Solar Desalination for the 21st Century

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Series C: Environmental Security

Solar Desalination for the 21st Century

A Review of Modern Technologies and Researches on Desalination Coupled to Renewable Energies

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INTRODUCTION

The solar desalination workshop for the 21st century was sponsored by NATO program Security Through Science. In a great number of countries water scarcity, coupled with a significant growth in population especially in developing countries, poses the serious problem of supplying fresh water. The countries affected by water scarcity are found in the African, Asian, European and American continents, and also are on the southern and eastern coasts of the Mediterranean Sea. Severe drought usually generates a general malaise in populations which are already affected by a number of social and poverty problems, which often lead to significant and uncontrolled emigration towards richer countries, especially if one takes into account the increasing economic and lifestyle gap between north and south Mediterranean countries. Emigration could be contained if basic life needs were guaranteed to the population in their homelands, particularly potable water supply. Abundant solar energy combined with desalination could provide a sustainable source of potable water, but unfortunately, the optimum configuration for solar desalination that would provide inexpensive fresh water is difficult to reach. Further exhaustive research, field developments, and proper mobilization and coordination of funding, research and development is needed to achieve this goal.

Notwithstanding the complexity of the water scarcity problem, in recent years the development of new technologies has given hope for a solution, suggesting many different ways of how seawater desalination could provide a population with the needed amount of fresh water to guarantee a normal lifestyle. Well proved technologies such as Multi Stage Flash or Reverse Osmosis desalination show how it is possible to produce fresh water from seawater (or from brackish water) at a cost between 0.5 and 1 Euro per cubic meter of produced water, hile ensuring the highest standard of water quality suggested by the World Health Organization (WHO). Numerous examples of plants are currently operating nowadays in many wareas of the world, i.e. U.S.A., European countries (Italy, Spain and Greece), the Middle East and North African countries.

In recent years a growing technical and scientific community is dealing with the problem of optimizing current desalination processes and developing new ones. The most recent research topics have been focused on the consolidation and improvement of thermal desalination processes, the development of new and more efficient Reverse Osmosis plants and more recently the use of Renewable Energies to be coupled with the production of fresh water from the sea. The use of renewable energy for desalination purposes, in particular, has involved a number of research centers, universities and governmental authorities, due to the potential it may have in the field. As a matter of fact a continuous increase of fossil fuels costs is inevitable in the world market, especially due to economically huge and fast developing countries. This in turn implies that the costs of desalinated water from conventional plants (Multi Stage Flash, Multiple Effect Distillation, Reverse Osmosis) will increase steadily thus making solar energy more and more economically viable in the near future. The use of solar energy may also guarantee water production when conventional energy/fuel supply is lacking due to wars, oil crisis, political disorders, etc. Moreover the desertification process which is expected in many temperate zones (South Europe and Mediterranean Sea, South United States, etc.) will probably cause a further increase in water demand. Thus the use of solar energy for the production of fresh water seems to be an excellent choice, given also the strong relationship between water scarcity and solar energy availability.

The workshop participants are experts in the field of desalination. Several researchers have presented the state of the art of conventional desalination technologies focusing on energy consumption, production costs and environmental sustainability of conventional processes. Other researchers focused on various aspects of solar desalination. Presentations and discussions focused on main features and advantages of solar desalination, the most promising technologies to be developed and the recent trends. Features of other types of renewable energies are also discussed, in order to complete the outline of renewable energies applied to desalination. Public authorities presented their projects aimed to support the solution of water shortage in their countries and discussed the potential of new technologies and the technical and practical steps to be taken to start new projects on solar desalination.

The workshop succeeded in uniting people from different countries and areas of interest, so they could discuss the possibilities of producing fresh water from the sea by means of solar energy or by other renewable energies. Participants presented their research activities, findings, new perspectives and projects (already realized or to be realized), through exchange of ideas, knowledge and information about this topic, outlining the possibilities of development and of use of these new technologies. The papers presented in the workshop include a variety of topics on solar and convention desalination as well as various sources of renewable energy. This book has seven sections, which include: (1) Opening, (2) Overviews on Solar Desalination (3) Modeling Tools and Optimization, (4) Solar Desalination Potential and Local Applications, (5) Solar Technologies With Industrial Examples, (6) New Technologies Applied To Solar Desalination, (7) Conclusion.

In the following pages a summary of the ARW Opening and Conclusions is reported, together with the main outcomes from the ARW. Moreover the list of all participants with their affiliation and a photo of the group have been included.

SCIENTIFIC PROGRAM OF THE NATO ARW

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- Development of solar desalination system concepts for irrigation in arid areas conditions (Chaibi T. and Bourouni K.)
- Techno-economic evaluation of a solar powered water desalination plant. (Fiorenza G., Sharma V.K., and Braccio G.)

3. Modeling Tools and Optimization

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- A review of desalination by solar stills (Aybar H.)
- Multi Effect Humidification Desalination System (Muller-Holst H.)
- Beyond pilot projects: The feasibility of immediate technology transfer from tried and tested maritime and offshore reverse osmosis systems to stationary solar and wind powered desalination solutions (Thiesen S.)
- Using solar ponds in thermal and membrane distillation (Safi M.)
- Solar driven desalination systems based on membrane distillation (Rommel M., Koschikowski J., and Wieghaus M.)
- Potential application of solar heat collectors to an EASYMED thermal desalination unit (Renaudin V., Alonso D., Kafi F., and Hornut J.M.)
- Membrane desalination driven by solar energy (Banat F., and Qiblawey H.)

6. New Renewable Technologies Applied To Solar Desalination

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- Small autonomous RO desalination systems powered by renewable energies technological advances and economics (Papadakis G., Mohamed G., and Manolakos D.)
- Seawater bitterns as a source of liquid desiccant for use in solar-cooled greenhouses (Davies P.A., and Knowles P.R.)

- Desalination with wind and wave power (De Almeida A. T., Moura P. S.)
- Production of desalted water in a hybrid RO/MSF plant from RDF combustion: modeling and economics. (Fois E., Lallai A., Mura G.)
- Autonomous desalination units based on renewable energy systems – a review of representative installations worldwide (Papapetrou M., Epp C., and Tzen E.)

7. Conclusions (Rizzuti L., Ettouney H., Balaban M.)

OPENING

(L. Rizzuti, and H. Ettouney)

During the past few decades there has been great effort to raise funs for the development of efficient and inexpensive solar desalination systems for decentralized small scale production that would supply several thousand remote and small communities that have only limited access to good quality water or are supplied through long pipelines or batch tankers. As large centers for water desalination are becoming part of urban development in several countries around the world, the use of solar energy would reduce production costs.

The research group from the Chemical Engineering Department, University of Palermo, led by Prof. Lucio Rizzuti organized the solar desalination workshop with funding from the NATO PROGRAMME SECURITY THROUGH SCIENCE. Dr. Hisham Ettouney co-directed the workshop; he is currently a professor of Chemical Engineering at Kuwait University. The workshop was co-organized by Miriam Balaban, secretary of the European Desalination Society and editor of Desalination, Prof. Karim Bourouni, from the Ecole National d'Ingégnieurs of Tunis, Prof. Giorgio Micale, and Dr. Andrea Cipollina, from the University of Palermo.

The list of participants shows contributions from universities, research institutes, industry, and public authorities. Participants came from the EU countries, the MENA region, and non-EU countries. The workshop lasted three days. Each presentation lasted 30 minutes including discussion time. The workshop sessions and participants accommodation were in the same place to allow continued discussions throughout the day. Workshop topics included various aspects of solar desalination, i.e., review of existing units, field data, system economics, modeling, performance evaluation, development of novel configurations, hybrids, etc.

One of the main objectives of the workshop was to give an extensive overview of the current status of solar desalination, through presentation and evaluation of existing and future solar desalination projects. This provided much needed information about most common technologies, typical plant size, and estimates for product cost. From the findings of these objectives the need to find ways of taking existing solar desalination technology to a wider range of end-users emerged.

CONCLUSIONS

(L. Rizzuti, M.Balaban, and H. Ettouney)

The solar desalination workshop sponsored by the ARW NATO preprogram was a valuable and a successful event. The workshop allowed several individuals of the desalination, solar desalination, and public authorities to present their work and discuss their findings with other colleagues and researchers in the same. The workshop gathered researchers from EU, Non-EU, MENA, and the USA.

Several important technical issues were discussed during the workshop; e.g., industry status and existing technologies, renewable forms of energy, costs of small versus large units, costs of water transportation versus small solar desalination units, modern modeling tools, novel cycles, hybrids of solar, conventional, fossil fuel, and renewable energy, and performance of small solar desalination units. Studies included review and state of the art accounts, inventory of solar desalination systems, mathematical modeling, performance evaluation of small units, and costs.

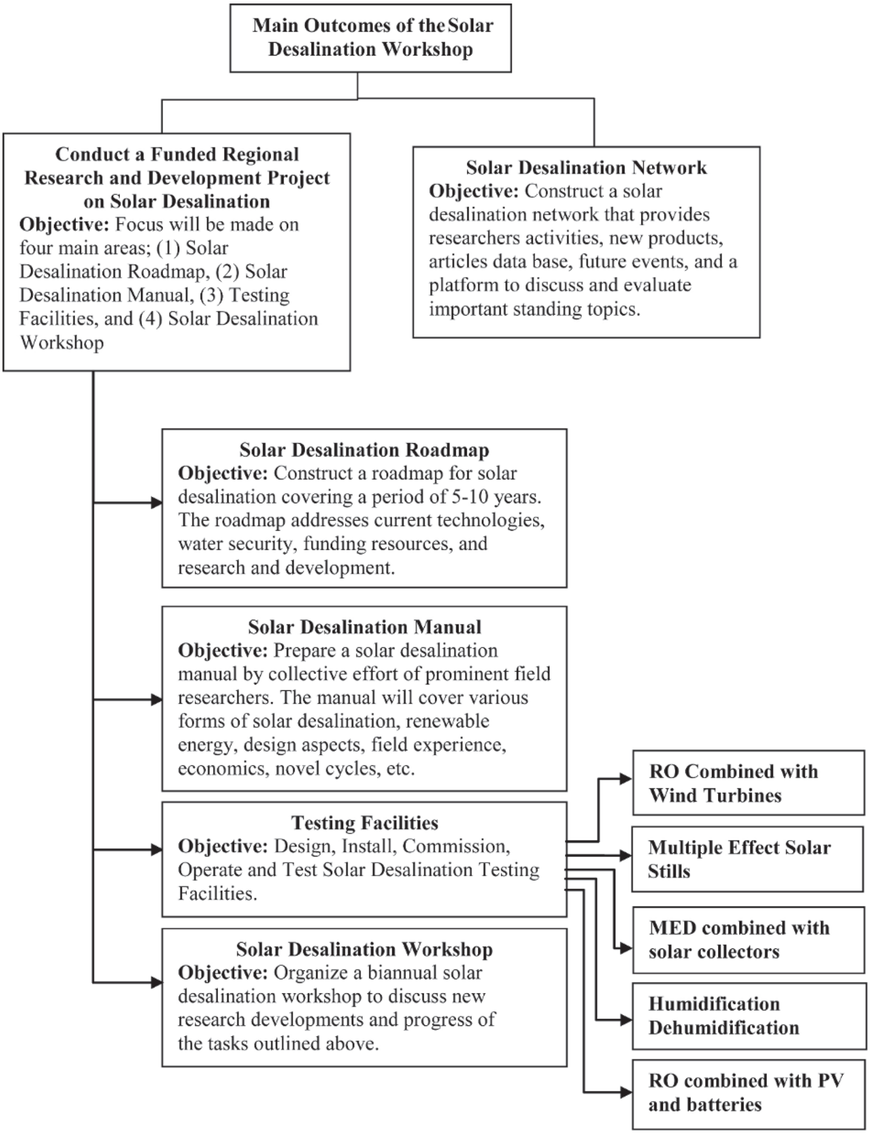
Current status of solar desalination shows the existence of small scale production units. Such units are still on a limited scale and are more expensive than conventional large scale desalination. In addition, the experience gained from design, construction, and operation of these units has not increased over the years. So basic research needs to be improved, also with regard to design, construction and operation of the plans. In fact there are continued research efforts by various institutes, where one or more prototype of solar desalination system is developed on experimental scale, but attempts to commercialize or to become part of the activities of water and energy public authorities still lag behind conventional desalination.

The studies showed the economic competitiveness and reliability of solar desalination in comparison with transportation of fresh water over long distance or by tankers.

The most evident conclusion of this workshop is the need for further extensive work, aiming to make solar desalination more feasible and economically competitive. Adoption of solar desalination can be made for either small scale (de-centralized) units, which are suitable for remote and small communities, or for larger size units, which may become part of the existing fossil fuel desalination industry.

Two further plans resulted from the workshop. The first is the development of a solar desalination network, which will maintain intensive data base on researchers, current projects, manufacturing companies, publications, software, and inventory of existing plants. The network will have a permanent web site and an electronic newsletter published frequently. The network will maintain close contact with known desalination conferences (IDA, EDS, WSTA, etc) to offer specialized sessions on solar desalination.

