balance the Production Cost by a 20,000 m³/d Solar Pond Desalination System with the one by a Conventional Plant

PARAMETERS	CASE 1		CASE 2	CASE 3	
System life (years)	30		25	25	
Interest rate (%)	5		5	8	
Unit cost for a 100,000 m² pond ($/m²)	25	28	25	18	25
Thermal conversion efficiency (%)	13	15	15	15	22

Table 9. Typical Values of Energy and Water Production Cost by Large Sized Conventional Plants

PRODUCT	DEVICE	COST
Thermal energy	Natural gas-fired boiler	0.01 $/kWh
Electrical energy	Combined-cycle power plant	0.03 $/kWh
Fresh water	Grid-connected RO desalination plant	0.75 $/m³
Fresh water	Diesel generator powered stand-alone RO desalination plant	0.90 $/m³

Table 10. Sets of Values Assigned to the Parameters in order to Balance the Production Cost by a 10 MW Solar Pond Power Plant with the one by a Conventional System

PARAMETERS	CASE 1	CASE 2	CASE 3	CASE 4
System life (years)	30	25	20	30
Interest rate (%)	5	5	5	8
Unit cost for a 100,000 m² pond ($/m²)	10	10	10	10
Thermal conversion efficiency (%)	21	23	27	34

10. CONCLUSIONS

- Salt gradient pond promises to be the most economic technology for the thermal conversion of solar energy, as it especially comes out from the comparison with medium temperature solar thermal collectors. Furthermore it turns out to be gainful for producing thermal energy even with respect to a boiler firing conventional fuel such as coal, oil, and gas. It must be emphasised however that in the South Mediterranean regions low temperature heat requirements for domestic or industrial use are normally modest and fulfilled mostly by resorting to biomass; therefore the technology under investigation appears to be scarcely attractive for these purposes.
- In the present-day scenario, salt gradient solar pond can not realistically compete with conventional systems for power generation: in fact the production cost proves to be over twice higher, even assuming the most favourable hypothesis. Obviously that gap could drastically decrease or even zero for applications in remote areas, where the running of a diesel powered generator may turn extremely heavy. In such a situation, however, the crucial issue becomes the power demand, which has to achieve an adequate level in order to validate the putting in place of a medium to large sized pond.
- The over cost of fresh water is only around 20% with respect to conventional technologies; this value proves to be fairly small, most of all because the supplied thermal energy is cost-effective and fully fitting the needs of a MEE device. In case of remote areas applications, the whole power requirements of the desalination plant can be covered by the pond itself at a lower cost than a traditional generator, causing a further decrease up to nearly 15% in the above-mentioned gap. Moreover, at standard values of efficiency and depreciation rate, a non prohibitive cost of 18 $/m² is sufficient to achieve the break even point with traditional systems; in more favourable financing conditions, this target can be hit even with a cost higher than 25 $/m² or, alternatively, an efficiency lower than 15%. Obviously this picture becomes even more encouraging if government grants for renewable energies are locally made available. Finally, it is to be underlined that the existence of a substantial demand does not constitute a problematic issue for such an application, given that rural villages typically suffer from the shortage of fresh water.
- Salt gradient pond technology presents notable weak points, which deeply limit the current number of medium to large capacity running plants. First of all a

free and huge expanse of ground (over three times as much as any other solar energy conversion device), provided with adequate properties, must be available; secondly a high initial investment, a great effort for designing and simulating, and a long time for carrying out and fully operating are needed. In addition the forecasting stage presents notable difficulties, since field data are in short supply and it is indispensable a careful estimation of the initial investment, the plant efficiency, and the depreciation rate; in fact a variation per cent in those factors, which are all somehow site related, causes a nearly equal one in the final production cost. In summary general analyses cannot realistically attain more reliable results than the very promising ones illustrated in this paper.

11. ACKNOWLEDGEMENTS

One of the authors (VKS) would like to express his sincere thanks to Prof. G. Furlan, Head, Training and Research in Italian Laboratories (TRIL) Programme of I.C.T.P., Trieste for the financial support provided throughout his stay at ENEA Research Centre, Trisaia, in Italy.

12. REFERENCES

[1] Cesare Silvi, "Survey of Energy Resources 2001 – Solar Energy". World Energy Council, London, UK, 2001.

[2] A joint project of U.S. Department of Energy (Office of Power Technologies, Energy Efficiency and Renewable Energy) and the Electric Power Research Institute. Renewable Energy Technology Characterizations, EPRI Topical Report No. TR 109496, December 1997.

[3] World Health Organization: "Guidelines for drinking water quality", Geneva, 1984, Vol. I, recommendations.

[4] Food and Agriculture Organization of the United Nation, "The FAOSTAT Database. Population: annual time series", June 2000, Rome.

[5] World Resources Institute (WRI), "World Resources Report". Published in 1997 by WRI, Washington USA, 1997.

[6] Candace MacLaughlin, "2000 IDA Worldwide Desalting Plants Inventory". Report No. 16, International Desalination Association, USA, 2000.

[7] Weinberger H., "The physics of the solar pond". Solar Energy, 8/2, 1964, pp. 45-56.

[8] Tabor H., Weinberger Z., "Non-convecting solar ponds". Solar Energy Handbook, Ed. McGraw-Hill, New York, 1980, Ch.10.

[9] Lodhi M. A. K., "Solar ponds in alkaline lake and oil well regions", Energy Conversion and Management, 37/12, 1996, pp. 1677-1694.

[10] Kumar A., Kishore V. V. N., "Construction and operational experience of a 6000 m^2 solar pond at Kutch", India, Solar Energy, 65/4, 1999, pp.237-249.

[11] Ahmed M., Arakel A., Hoey D., Coleman M., "Integrated power, water and salt generation: a discussion paper", Desalination, 134, 2001, pp. 37- 45.

[12] Glueckstern P., "Potential use of solar energy for seawater desalination", Desalination, 101, 1995, pp.11-20.

[13] Tabor H. Z., Doron B., "The Beith Ha'Rava 5 MW$_e$ solar pond powered plant (SPPP)", Proc., International Progress in Solar Ponds, Cuernavaca, Mexico, 1987.

[14] Caruso G., Naviglio A., Principi P., Ruffini E., "High energy efficiency desalination project using a full titanium desalination unit and a solar pond as heat supply", Desalination, 136, 2001, pp.199-212.

[15] Manning R. A., Wisneski T. P., Clark E. E., "TENRAC Report No. 82-S-3-3", Texas Tech University, Lubbock, Texas USA, 1983.

[16] Szacsvay T., Hofer-Noser P., Posnansky M., "Technical and economic aspects of small-scale solar pond powered seawater desalination systems", Desalination, 122, 1999, pp.185-193.

[17] Holihan P., "Solar Thermal and Photovoltaic Collector Manufacturing Activities" on Renewable Energy Annual 2001, U.S. Department of Energy/Energy Information Administration (Office of Coal, Nuclear, Electric and Alternate Fuels), DOE/EIA-0603 (2001), Washington USA, November 2002, Ch. 2.

[18] G. Fiorenza, V. K. Sharma, G. Braccio, "Techno economic evaluation of a solar powered water desalination plant", Energy Conversion and Management, 44, 2003, pp. 2217-2240.

[19] Hull J. R., Nielsen C. E., "Solar Pond Research and Development", Solar Collectors, Energy Storage and Materials, Ed. MIT Press, 1991, Ch.10.