The second plan is a sponsored project that gives an outline for (1) solar desalination road map, (2) testing facilities, (3) solar desalination manual, and (4) a second solar desalination workshop. The project will provide working documents through which new projects on items (2) and (3) will be made. The project will sponsor a second solar desalination workshop. The attached flow diagram shows a summary for the proposed work.


Main Outcomes of the Solar Desalination Workshop
Conduct a Funded Regional Research and Development Project on Solar Desalination
Objective: Focus will be made on four main areas; (1) Solar Desalination Roadmap, (2) Solar Desalination Manual, (3) Testing Facilities, and (4) Solar Desalination Workshop
Solar Desalination Network
Objective: Construct a solar desalination network that provides researchers activities, new products, articles data base, future events, and a platform to discuss and evaluate important standing topics.
Solar Desalination Roadmap
Objective: Construct a roadmap for solar desalination covering a period of 5-10 years. The roadmap addresses current technologies, water security, funding resources, and research and development.
Solar Desalination Manual
Objective: Prepare a solar desalination manual by collective effort of prominent field researchers. The manual will cover various forms of solar desalination, renewable energy, design aspects, field experience, economics, novel cycles, etc.
Testing Facilities
Objective: Design, Install, Commission, Operate and Test Solar Desalination Testing Facilities.
Solar Desalination Workshop
Objective: Organize a biannual solar desalination workshop to discuss new research developments and progress of the tasks outlined above.
RO Combined with Wind Turbines
Multiple Effect Solar Stills
MED combined with solar collectors
Humidification Dehumidification
RO combined with PV and batteries

List of Attendants by Region and Country

MENA

Egypt	El-Nashar
	Fath
	Ettouney
Jordan	Abu-Arabi
	Banat
Morocco	Elmidaoui
Algeria	Boukar
Tunisia	Baba
	Ben Bacha
	Bourouni
	Chiabi
	Orfi
	Safi

Non-EU

USA	Balaban
	Subhas
Ukraine	Nikulshin
Bulgaria	Gramatikov
Uzbekistan	Khaydarov
Turkey	Aybar
	Turkman

EU

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	Beccali
	Brucato
	Cipollina
	Fois
	Micale
	Sclafani
	Sharma
UK	Bogle
	Davies
France	Renaudin
Netherland	Thiesen
Spain	Alarcon-Padilla
	Blanco-Galvez
Germany	Knies
	Kopsch
	Muller-Holst
	Rheinlander
	Rommel
Greece	Papadakis
	Papapetrou
Portugal	De Almeida

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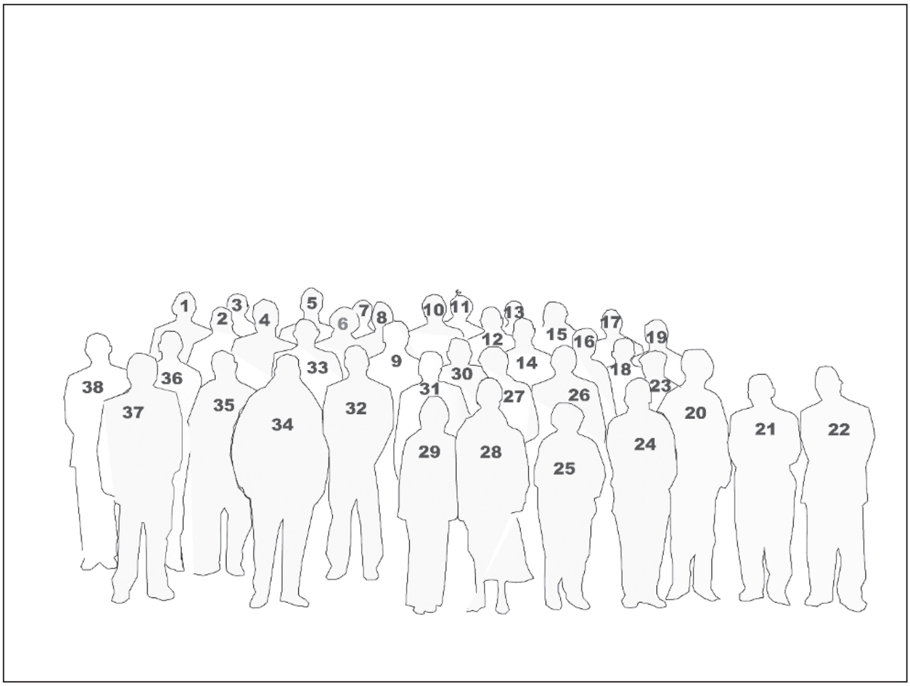

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PREFACE

The sun and the sea harbor mighty resources which, linked together, could nurture mankind. Inland waters in sun-drenched remote areas, though limited, are already bringing sustenance to families and small communities using small solar stills.

Yet though solar and desalination technologies have matured to an economic industrial scale, their harmony is yet to be composed. As evidenced in the papers in this book there is considerable research devoted to solar desalination. Moreover, statistically, papers on the topic are highly cited in the journal, Desalination. Most of these papers, however, are theoretical and report on small plants in remote areas. An indication of possible developments has been in the direction of solar ponds and multi-effect distillation. A substantial financial boost by government and industry to fund research and development is required to investigate whether solar desalination can be lifted to a commercially viable affordable sustainable technology. A dynamic thrust forward is required to advance the technology – especially to economically link solar energy to desalination and scale up through demonstration plants.

Massive sums have been allocated by governments, and the world's keenest minds have been enlisted for military objectives. While leading to weapons of mass destruction, they have also sometimes resulted in benefits to mankind such as the high tech industries, the peaceful use of nuclear energy and reaching out to outer space. Could we not skip the negative objectives and leap directly to the peaceful objective of alleviating hunger and poverty by supplying the rapidly depleting source of water to a rapidly growing population? Would application of the solar source not become an attractive business?

The giant petroleum companies are already showing their concern and interest due to increasing environmental alarm, depleting sources of fossil fuels and resulting high prices. Banks are looking into backing renewable energy schemes creating opportunities for investors and developers. So increasing oil prices, concern over energy security, and threat of climate change are driving renewable developers.

NGO's and governments have voiced token interest.

Our challenge is to develop technology for solar desalination so that clean energy can augment the critical need for clean water. At the meeting in Hammamet, it was decided to form a network of solar desalination

A proposal for functions of the network follows:
Create a database of people involved in any aspect of solar desalination
Create a bibliography
Hold regular seminars
Present at relevant meetings on solar energy and desalination
Invite representatives of industry
Communications – issue briefs of popular material for the press
Lobby
Promote a test facility
Education

Papers in this volume discuss research and experimental projects in countries around the Mediterranean. There is also a proposal for a larger facility making solar desalination a reality on a large scale. It is hoped that in future meetings members of the network will be able to report stepwise advances towards making solar desalination a reality.

Miriam Balaban
European Desalination Society
Desalination Journal

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The editors acknowledge also the other members of the ARW organizing committee Miriam Balaban, Karim Bourouni and Giorgio Micale for their scientific and logistical support.

Last but not least, all the ARW participants and the authors of this book, who significantly contributed to the successful progress of the event, are sincerely thanked.

SOLAR DESALINATION: A CHALLENGE FOR SUSTAINABLE FRESH WATER IN THE 21ST CENTURY

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Abstract. Combining renewable solar energy and desalination would generate a sustainable source of fresh water as well as energy. This combination is highly valued as it limits and reduces air pollutant emissions and green house gases generated by combustion of fossil fuels. Increase in energy demand during the first half of this century is expected to continue, which makes the cost of renewable solar energy highly competitive against fossil fuels. Desalination has been relied on to provide fresh water for large cities and countries across the world. The desalination industry continues to grow in countries in arid regions. Various aspects of solar desalination processes, solar energy, and conventional desalination are discussed. Scenarios for combination of existing units with renewable energy are evaluated. The paper also includes a brief review of a number of novel cycles for combining solar energy and desalination.

Keywords: solar plants, desalination, hybrid systems

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1. Introduction

The world natural resources of fresh water are constant. However, the world population continues to grow rapidly and is expected to increase from a present value of 6×10^9 inhabitants to 9×10^9 in the year 2050. This growth is associated with rapid expansion of urban regions, which consume large amounts of potable water (200-400 L/capita/d). Population increase and associated changes in lifestyle stress the limited water resources even further. Governments and municipalities struggle to secure sufficient fresh water resources for the ever-increasing demand by adopting strict policies for conservation, water reuse, imports, transportation, and desalination. Continuous progress and improvements in the desalination technologies have made it a feasible alternative and quite competitive against water imports or transportation. Moreover, environmental protection through the use of renewable energy must become part of the present and future desalination industry. Therefore, a program that includes conservation, reuse, desalination, and renewable energy would provide a sustainable source of potable water.

The current desalination market amounts to 25×10^6 m^3/d. It is almost equally divided among the MSF and RO processes. The MSF process was introduced in the early 1960's in several countries with small production units of less than 500 m^3/d (Al-Zubaidi, 1987). The MSF systems evolved over the past 40 years, where the unit capacity increased to very large unit capacity of 75,000 m^3/d. Simultaneously, the unit product cost was reduced to competitive prices of \$0.5/m^3 (Borsani, and Rebagliati, 2005). A similar scenario can be found for the RO process, where the very first commercial type of membranes were developed in the 1960's and were commercialized in the early 1970's. Various types of RO membranes can be used for desalination of river water, low salinity brackish water, and seawater. The RO unit price has always been reported to be lower than the MSF process; however, recent developments in thermal desalination systems have resulted in a similar unit product cost. Such developments include increase in the unit size, competitive tendering, and less stringent design specifications.

Current desalination technologies require large amounts of energy; either in the form of electric current to operate high pressure pumps for the RO system or pumps to transport various liquid streams. Also, thermal desalination requires heating steam for the evaporation process in MED or vapor flashing in MSF. Electric power consumption is currently rated at 5 kWh/ m^3 for the RO, 4 kWh/ m^3 for MSF, and 3 kWh/m^3 for MED (Borsani, and Rebagliati, 2005). The heating steam for thermal desalination is withdrawn from the cogeneration power plant. Field testing as well as mathematical modeling are used to convert the heating steam load into electric current; approximately the heat steam load is equivalent to 15 kWh/m^3 for a thermal desalination process with a performance ratio of 8 (kg product/kg heating steam) (Darwish et al., 1997). The larger power consumption cost of thermal desalination is met by similar cost for membrane replacement.

The current status of the desalination market could remain unaltered for the first half of this century. This would include desalination processes (mainly RO, MSF, and MED) and use of oil and natural gas fuels as a source of energy. However, the increasing demand for energy would result in further increase in fuel prices. Several forms of renewable energy sources are becoming attractive and competitive to oil and gas: wind, photovoltaic, solar collectors, and biomass. An increase in the use of nuclear power could be another source for providing lower cost electric power. However, nuclear power continues to have a negative public image and faces several controversial issues.

Although a large portion of solar research focuses on the design and analysis of the conventional solar stills, sizeable research also considers the possibilities of hybrids of solar energy and conventional desalination systems. Figure 1 shows a classification of indirect and direct desalination. As shown, direct desalination includes only solar stills. Indirect desalination includes solar collectors, which generate hot water that can be fed to conventional thermal desalination processes. Electric power to operate the pumping units in thermal desalination could be obtained from wind farms, turbine towers, or photovoltaic cells. The RO or MVC process would only require electric power, which can be generated from photovoltaic cells together with batteries. In addition to batteries, other forms of energy storage include phase change and sensible heat. Proper design of these units would provide sufficient thermal load to heat the feed water in thermal desalination or operate a power cycle that generates electricity.

Environmental protection is an important issue in the use of solar and other sources of renewable energy. Desalination, either membrane or thermal, requires large amounts of energy. Continuous use of fossil fuels contributes to the generation of green house gases in addition to various pollution products; i.e., nitrogen and sulfur oxides, polyaromatics, ozone, and particulate matter. Use of solar energy alleviates a considerable part of air pollution problems as most of the desalination plants are found in co-generation sites (Kalogirou, 2001).

Use of solar desalination on a large scale could be adopted in a hybrid form with existing desalination and fossil fuel power plants. In this regard, small systems can be designed, i.e., photovoltaic cells or collectors, to provide energy for one of the desalination units during the daylight hours.

Success of such arrangement and accumulated field experience would ultimately lead to further expansion and adoption of supporting units, i.e., energy storage or batteries, to increase the number of operating hours (Sagie et al., 2001).

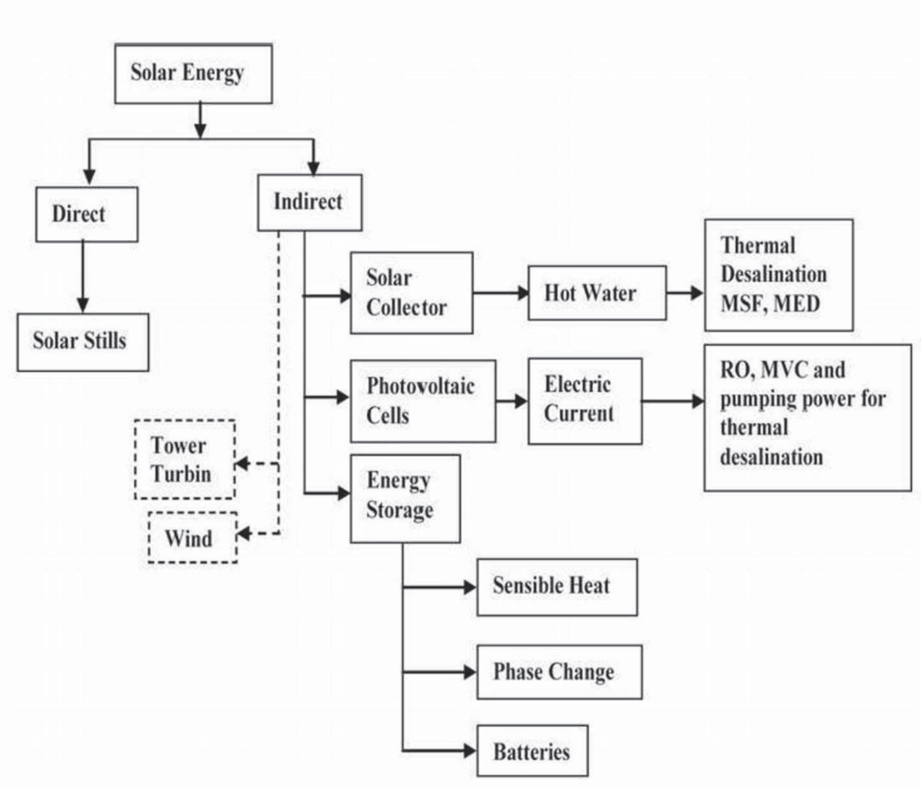

Figure 1. Classification of direct and indirect solar desalination.

Another possible difficulty in adopting solar desalination could arise because most, if not all, natural water resources, desalination, and power plants across the world are owned and distributed by the government. However, several successful schemes have been achieved through the BOOT scheme, where desalinated or reclaimed water by novel schemes were successfully designed, commissioned, and operated. This choice might make it feasible to start a solar desalination system on large scale.

The next sections include the review of a number of major research topics in solar desalination. These include solar stills, humidification-dehumidification, and hybrids with conventional desalination methods, and novel cycles. The discussion focuses on evaluating the current status of solar desalination and lays out a possible scenario for future developments.

2. Solar Stills

A conventional solar still has a simple geometry. The still is formed of a square or rectangular box, which is equipped with a sloped glass cover. The walls and base of the box must be made from materials that can withstand the elements. Materials such as wood, plastic, or metal are reported in literature studies. The top cover of the box is made of transparent glass to allow for the passage of solar energy. The desalination mechanism is similar to that of nature. A shallow pool of brackish or seawater absorbs solar energy and as a result vapor of fresh water is formed in the space above the water. The vapor condenses on the inside of the glass cover and is then collected in a side trough. Figure 2 shows a schematic of the most basic form of solar stills.

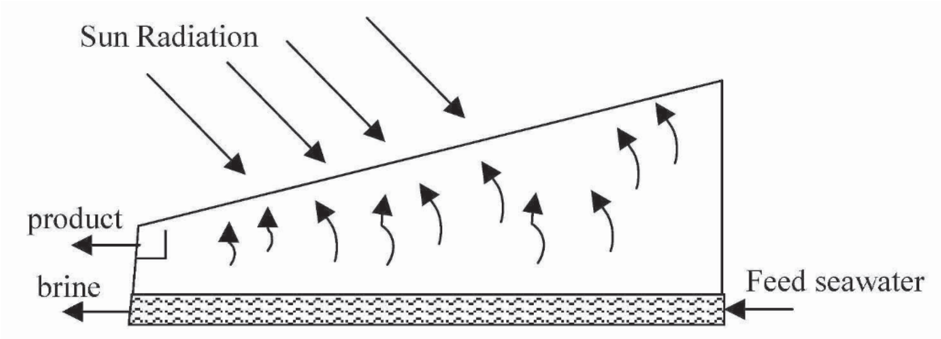

Figure 2. Schematic of simple solar still.

Parameters that affect efficiency of water stills include water depth, solar radiation intensity, cover inclination and material, feed water temperature. A simple solar still has a low production rate of 1 L/m^2/d. However, simple modifications in the system design may result in the increase of the production rates. For example use of wick material instead of water basin (Bouchekima, 2003) or adjustment of the glass cover inclination (Singh and Tiwari, 2004) can increase the production rate by up to 50%. Also, use of multi-effect stills can increase the production rates fourfold (Adhikari and Kumar, 1999; Graeter et al., 2001). The following is a brief review of some of the recent research on design and performance evaluation of solar stills.

Vertical solar stills occupy smaller land area and can provide similar production rates. Boukar and Harmim (2004, 2005) evaluated the performance of vertical solar stills in southern Algeria. Their study is motivated by the need for a desalination system that has simple technology and minimum engineering skills.

Several investigators studied the effect of combining solar collectors together with stills (Badran and Al-Tahaineh, 2005; Voropoulos et al., 2001, 2003). This configuration increased the production rate by up to 50%. Also, the system productivity became uniform and was not affected by day or night operation. Adding the collector to the solar still system would increase the capital cost, but the increase in production rate would offset the incurred cost.

The multistage solar stills seem to improve the system efficiency. Their design allows evaporation between the maximum possible temperature, 90°C, and lowest system temperature, of about 5°C higher than the feed water. Although the performance of the multistage solar still requires more advanced engineering to construct and operate, it can provide up to 6 L/m^2/d (Graeter et al., 2001). Adhikari and Kumar (1999) reported an optimum of 3 effects that provides the lowest water product cost.

Natural convection effects in vapor space in solar stills are studied by Omri et al. (2005). The analysis shows that adjustment of the glass cover inclination angle results in a maximum optimum for the water temperature in the system. A similar conclusion is made by Tiwari and Tiwari (2005) through experimental adjustment of the glass cover angle for a solar still system in India.

The study by al-Hayek and Badran (2004) shows that use of the asymmetric solar still, where mirrors are added to the side walls, increases the system productivity by 20%. Aybar et al. (2005) used wick material in the inclined water still and system productivity increased by threefold due to the increase in residence time and the decrease in thermal resistance to absorption of solar radiation. Separation of evaporation and condensation zones was tested by Rahim (2001). Results showed two to threefold increases in system productivity upon separation of the condensation zone. This is because condensation on the glass cover increased the resistance for the passage of solar radiation. Another design adjustment considered by Rahim (2001) was to add a metal plate in the seawater/brackish water pool. This arrangement generated a shallow pool and a large storage volume which was able to maintain a uniform temperature through the system and sustain evaporation even during the hours.

The above review cites but a few of the vast literature studies on solar stills. We concluded that the basic form of horizontal solar still could not be the optimum configuration. As discussed above, few modifications in the single stage still can provide higher yield. Definitely, the multi-effect solar still is more efficient than a single stage; this is quite similar to the comparison of a single stage flashing or evaporation against a multistage system. Further improvement in the solar still system is achieved by combining it with a solar collector and large tank for storing hot water. The solar collector provides hot water, which can be used directly in the still or stored in a hot water storage tank, so obtaining uniform production rate during daytime or nighttime. Fig. 3 shows a schematic of a solar still combined with a collector, storage tank, and feed preheater. The feed preheater can be omitted in the case of multieffect solar still, where the brine reject temperature from the last effect reaches the feed water temperature.

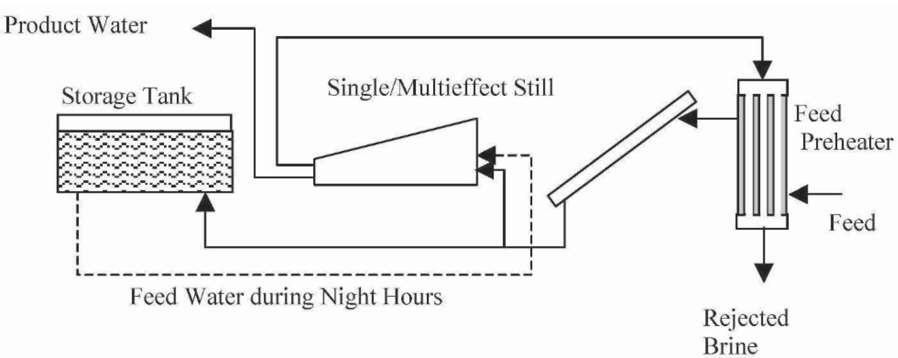

Figure 3. Schematic of a solar still configuration together with feed preheating, collector, and hot water storage.

3. Hybrids of Solar and Conventional Desalination

Development of hybrids of solar and conventional desalination requires careful analysis and innovative engineering solutions. Hybrids of RO and solar energy are relatively less complicated than hybrids of thermal desalination (Childs et al., 1999). However, the large production capacity of RO desalination plants requires careful evaluation and assessment of various power schemes. For example, the desalinated water production in Saudi Arabia is well above $5x10^6$ m^3/d and is expected to double over the next decade. Assuming that this entire capacity is switched to RO, which has a power consumption rate of 5 kWh/m^3, it will require a total electric power of 1042 MW. A choice of photovoltaic panels combined with a battery system for night time operation, would require close to 21 km^2 of photovoltaic panels to provide the required energy. Another scheme for renewable energy could be generated from wind farms together with battery system to cover periods of insufficient wind speeds (Lindemann, 2004).

Another scheme is proposed by Manolakos et al. (2005), which includes a low temperature rankine cycle. The proposed system produces high pressure vapor, which can be used to operate various pumps in the RO system. The system is intended for remote areas with limited infrastructure, where skill requirements and part replacement are minimal. Also, the system can be manipulated to generate electric power for instrumentation and control system.

Hybrids of thermal desalination and solar energy are more complex due to the large production capacity of the thermal desalination plants. Also, most of the thermal desalination plants are designed and operated in cogeneration mode together with power plants. In the Gulf States about 70% of the installed power is consumed by air-conditioning. The remaining power is consumed by other urban activities, industry, and desalination plants. For example, desalinated water in Kuwait comes from MSF, with a capacity approaching 1.92×10^6 m^3/d. Thermal energy utilization in the MSF is very large, as the temperature of the brine recycle stream, which is close to 10 times the product flow rate, is increased by 10 ^oC. Also, the electric power consumed is approximately 4 kWh/m^3. Therefore, a solar energy system has to generate 320 MW of electricity. The system has also to include collectors to heat the brine recycle stream. Assuming a collector that can handle a temperature range of 90-100 ^oC with a specific capacity of 45 $L/(m^2\ h)$ would result in a collector area of approximately 16 km^2. Figure 4 shows a schematic of thermal desalination, fossil power plant, and solar energy hybrid. The system can be designed to provide partial energy through the solar collectors, PV panels, or the wind farm. The system also includes solar stills which can operate on the brine blow down or the rejected cooling seawater. Although both streams have the same thermal energy, the brine blow down is treated and will cause less scaling, foaming, or corrosion.

Cipollina et al. (2005) evaluated simple hybrids of solar and thermal desalination. They considered use of hot brine or cooling seawater as a feed for solar stills. For example, use of solar stills in the case of Kuwait to increase the production rate by 20% and assuming that the still productivity is 10 $L/(m^2\ d)$; then a still area of 30 km^2 will be required. Evaluation of such proposals should consider the environmental benefits and the accumulated experience in development of solar stills. Also, it should be noted such large systems would result in considerable reduction in the product cost.

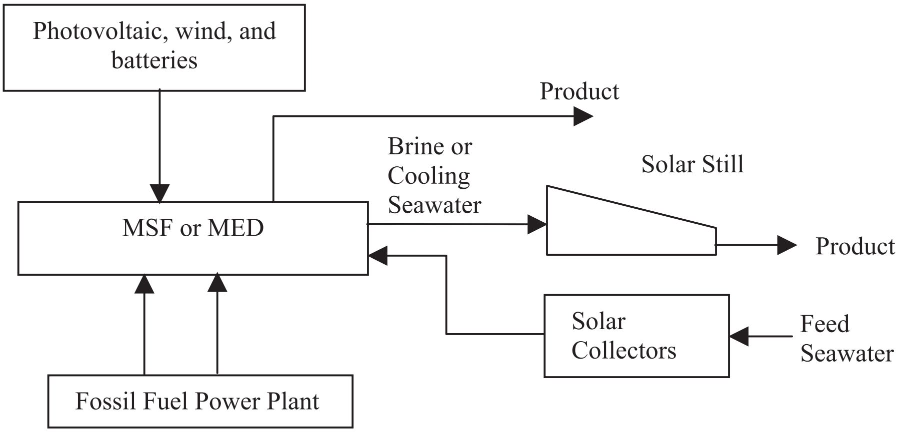

Figure 4. Hybrid of solar stills, collectors, and conventional desalination.

Zejli et al. (2004) developed a mathematical model to study the performance of adsorption heat pump combined with solar energy collector and MED. The analysis show large increase in the thermal performance. However, no account was made for the large system capacity or operation during the night hours. Similar results were also reported by El-Dessouky and Ettouney (2002) for several thermal desalination systems and showed two to fourfold increases in the thermal performance ratio. García-Rodríguez and Gómez-Camacho (1999) and García-Rodríguez et al. (1999) studied use of solar assisted fossil fuel MSF and MED plants. The analysis shows that these schemes are highly competitive against conventional fossil fuel plants. However, the analysis was limited to small scale plants, with capacities up to 3000 m^3/d. Finally El-Nashar (2001) studied the feasibility of solar MED for the case of arid remote locations.

4. Novel Cycles

Novel cycles for use of solar radiation are thought by investigators to maximize the system yield, improve efficiency, and reduce cost. Review of a number of literature studies show studies on modification in the design of the conventional unit, and multieffect stills, use of heat pumps, and use of membranes. The following is a brief discussion on the main outcome of a number of studies.

- De-Koning and Thiesen (2005) developed a novel design of a solar still. The system includes two separate chambers for evaporation and condensation. Also, mirrors are used to concentrate the solar radiation to produce close to 40 L/m²/d.

- Heidari and Shiati (2005) proposed a system that combines lithium bromide absorption heat pump together with solar collectors. Although, the authors presented the system layout, performance of this configuration is known to provide a high performance even for single effect systems (El-Dessouky and Ettouney, 2002).
- Koschikowski et al. (2003) combined membrane distillation and solar collector. The collector heats the feed water to a temperature range of 60-80°C. The membrane is hydrophobic and allows only water vapor to permeate. The membrane is not prone to scaling or fouling as in the RO process, therefore feed treatment is not required. The condensation process occurs in the permeate compartment and the latent heat of condensation is recovered by the water feed. Reported productivity ranges from 20-30 L/m²/d. These values are reported to a configuration without hot water storage tank, therefore it might be possible to increase the system productivity to values above 50 L/m²/d upon the use of a hot water storage tank.
- Al-Kharabsheh and Goswami (2003) developed a solar still system that utilizes the pressure differential of vapor pressure and gravity to move feed water, brine, and product between storage tanks, the solar still, and the condenser. The system benefits from separation of the evaporation and condensation zones. Also, it contains a finned air condenser. The system still needs recovery of the thermal energy in the brine concentrate and the product water.
- The performance of an experimental solar assisted heat pump is studied by Hawlader et al. (2004). The system gives performance ratio around one, which implies need for further optimization.
- Kunze (2001) developed a novel and compact solar still. The special design of the system provides up to 40 L/m²/d fresh water. Combining this system together with a heat storage tank might result in a further increase in the system productivity with estimates of up to 100 L/m²/d.

5. Humidification Dehumidification

Conventional HDH process is formed of three main parts, see Fig. 5. These are the humidifier, where the intake air humidity is increased to saturation conditions, the condenser, where the humidified air is cooled to condense the product water, and the feed seawater heater. It should be noted that the intake seawater is preheated in the dehumidification unit. The feed seawater is further heated in the feed heater in order to achieve the desired design conditions. These are achieved with the aid of an external heat source, for example solar collector, heating steam, diesel engine, or other forms of low grade energy.

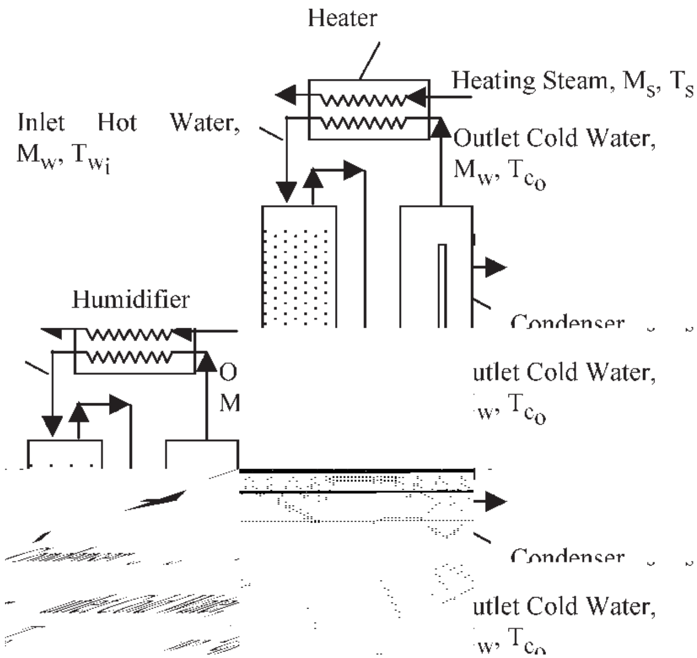

Figure 5. Conventional humidification dehumidification desalination process.

There are several other forms of the humidification-dehumidification-desalination process, which include vapor compression, membrane separation, and desiccant absorption (Ettouney, 2005). A schematic for the vapor compression process is shown in Fig. 6. This system was proposed by Vlachogiannis et al. (1999). In this configuration, the humidified air is compressed to higher pressure. This results in simultaneous increase in the air temperature and pressure. The compressed air is then cooled against the feed seawater. This results in water vapor condensation. The system includes the conventional air humidifier and the air/vapor compressor. The system shown in Fig. 5 includes simultaneous heating of the humidifier air and water streams through exchange of heat with the compressed humidified air stream. This setup can be modified by using a separate water preheater (water vapor condenser) system, as in the conventional HDH system. This is more technically feasible, since the air humidification unit and the water vapor condenser are not a specially designed system, as shown in the unit in Fig. 6.

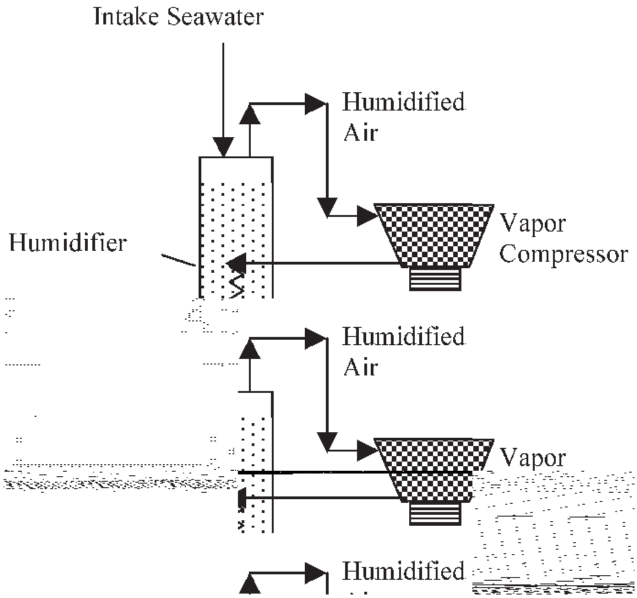

Figure 6. Humidification vapor compression.

A schematic for the humidification desiccant absorption/adsorption is shown in Fig. 7. The desiccant material can be in liquid form, i.e., lithium bromide solution, or in a solid form, i.e., zeolite. The adsorption process is unsteady, therefore it is necessary to use two solid beds, one for the adsorption processand the second for regeneration or water vapor desorption. The main feature of the absorption/adsorption processes is the generation of a large amount of heat, which can be used for preheating the feed water. Desiccant regeneration requires use of an external heating source, which could be heating steam or a diesel engine. The main merit of this process is its proven high efficiency (El-Dessouky and Ettouney, 2002). However, a main drawback is the lack of field experience in design, operation, and maintenance of the desiccant absorption units. Also, it is evident from the process diagram, see Fig. 7, the need to operate a large number of units, which include air humidifier, absorption/adsorption bed, regeneration unit, desiccant heat exchanger, and water vapor condenser.

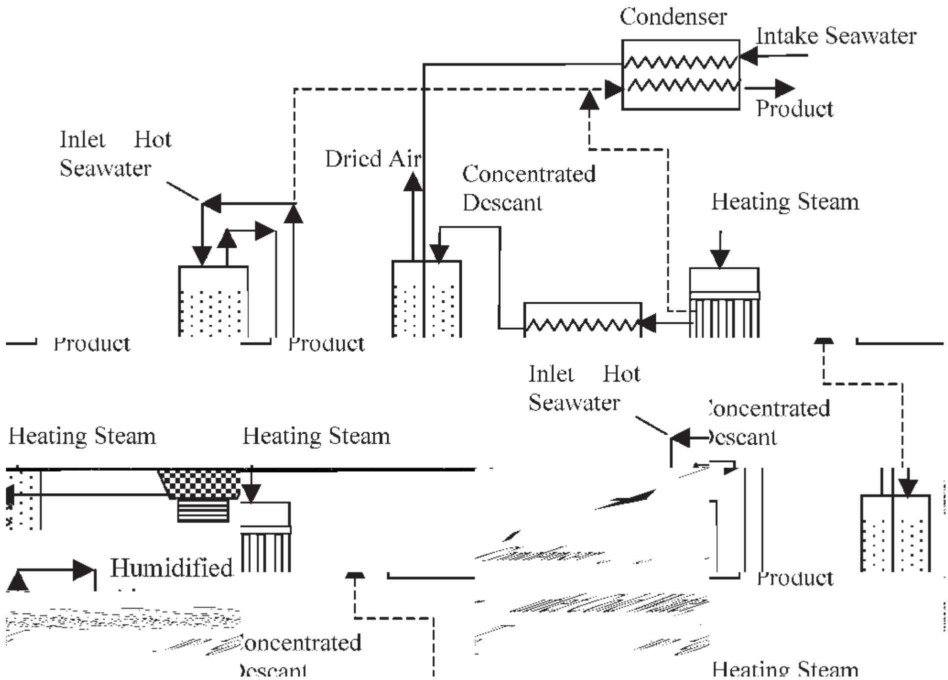

Figure 7. Conventional humidification dehumidification desalination process.

The humidification membrane air drying system is shown in Fig. 8. The humidifier characteristics are similar to those in the conventional HDH. As is shown, the humidified air stream is compressed and passed through the membrane unit. The selective properties of the membrane result in permeation of the air humidity from the feed to the permeate side. As shown in Fig. 8, the compressed dried air leaves at the other end of the membrane drying unit.

The literature includes a number of studies on the humidification dehumidification desalination systems. Findings in few of these studies are given in brief. Goosen et al. (2000) reviewed various layouts of thee humidification/dehumidification desalination systems as well as single/multiple effect solar desalination. The authors stressed the fact that many of these units are limited to theoretical evaluation or prototype scale; however, increase in future demand for fresh water might make several of these processes viable for fresh water production. Müller -Holst et al. (1999) described the performance of an optimized humidification/dehumidification desalination system. A main feature of this patent configuration is that the flow of the air stream is driven by natural convection. The system is also associated with a solar collector. Therefore, continuous operation of the unit requires the use of a heat storage system. The system is designed for operation in remote areas with minimal maintenance requirements. This is achieved in part by low temperature operation, which minimizes the rate of scale formation. Farid and Al-Hajaj (1999) constructed a small-scale humidification dehumidification unit with a capacity of 2 L/m^2. Such capacity is much larger than that for a single basin solar still. The system utilized a combination of a water heater and a solar collector. Other studies by Al-Hallaj et al. (1998) and Nawayseh et al. (1997) covered additional aspects, which include modeling, evaluation of the heat and mass transfer coefficients, and field performance. Chafik (2004) evaluated the performance of a multieffect humidification dehumidification system, where the air is heated and humidified in a solar collector arrangement. This procedure increases the air humidity to very large values and increases the system productivity. The air humidity chart for this process is shown in Fig. 9. As is shown, for a five effect system, the air humidity is increased from 0.0106 kg H_2O/kg dry air to 0.037kg H_2O/kg dry air. Chafik (2004) reported an optimum of five effects that produces the minimum cost for desalinated water.

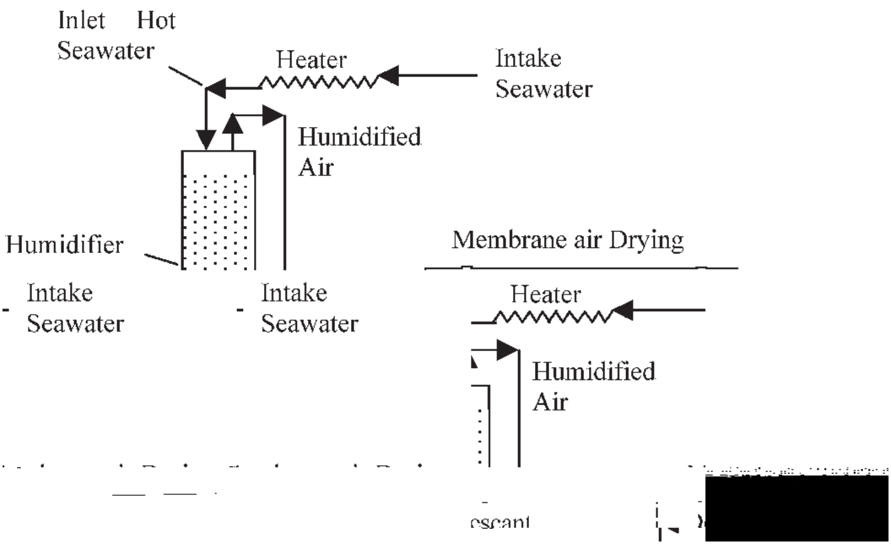

Figure 8. Humidification and membrane air drying.

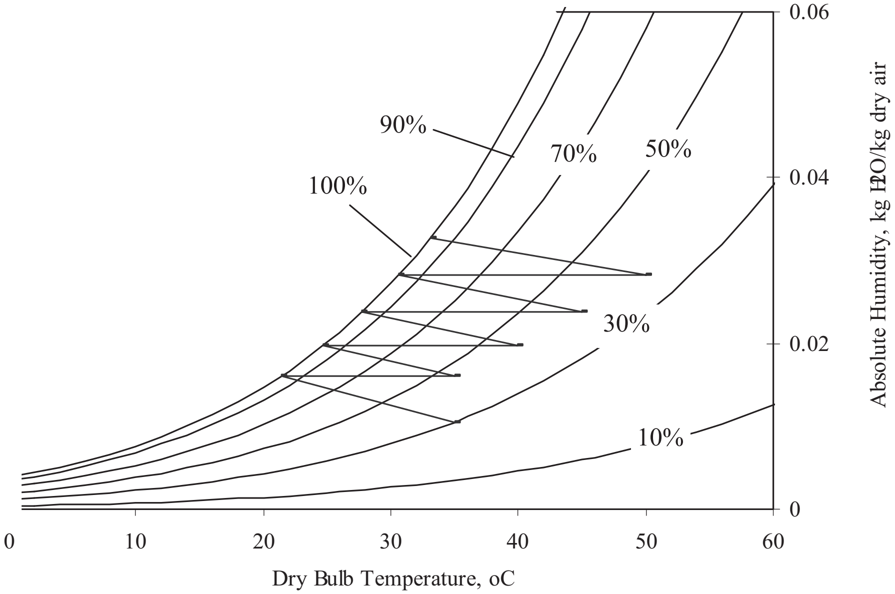

Figure 9. Humidity chart for multiple air heating humidification dehumidification process.

Common findings among various literature studies indicate that production rate of distillate water increases as hot water temperature increases. Production rate of the distillate water reaches a maximum when air and water flow rates increase. In all cases increasing the air or water flow rates would improve mixing within the system and increase the humidification rate. At higher water or air flow rates the evaporation efficiency is decreased because of the increase in the sensible heat load of the system. This reduces the water evaporation rate and humidification efficiency. Reduction of the condenser heat transfer area requires use of finned tube configuration. This is necessary because of the low heat transfer coefficient on the humid air side; this is irrespective of water vapor condensation, which accounts for a very small percentage of the entire air stream.

6. Conclusions

Desalination combined with solar energy provides one of the most attractive sustainable sources of fresh water and energy. Researchers have investigated and developed several promising configurations. Although many of these systems have relatively high cost, when compared to conventional desalination or fossil fuel power, it is important to consider environmental benefits and source sustainability. Also, the higher cost is caused in part by the small scale of the tested units.

Development of hybrids of solar desalination and power on site with existing large desalination and power plants might be a good starting point. Several schemes for solar desalination and power could be immediately combined with either thermal or membrane desalination processes. Hence, accumulated field experience should result in expansion and growth of the most successful and promising schemes.

For remote and rural areas the simplest form of a solar still is the best choice for production of fresh water, as it simplifies part replacement, cleaning, and other tasks that require advanced training, i.e., control units, or elaborate piping in a multieffect system.

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DEVELOPMENT OF SOLAR DESALINATION SYSTEMS CONCEPTS FOR IRRIGATION IN ARID AREAS CONDITIONS

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Abstract. The work was motivated by the increasing awareness of the need for enhancing water supplies schemes in arid lands featuring an appropriate technology for solar energy use in the irrigation field. The present paper introduces the effect of water cost production on crops yields and these are then incorporated in the financial balance. It shows that the water desalination use in irrigation could be profitable for farmers, particularly for produce of high commercial value. The solar desalination in irrigation is only worthwhile if higher crop production is adopted and assuming a high qualification of farmers. However, further technical development and lower investment costs are needed for solar desalination concepts in order to get water costs down to levels competitive to more conventional desalination methods.

Keywords: desalination, Solar energy, Economy, Irrigation, greenhouse

1. Introduction

Arid lands today face more difficult problems than ever before. The world's sand deserts appear to be enlarging, and droughts are contributing to the economic devastation of whole nations. Arid lands suffer from the crisis. They face falling water tables and increasing groundwater salinity[1].

Nevertheless, arid lands have generally a great solar energy potential. Probably, this potential can be best developed by solar desalination

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concepts and methods specifically suited to supply dry regions with fresh water[2].

Solar desalination systems need low operation and maintenance cost but large installation areas and high initial investment. However, this is the best solution for remote areas and small communities in arid and semi-arid regions with lack of water.

Most studies, published in the last decade have considered small scale solar desalination systems for application in remote areas. Some of them have proposed medium and large scale systems which already are or could be cost effective in the near future.

The present study is concerned with analysis of solar desalination systems that could be applied in rural arid areas. It also describes some research works carried out in Tunisia in the field of solar energy desalination in conjunction with greenhouses in arid areas. The decision to install the solar desalination plans to supply water for greenhouses crops is a very important strategic one, because the investment costs are high. However, once this decision is made, the type of crops to be used in any specific situation has to be decided in order to get profitability for the farmer. In this paper an outline of three production schedules variants with different commercial value. However, a major difference in the case of greenhouse-integrated still is considered; where the main problem is to know the yield production lost, caused by lighting reduce at the crop level. Furthermore the economic evaluation of the water desalination using the two desalination concepts for the production schedules variants is worked in detail.

2. Solar Desalination Systems Concepts for Irrigation

Water production from a solar still is less than the water requirement for a crop grown in an open irrigated field, but may be suitable to supply fresh water to protected cultivation. Solar desalination should be used in combination with water efficient greenhouse concepts based on controlled environment.

However, the use of desalinated water using solar energy for agricultural purposes has not yet gone beyond the experimental phase. A more complete survey of a system combining a solar still with a greenhouse was first presented by Tombe and Foex in 1961[3] and later an improved version of the concept was developed by Boutiere[4] in 1972 and by Bettaque in 1977[5]. The concept utilised partly transparent absorbed materials instead of opaque ones and consisted of a double glassed roof. The inner layer of the glass roof was covered with a shading material. Salt water flowed down over this shading material between the two layers. A part of the global irradiation was absorbed at the inner layer of the roof where the salt water evaporated. The water vapour condensed at the inner surface of the outer layer, run down along the glass and was collected by gutters for water distribution to the crop.

According to Selcuk[6], this integrated system solution with double glassed roof, though successful in operation, could not have maintained the best conditions required for the most efficient performance of the solar still and the greenhouse. Consequently, he proposed a solar still concept completely separated from the greenhouse.

From 1979 to 1984, at the University of Hanover in Germany, a closed greenhouse with integrated solar water desalination, called ITG-system, was developed, evaluated by Strauch and Zabeltitz[7], and compared with a modified Betaque system. The concept of the ITG-system, suitable for tropical desert conditions, is based on combination of collecting the water evaporated and transpirated by condensation on the enclosure and water produced by a solar still attached to the southern side wall of the greenhouse. The modified double glassed roof integrated still (system Betaque) includes below the south oriented outer glass a second glass sheet, acting as absorber and evaporator.

Results of experiments carried out on these systems show the increase of the ITG-system efficiency compared to Betaque system, 29% against 16%, and a productivity of 2 - 2,5 $l/m^2/day$ in ITG-system against 1 $l/m^2/day$.

However, in the period 1978 to 1981, Dumont and de Cachart[8] proposed in their study a greenhouse with solar distillation using a developed Betaque concept. The flow of the water for distillation as a film was maintained from a series of sprinklers located at the top of the framework. The results of experiments show that the average daily production of fresh water was in the range of 2- 3.5 $l/m^2/day$ in favourable conditions.

New designs of solar still combination, suitable for hot climate applications, have been proposed by some authors. Fath[9] presented the naturally ventilated greenhouses solar still where the fresh water production capacity has been about 1,3 - 1,8l/day/m^2. In 1989, Hassan et al.[10] proposed a multi-stage roof integrated solar still. This type of solar stills showed a productivity of 13.5 to 17.5 times the evapo-transpiration inside the greenhouse.

The different designs and conception of the integrated greenhouse solar still presented above, constitute an exciting possibility for supporting small scale agriculture in places where only saline water is available. But, it is always a debatable subject whether placing the still inside has any advantages over placing it adjacent to the greenhouse. It is generally concluded that very integrated solar still and greenhouse designs have higher construction costs.

3. An Overview of the Tunisian Experiences

3.1. SOLAR DESALINATION PLANT WITH SINGLE EFFECT PROCESS USING HEAT PIPES COLLECTORS.

This plant constitutes a joint research effort to gain actual field experience for greenhouse irrigation. The plant is composed of three parts (Fig. 1):

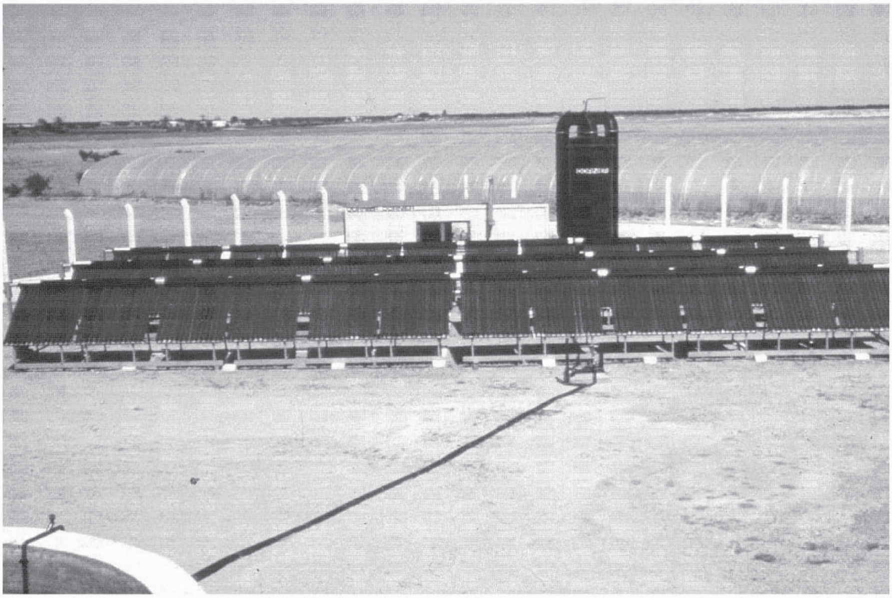

Figure 1. Solar desalination plant with single effect process using heat pipes collectors in Hazeg (Tunisia).

The collectors: The collector of 80 m^2 is composed of three ranges of heat pipes. Each range links 12 heat pipes panels. Brackish water pumped from the well is filtered and passed through a heat exchanger where it is heated by the distilled water which circulates into the heat pipes.

The evaporator: the salt water leaves the heat exchanger at about 60 ^{0}C and is directed to the top of the evaporator where it is discharged into a porous media of polyethylene balls. During its flow, a part of salt water is evaporated and the other part is recuperated at the bottom to be stored or used for greenhouse heating.

The condenser: during its forced rising from the bottom to the top of the condenser, a part of the vapour is mixed with a fresh water sprayed at the top of the condenser to be cooled for its condensation. Distilled water is then pumped through the heat pipes and the heat exchanger part of it is sprayed again at the top and the remainder is stored.

Since 1987, tests on various components of the system have been performed [11].The amount of fresh water produced by this process is relatively very small, around 5-6 l/m^2, day. This production constitutes almost half the quantity of fresh water intended to be produced by this plant. The fresh water produced is used for irrigation of two plastic greenhouses with the area 1200 m^2.

3.2. INTEGRATED SOLAR DESALINATION SYSTEM IN GREENHOUSE

The concept is based on water desalination system integrated in a greenhouse roof (Fig. 2). Its principle is to allow transmittance of the spectral part of the solar radiation which is effective for photosynthesis, i.e. wavelengths between 400 and 700nm. The remaining part of the spectrum, which represents about 50% of the total solar energy, can be absorbed and converted into heat for water desalination. This is accomplished by a double glassed roof structure performing as an absorber and evaporator.

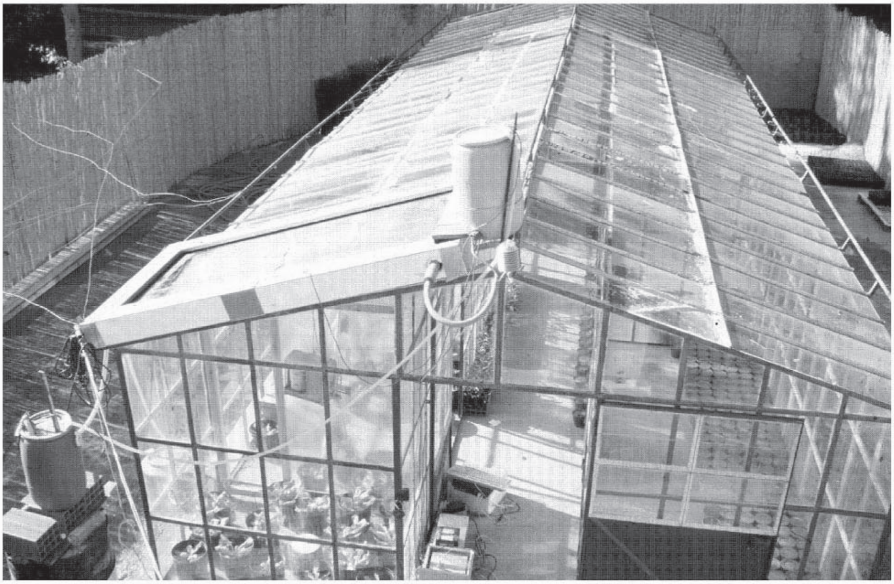

Figure 2. Integrated solar desalination system greenhouse at the INRGREF (Tunisia).

The heat gained is absorbed by the brackish water for distillation. The water flows over the filter as a thin film and is re-circulated to be stored at a higher temperature in a tank. The water flowing over the filter at a temperature higher than ambient air, partially evaporates and condenses on the external glass of the greenhouse. The condensed water trickles down the external glass and is collected in a reservoir which supplies the greenhouse with fresh water for irrigation. This type of system has a water production capacity of about 1.5 to 2 l/m^2, day for days with high irradiation.

4. Economic Analysis

4.1. METHOD OF ECONOMIC EVALUATION

Although several methods are in use for the economic evaluation of desalination plant, probably the most appropriate and comprehensive one that utilizes the cost benefit ratio, where the cost is the present worth of the water desalinated based on its life cycle, and the benefit is the actual quantity of desalinated water produced over the same life - cycle [12]. This calculation method is preferably employed at the beginning of the economic analysis. Its advantage is that it is relatively easy to understand and that it shows the approximate development of the occurring costs as well. The system cost C represents the sum of the plant and of any added costs charged to the customer. It arises from two major categories: (1) initial costs Ci, and (2) annual costs Ca.

Typically, the initial cost Ci is the capital cost and the annual cost may include the costs for all the above components, of (1) labour for operation (2) replacement materials and maintenance. The total present value cost C of the plant can be determined by the following formula[11]:

$$C = Ci + (P + OM) / PVF \tag{1}$$

where:
Ci: Investment cost of the plant
OM: maintenance cost of the system
P: personnel cost
i: interest rate (%).
n: life time of the plant (years)

PVF: Present Value Factor where

$$PVF = ((1+i)^n - 1)/ i (1+i)^n \tag{2}$$

The product cost of the fresh water production is given by:

$$WC = C / \Sigma Et \quad (3)$$

where: Et: is the production of the fresh water (m^3/year)

Our calculations are done under the assumption that the capital costs exclude certain specific site costs, such as those for the purchase of land and for the storage or distribution of the final product water from the system. An interest rate of 9% on capital has been assumed during construction period. The costs of operating and maintenance are based upon input from equipment suppliers and end users. They are considered to increase in time at the rate of 16%. The electrical energy costs used for pumping water in the systems are not included in the analysis.

The technico- economic analysis for both concepts has been carried out numerically in Table 1. Comparing unit product cost in Table 1 reveals the significantly higher costs for water from the two types of plants. The two plants listed in the table are demonstration units, and costs are extrapolations based on short production periods and /or projected plant costs.

An important role is played by rain water in the economic analysis. The cost of the distilled water becomes cheaper if rain water collection is considered in the analysis. Table 1 gives the clear account of rain water contribution in the total fresh water cost produced by the system. Considering, the collection of rain water from the collector areas of the systems during a typical year in an arid region of Tunisia, estimated at 0.07 m^3/m^2, year (100mm/year) at 50% efficiency and a dilution with brackish water feedstock in a 1:07 ratio. The cost will be cheaper, compared to the water product cost with only dilution 1:1, by about 6.7% and 1.6%, for respectively Greenhouse-integrated still single effect process with heat pipe collectors.

4.2. CROP WATER REQUIREMENTS AND SOLAR DESALINATION YIELD

In practice, water requirements in greenhouses are mainly determined by the total radiation, depending on the local climate factor, and by the optical characteristics of the material which forms the cover.

As in natural conditions, it is normal to find relationships between the maximum reel evapo-transpiration under greenhouse (Es,max) and the daily global irradiation (Rgs) penetrating through the greenhouse roof.

For typical southern Mediterranean conditions, the global radiation varied between 630 W/m^2 during July and 370 W/m^2 during December. The calculation of the maximum reel evapo-transpiration (Es,max), in such conditions, gives a value of 3.65 to 6.45 l/m^2,day mm/day for respectively a typical external total radiation of the months of December and July months and a total transmittance of 0.7 (polyethylene cover). These values agree by 90% with those found during 10 years of experimentation and observations on the estimation of the evapo-transpitaion of crops under plastic greenhouses [13] along the coast of Tunisia.

TABLE 1. Distilled water cost obtained from the two different processes (20 years life and 9% rate of interest – PVF = 9.13)

	Collectors area [m^2]	Ci cost [$]	Present value OM and P costs [$]	Present value of the total annual costs [$]	Product of fresh water		Product cost [$/$m^3$]		
					m^3	m^3/m^2	Distilled water	With dilution 1:1	With dilution and rain collection
Greenhouse-integrated still	100	10.000	2000	12000	1100	11	11	5.5	5.1
Single effect process with heat pipe collectors	80	51 000	14000	65000	3000	37.5	21.6	10.8	10.6

Compared to plastic greenhouses covers, the reduction in the transpiration is, in absolute terms, not significant in the winter. In the summer, however, it is of the order of 1.8mm /day. These results confirmed by Van Bavel et al, [14] who found the presence of the water on the roof may make a reduction in the evapo-tanspiration of the order of 2mm/day in summer time. We expect that this will effect plant growth significantly, favouring the greenhouse-integrated still environment.

TABLE 2. Rate of irrigation water supplied by the two different processes

	Product of mixed water available for irrigation l/m^2, day		Rate of satisfaction in water irrigation for protected cultivation P/ E s, max	Rate of satisfaction in water irrigation for open area P/ E max
Greenhouse-integrated still	Winter	2.5	0.8	-
	Summer	4.5	1	-
Single effect process with heat pipe collectors.	Winter	8.3	2.27	1.91
	Summer	14	2.17	1.82

Table 2 shows that the quantity of water produced by the two types of plants, mixed with the rate of 100% of well water, could cover the water required for conventional greenhouse systems as well as for open area. However the greenhouse-integrated solar still should be used in combination with water efficient greenhouse concepts, based on controlled environment, as the rate of satisfaction in water irrigation is almost equal to the requirement of crop growth in summer time estimated as about 4.5 l/day, m^2 of cultivated area and less by 20% in winter time when the water requirements is 2.5 l/m^2, day.

5. Adding Value Through Solar Desalination for Greenhouse Irrigation

Most proponents of desalting schemes agree that the water will be too expensive for use in irrigation as practiced today. However, desalination of brackish water proves economically rewarding in special situations such as domestic, tourist and industrial purposes where the local economy can afford it The economic objective of irrigated agriculture in regions of absolute scarcely of water, such as the middle east and some parts in Africa, would, focused on the uses of water on crops which have values sufficient to justify farmers purchasing new water at the cost of water desalination. Achieving this threshold would depend on the applied technology system in agriculture, water quality reallocation in irrigation, optimization of all crops inputs, harvesting and post harvesting processing.

The present section introduces the financial consequences when using the two types of solar desalination, described previously. The financial balance analysis was performed for the following three production schedules variants:

Variant I

Double occupation of the greenhouse

For this variant, we opt for a double occupation of the greenhouse as planting the tomato crops between 15 September to 5 March followed by melon crops from 15 March to 15 August.

Variant II

Triple occupation of the greenhouse

In this variant, the endive will occupy the greenhouse for 6 months giving a double_production from 1 October to 30 December and 15 January to 15 April between followed by green peepers from 1march to August.

Variant III

Cut flowers for market: three crops per year.

The economic value of the yearly yield production for each variant, presented in table 3, is estimated on the basis of predictions of the product price at harvesting time.

The major simplification assumed in this estimation concerns:

i) the price of the products is supposed to be fixed to the average monthly product price in Tunisia market.

ii) the yield losses are estimated on the bases of the correlation between the amount of light received on the crop and yield lost (1% of light lost corresponds to 1% yield lost) [15 and 16]. These losses will concern only the greenhouse integrate still that assumed to have a 30% light losses compared to the conventional greenhouse.

iii) the average prices costs for the crops in the different seasons in Tunisia are estimated to be for the Tomato 0.3 $/kg, Melon 0.4 $/kg, Green pepper 0.45 $/kg, Endive 2.7 $/kg (we assume that the prices of the endives are similar during the 2 harvesting time in variant II) and cut flowers 0.5$/stem.

The methodology used in the parametric study to perform the yearly net farmer revenue (NFR) parameter in $\$/m^2$ of cultivated area, when using the solar desalination for irrigation, is the following:

Estimate the yearly production cost revenue in $\$/m^2$, year taken from Table 3 (PCR), for the 2 production alternatives.

Determine the water cost (WC), produced by the solar desalination systems and consumed after its dilution in 1:1 ratio, by $1m^2$ of crops during one year in $\$/m^2$,year. This parameter is calculated by the product of the water cost presented in table 1 and the total amount of water consumption of different crops chosen for this analysis: Tomato 0.5 m^3/m^2, melon 0.5 m^3/m^2, Endive 0.3 m^3/m^2, Green peppers 0.5 m^3/m^2, Cut flowers 0.7 m^3/m^2.

Estimate the yearly investment cost (IC); greenhouse infrastructure, cover materials in $\$/ m^2$, year. This parameter assumed to be equal to 0.8 US$\$/m^2$,year for conventional plastic greenhouses (discount rate 15% and 20 years lifetime for the greenhouse infrastructure and 3 years for the plastic covers). For establishing a rose project in variant III, the capital and the production costs are estimated in the range from 30 to 50 US$\$/m^2$ (excluding land and land clearance), with an average of US$ $40/m^2$, depending on the size of the project, type of construction, and equipment. In the greenhouse solar still, this cost is included by about 50% in the fresh water cost because of the totally integration of the greenhouse with the solar desalination system.

Estimate the labor and the maintenance costs in 1.5 $/ m², year, assuming that the effective working days is 200 days/year. In Variant III where cut flowers are opted, labors should be well qualified and their cost is assumed to be 3 $/m².

Estimate the market and transport fees (MTC) in $/ m², year assumed to be 5% of the yearly production cost revenue.

Based on the above method, the net farmer revenue (NFR) for the economic balance can be evaluated with the following equation:

$$NFR = PCR - WC - IC - LC - MTC \quad (4)$$

TABLE 3. Financial yield of two types of greenhouses: greenhouse-integrated still and the conventional greenhouse, per year and crop in $/m². The first value of the yearly production represents the production estimated for less qualified farmer and the second one for qualified farmers

		Greenhouse-integrated still		Conventional greenhouse used in conjunction with the Single effect process with heat pipe collectors.	
Variant	Crop	Yearly Production (kg/m²)	Yearly crop value ($/m²)	Yearly Production (kg/m²)	Yearly crop value ($/m²)
Variant I	Melon	2.8 – 4.2	1.12-1.68	4 – 6	1.6-2.4
	Tomato	5.6 – 9.1	1.68-2.73	8 – 13	2.4-3.9
Variant II	Green Pepper	3.5 –5.6	1.57-2.52	5 – 8	2.25-3.6
	Endive	1.05– 1.6	2.83-4.32	1.5– 2	4.05-5.4
	Endive	1.05 – 1.6	-	1.5 – 2	-
Variant III	Cut flowers: rose variety: sweetheart type (3crops/year)	84-225 [stems/m²	42-113	120-320 [stems/m²]	60-160

The yearly net farmer revenue is represented in Table 4 for the each alternatives described previously. The analysis of the 3 alternatives is described in the following:

<u>Variant I</u>

The net farmer revenue is negative for the two solar system desalination. Hence, the use of the low crop market (tomato and melon) will not make a profit for the farmer compared to the produced fresh water cost. The combination of the 3 variants with solar desalination for greenhouses irrigation will not be profitable with the present production value of tomato and melon crops in Tunisia horticulture experiences, estimated in our analysis.

Variant II

The NFR parameter begins improve when the price of the crops increases to make profit for the farmer. Thus, the application of the endive crops with higher value than tomato and melon (2.7$/kg) could justify the use of water desalination for irrigation greenhouse, especially for the greenhouse integrated still system when we are in the presence of well qualified farmers (4 $/m^2$/year). If the roof-integrated concept is compared to desalination technologies based on solar collectors (Variant I and II) the NFR parameter is higher by 3.25 $/m^2$, year for the Single effect desalination processes which could, to some extent, compensate for the lower crop value.

Variant III

In cut flower production (Rose variety) with high value cost, investment of solar desalination systems becomes worthwhile as the net farmer revenue parameter reaches higher values for desalination technologies based on solar collectors (> 85 $/m^2$,year) even for higher water cost production (8-11$/m^3$). This parameter is higher by about 20$/m^2$, year than the greenhouse integrated still with water cost production of 5$/m^2$. The yield losses, due to light loss considered in the greenhouse solar still, are a far greater consideration than for the 2 previous variants but, on account of the high market value of the crop, they are more rapidly called into question when yield is affected. The estimation of the amount of yield losses presented previously only permits certain provisional conclusions. The choice of cut flowers varieties suited to difficult lighting conditions merit study.

TABLE 4. The net farmer revenue in $/m^2$, year for the 3 types of solar desalination applied for the three variant alternatives

	Greenhouse-integrated still		The Single effect process with heat pipe collectors.	
	Less qualified farmer	Qualified farmer	Less qualified farmer	Qualified farmer
Variant I	-3.97	-2.44	-9.13	-6.94
Variant II	0.24	4	-3.09	0.75
Variant III	7.1	73.6	-8.32	86.68

6. Conclusions

On the basis of the cost parameters presented, principal findings for the two analyzed desalination technologies are the following:

Investment as well as annual cost of the desalination processes increase with increasing production capacity.

The greenhouse-integrated system is estimated to have the lowest investment and annual cost and also the lowest water cost.

Operating costs per unit water production of the desalination plant processes decrease with decreasing plant capacity.

Desalination of brackish water is much cheaper when using local materials and manpower as much as possible. The unit area of heat pipes collectors costs 7 times than the integrated solar still greenhouse.

Technology simplification and higher efficiency is necessary to reduce the cost for indirect systems with solar collectors.

Lower costs for indirect systems can be achieved by developing more efficient recovery systems and extending the operation time to nights and cloudy days. This requires heat storage for a few days, e.g. in insulated tanks or pits in the ground.

The desalination process is relatively costly and therefore it has to be used in high value agriculture in very specific localized areas. This is particularly marked when the commercial value of the cut flowers is high (Rose variety).

Profitability of the greenhouse solar still is guaranteed in some cases where production losses are very small, but no longer applies when losses increase.

The evaluation of the Net Farmer Revenue, in solar greenhouse still concept, based on the assumption of the 1% of the light losses leads to 1% of yield lost production is not conclusive because it could be not realistic as the crops react in different ways to the lack of the light available at the crop level. Thus, a small drop in crop yield can easily put the profitability of the system into doubt.

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TECHNO-ECONOMIC EVALUATION OF A SOLAR POWERED WATER DESALINATION PLANT

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Abstract. Water desalination technologies and their possible coupling with solar energy were evaluated. The topic has a remarkable interest especially for the countries located within the Southern Mediterranean belt, generally characterized by vast arid and isolated areas with practically no access to electric power from the national grid. Economic factors being one of the main barriers to the diffusion of solar devices so far, an attempt was made to estimate water production cost for two different solar desalination systems: reverse osmosis and multiple effect evaporation process driven by photovoltaic and solar thermal energy, respectively. The results, obtained for plants with a capacity varying between 500 and 5,000 m³/d, were compared to the values relevant to a conventional desalination system.

Keywords: water demand, desalination technologies, energy requirements, solar thermal and photovoltaic systems, remote areas, economic analysis.

1. Introduction

Nearly one fourth of mankind is suffering from an inadequate fresh water supply. The foreseen growth of population worldwide (especially in the developing countries), will make the situation even more critical over the next two decades. Desalination of brackish or sea water represents a consolidated system to resolve the water emergency. The main drawbacks to this solution however are high energy consumption and high cost.

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Therefore, it is imperative to evaluate the possibility of using local renewable resources to desalt water. In the case of a medium capacity desalination plant (approximately 1,000 m³/d), the production of fresh water via solar energy can be achieved through either a solar thermal or a photovoltaic system coupled with a multiple effect or a reverse osmosis desalination process, respectively. Since high cost is the greatest hindrance to solar energy application, the main objective of this work is to estimate the water production cost for the above-mentioned two technological options, when varying capacity and assuming a typical value of South Mediterranean area for solar radiation.

2. Water Requirements

Although water emergency concerns more than 80 countries, the situation is especially alarming in the countries within South Mediterranean belt. The world population (Table 1), today just over 6 billion, is expected to reach nearly 8 billion in 2025 and 9 billion in 2050.

TABLE 1. Distribution of population worldwide during the years (millions of inhabitants)[1]

Year	USA	EU	Africa	Asia	Total
1950	158	296	221	1,377	2,522
1960	186	316	277	1,668	3,022
1970	210	341	357	2,101	3,696
1980	230	356	467	2,586	4,440
1990	254	365	615	3,114	5,266
2000	278	376	784	3,683	6,055
2010	298	376	973	4,136	6,795
2020	317	371	1,187	4,545	7,502
2030	333	362	1,406	4,877	8,112
2040	343	349	1,595	5,118	8,577
2050	349	332	1,766	5,268	8,909

It is estimated that the rise in population over the next 20 years will be around 50% in Africa, 25% in Asia, 14% in the USA, but surprisingly there will be a negative balance in Europe. It is obvious from these figures that over the next decade or so, the considerable growth in world population will be mainly concentrated in the developing countries and particularly in Africa, causing a severe water shortage. Moreover, due to the presence of wide deserted or semi-deserted areas in a number of South Mediterranean countries, the fresh water reserve per capita is already scarce and will be further reduced. In order to face current and future serious lack of water problems, most of these countries have already engaged in alternative solutions such as desalination.

3. Solar Powered Water Desalination Systems

Solar energy is a very appropriate driving source for desalting water. For this purpose the most basic system is the so called solar still. Solar heat makes to evaporate the salt water contained in a basin; the vapour is then condensed on the glazed covering and collected in a reservoir using appropriate ducts. Despite its simplicity, this technology is affected by an high initial investment, extreme vulnerability to adverse meteorological conditions, and additional charges for driving the pumps and the frequent maintenance interventions. The key barrier is however the enormous soil requirements. As a rule of thumb, a solar still can produce around 4 liters/d per m^2. Therefore, to satisfy the drinking water requirements of 1,000 people, a basin having a total area of approximately 50,000 m^2 is necessary. So the application of this technology is very limited, above all in the urban areas where land is scarce and extremely expensive. On the other hand, solar stills could be attractive for domestic uses, especially in the areas having no access to the electric grid.

Although solar energy presents favorable aspects to desalt water and has been used for this purpose for a long, the fact remains that even today its application on a significant scale is very limited. From the literature survey, it was observed that only about 100 desalination plants driven by renewable energies (both solar and wind) are working, disseminated in over 25 countries. They are mainly intended for study or demonstration purposes: in effect the average capacity[2] is around 20 m^3/d.

The present investigation aims at fully exploring the real potential of this technology. In this framework, it is crucial to investigate the possibility of powering medium-to-large capacity desalination plants.

In theory, any desalination process could be driven by the different solar energy. As shown in Table 2, solar thermal collectors can be used to feed thermal processes, such like multi-stage flash (MSF) or multi-effect evaporation (MEE), while photovoltaic can drive processes using electric energy, such like mechanical vapour compression (MVC) or reverse osmosis (RO). High temperature concentrating collectors, producing both electricity, and eventually heat through a cogeneration arrangement, can feed all types of processes and hybrid systems also (for instance RO/MSF).

TABLE 2. Possible options for coupling between solar energy and process of desalination

SOLAR ENERGY	MSF	MEE	MVC	RO
Photovoltaic			●	●
Solar Thermal	●	●		
Solar Thermal (electric)	●	●	●	●

For low-to-medium scale applications, which are the main goal of this work, the coupling options with the highest potential are the reverse osmosis process powered by photovoltaic modules (PV/RO)[3] and the multiple effect evaporation process driven by advanced low temperature solar thermal collectors, such as evacuated tubular collector (ST/MEE)[4] .

4. Economic Analysis of the Two Options

No device is useful unless it is cost-effective. The economic feasibility, however, depends upon the optimization of the trade-off between high useful energy collected under specified design conditions and low material and manufacture cost. Special attention was paid to the two different options for possible coupling between a solar system and a desalination unit (PV/RO and ST/MEE), in order to:

- accurately estimate the production cost of desalted water;
- single out the possible factors to fill the gap between the production cost by solar and conventional technologies;
- address other basic aspects of a solar system such as the initial investement and the required area.

Overall water production cost is influenced by several local factors, like the market status of solar systems, financing conditions, labor and pre-treatment cost, fuel and electricity price. The values of the technical parameters and solar irradiance assumed to estimate the water production cost, are reported in Table 3, whereas the values of the common economic parameters are listed in Table 4.

The price of electricity assumed corresponds to the average value applied in the countries under investigation and thus appears very low in comparison with the market situation in Western Europe. Specific economic values for each considered solar desalination system are given in Tables 5 and 6.

TABLE 3. Values for the technical parameters assumed in the analysis

Utilization factor	0.9
Annual solar energy (kWh/m²)	2,000
Peak radiation (W/m²)	1,000
PV modules efficiency	0.1
Motive steam temperature for MEE (°C)	70
Solar collector average efficiency	0.5
Electric energy need in RO (kWh/m³)	5
Electric energy need in MEE (kWh/m³)	2
Thermal energy need in MEE (kWh/m³)	60

TABLE 4. Values of the common economic parameters adopted to calculate the water cost

	PV/RO	ST/MEE	Conventional
System life (years)	25	25	30
Interest rate (%)	8	8	5
Maintenance (% of plant cost)	2	2	2
Manpower ($/m³)	0.1	0.1	0.05
Pre-treatment ($/m³)	0.035	0.025	0.035
Electricity ($/kWh)	-	-	0.04

TABLE 5. Values assigned to estimate the water cost by the PV/RO system

PV modules cost for a 10 MW size ($/$W_p$)	3
PV modules cost for a 100 kW size ($/$W_p$)	6
Battery supply (h)	12
Battery cost (% of modules cost)	15
Annual rate of batteries replacement (%)	12
Electronic device cost (% of PV plant cost)	5
RO plant cost for a 10,000 m³/d size ($/(m³/d))	1,000
Scale factor	0.9
Membranes cost (% of RO plant cost)	60
Annual rate of membranes replacement (%)	10

Based upon the data presented in the previous tables, production cost of fresh water, using both solar driven systems (PV/RO and ST/MEE) and a conventional RO process driven by power from the electric grid, were calculated. Actually the last one constitutes on average the most competitive system from the economic point of view, above all in the range of considered capacities.

TABLE 6. Values assigned to estimate the water cost by the ST/MEE system

Collector cost for a 100,000 m² area ($/m²)	150
Collector cost for a 10,000 m² area ($/m²)	250
Storage cost (% of collector cost)	20
MEE plant cost for a 10,000 m³/d size ($/m³/d)	1,200
Scale factor	0.7

For each analyzed option the trend of the production cost, when the capacity varies between 500 and 5,000 m³/d, is shown in Fig. 1.

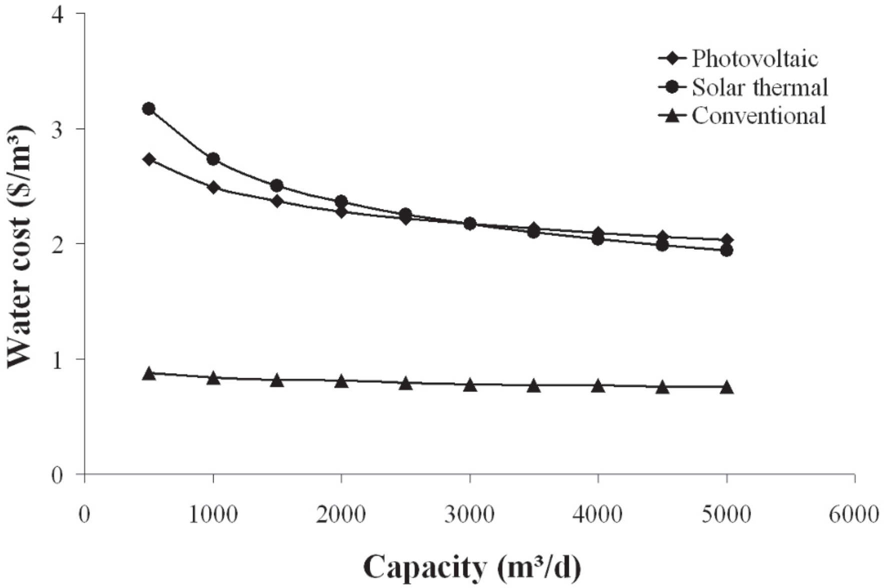

Figure 1. Water cost as a function of plant capacity by means of two solar systems (PV/RO and ST/MEE) and a conventional one.

In brief, the increase in the size of solar powered desalination plant no doubt lowers the water production cost, but it also has negative repercussions on the two factors previously mentioned.

1. Land occupation by the solar field is proportional to the plant capacity, from this point of view the PV/RO system is clearly preferable when compared to the ST/MEE system (nearly 8 m² versus little less than 20 m² per m³/d of installed capacity). This was the reason why the simple

solar still, which needs approximately 250 m^2 per m^3/d of installed capacity, can not be applied on a larger scale.

2. As shown in Fig. 2, the specific plant cost varies between 6,200 and 4,500 $/($m^3$/d) for the PV/RO system, and between 8,600 and 5,000 $/($m^3$/d) for the ST/MEE system. It should be noted that, though an increase in the system capacity cuts this cost significantly, it is still very high compared to that of a conventional system. For example, a 5,000 m^3/d PV/RO system needs an initial investment of more than 22 million US$ compared to about 5 million US$ for an ordinary RO system.

In conclusion, with increasing plant capacity, water production cost using solar technologies is markedly cut down, but there is a considerable rise in initial expenditure and a wider area is required by the solar field.

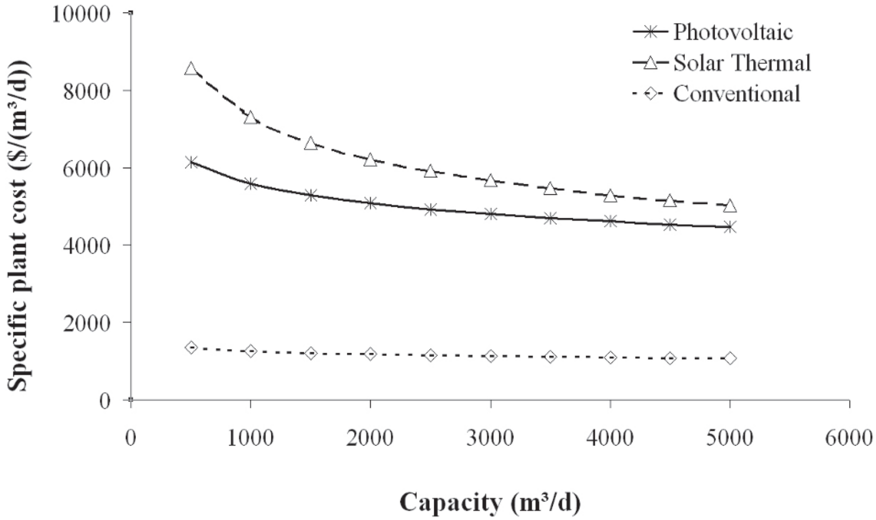

Figure 2. Specific plant cost as a function of plant capacity by means of two solar systems (PV/RO and ST/MEE) and a conventional one.

Specific operating cost as a function of capacity is presented in Fig. 3. It can be observed that for ST/MEE system this parameter varies between 0.5 and 0.7 $/$m^3$, more or less matching the values relevant to a conventional plant, whereas the cost is higher in the PV/RO system (approximately from 0.7 to 0.9 $/$m^3$). Operation of a solar plant does not appear to be very critical compared to the conventional system. The economic penalty is mainly due to the high initial capital investment.

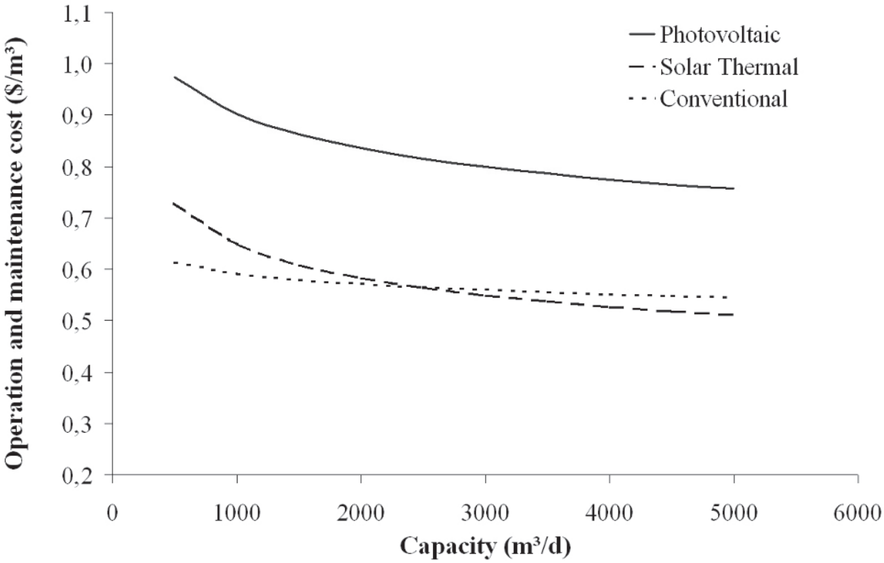

Figure 3. Operation and maintenance specific cost as a function of plant capacity by means of two solar systems (PV/RO and ST/MEE) and a conventional one.

It is true that solar system, in comparison with its conventional counterpart, does not appear to be competitive economically but in view of the expected enhanced reliability, a reduction in the PV modules price (between 2 and 4 $\$/W_p$) and a deeper market penetration of solar technologies in general, water cost for a PV/RO system (approximately 1.3 $\$/m^3$) will be in line with that of a standard system having no access to the electric grid (and this without any financial support).

5. Conclusions

The results obtained show that water production cost for a solar desalination plant having a capacity of 5,000 m^3/d is around 2 $\$/m^3$ using both ST/MEE and PV/RO. The technology can be used for low-to-medium scale applications, i.e. up to few thousands of m^3/d. As far as large-scale plants are concerned, coupling of desalination processes with high temperature solar technologies (parabolic trough solar electric generating systems and central receiver power plants) needs to be investigated thoroughly (a concept beyond the aim of the present paper).

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DYNAMIC MODELING TOOLS FOR SOLAR POWERED DESALINATION PROCESSES DURING TRANSIENT OPERATIONS

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Abstract. The status of process modelling systems is outlined here along with the description of a dynamic model for the analysis and prediction of multistage flash desalination units. Several different operating conditions describing the operations of a solar powered MSF unit were simulated in order to investigate the model capabilities and potential for simulating real plant operations. The model is compared to full scale plant data and to more accurate data from a laboratory scale experimental unit. Results show how an example of the new generation of modelling tools allows us to solve the complex model for many disturbances introduced to the desalination system. The model contains ordinary differential equations with sharp changes in operating conditions which have been known to cause problems to many modelling systems.

Keywords: dynamic modelling, desalination, MSF, gPROMS®, transient behaviour, solar powered unit

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1. Introduction

Much engineering analysis must be done on very complex systems. Desalination plants are complex systems involving distributed molecular and transport effects in a series of connected streams, chambers and units. In order to be able to analyse complex systems we need models and perhaps inevitably, given our desire for ever greater accuracy, the models have become so large we need powerful computers to undertake our analyses. Developing the model and then solving it has always been a very costly and time-consuming task, as well as being technically difficult. But in recent years a number of modelling tools have been developed to facilitate this process.

Engineering design involves the need to specify a unit or system of unit models which can manufacture a product to meet output specifications. Creativity is needed to develop new approaches which have the potential to improve on performance by existing units. In many parts of the process industries this is now done routinely using Computer Aided Process Engineering (CAPE) tools. Such tools mean that many alternative designs can be developed and evaluated and that designs can be optimised to obtain the best performance.

When new processes are being developed there is an important requirement to obtain accurate property data on which to base the design. This means that for process development there is a strong need to tie the design process with bench and pilot plant data to attempt to reduce uncertainty. CAPE tools allow us to do this more efficiently. A second trend is the need to obtain more accuracy for spatial distributions as the production of by-products, for example toxic wastes or unsafe local transients, needs to be reduced or eliminated. This can now be done with Computational Fluid Dynamics (CFD) calculations.

This paper discusses current approaches to modelling and some of the tools that are available and in common use. Modelling of desalination units using one of these tools is described in some detail along with results and comparisons with available experimental data.

2. Model Development

2.1. DEFINING A PURPOSE

The first key aspect of modelling is the specification of the objectives of the model. In many modelling projects the objective is to enhance understanding and this is done by incorporating systematic approaches to the prediction of physico-chemical phenomena that govern the system.

Models are usually built based on the laws of conservation but linked to these alternative transport and reaction mechanisms, which quantify phenomena, can be tested against data using a model to discriminate between alternative controlling phenomena. Models are most often used in process design to obtain a design which makes a product to a minimum quality specification and quantity at least cost. Increasingly other objectives are becoming more important such as: environmental (least waste, least water, least CO_2), safety (least toxic by-products), flexibility (maximising the window of operation), controllability (metrics based on closed loop responses to disturbances), and uncertainty (based on expected distributions of key variables).

The book by Hangos and Cameron (2001) sets out systematic approaches to model development and analysis which break down into the following steps: model goalset definition, model conceptualisation, model building and analysis, model verification, model solution, and model calibration and validation. If undertaking a first principles modelling task it is important first to establish the need for the model. Models for controllability will be different from those required for capital cost minimisation for example.

When process design is the objective simple models are used in computational tools so that overall designs for process flowsheets can be assembled quickly as targets for more detailed design of individual units. In order to develop designs computationally using CAPE tools a model is essential. Engineering analysis and design must be quantified to be able to ensure that the design is repeatable and reliable. Then models can be incorporated into one of the CAPE tools. There are many software programs for doing detailed design calculations obtaining internal flows and configurations such as the number of trays in a column or the size of a reactor's packed bed. These calculations are often done using specialist programs which require a more detailed level of modelling. Eggersmann et al. (2002) reviewed the current state of such programs. To determine an optimal design the design criteria must be quantified, usually as a mathematical expression i.e. as an objective function. Then CAPE tools can be used which will obtain the optimal design using the model. Of course this design is only as good as the model and its underlying assumptions.

The focus here is for the use of modelling in developing and clarifying understanding about the operations and governing phenomena in a unit. The process of developing models allows us to propose and test alternative phenomena provided a mathematical formulation can be developed and included at the appropriate point in the model. Alternative models can then be compared with experimental data to help discriminate between alternatives.

2.2. MODEL DEVELOPMENT

Modelling begins with conservation relations. They can be developed for mass, component mass, energy, momentum, or population of a species. The choice of which relations are required will depend on the nature of the system. For example the population balance relations are only required if there are discrete elements (for example solid particles, micro-organisms, or bubbles in liquid or vapour phase) whose properties affect the function of the system being analysed.

The general conservation equation for a lumped system is

$$\frac{d}{dt}(\mathit{state\ variable}) = \mathit{inlets} - \mathit{outlets} + \mathit{generation}$$

where the state variable is a measure of the current state of the system (temperature for energy or total mass for mass), the inlets and outlets are the inlet and outlet flows of the variable being conserved, and the final term is necessary if the variable is being consumed or generated (for example if there is a chemical reaction the conservation relations for individual species must include this term). If the system can be assumed to be at steady state then the time derivative term can be assumed to be zero giving the steady state balance relations. A similar approach is applied to distributed systems where the conservation relations are applied to a differential element and integrated across the length of the system.

Further constitutive relations will be required to model transfer rates, reaction rates, property relations, and equipment and control constraints as appropriate.

3. Computational Tools

3.1. SIMULATION SYSTEMS

For many years it was necessary to develop bespoke programs in High Level Languages such as FORTRAN to implement mathematical models. Over the last twenty years a number of tools have been developed to support the modelling process in Chemical Engineering.

It is important to make a distinction between simulation and modelling. Many simulation tools have been developed over the years and are in routine use for example Aspenplus, PRO/II, and Chemcad. These tools allow an engineer to put together a flowsheet linking existing models from a library. This permits exploration of the system level properties of the flowsheet but does not allow for exploration of the fundamental physical rules that govern a unit or group of units since assumptions about these have already been built into the models. It is usually possible to link user developed models to these systems.

While it is still sometimes necessary to develop stand alone programs this is rare. One reason is that developers require a model to work with other computational tools. This problem was tackled by the development of the CAPE-OPEN standard for interoperability (www.colan.org). This has made interoperability much simpler especially with the main computational tools used in the Process Industries. The standard is not yet uniformly adopted and does not take account of all factors but it is a substantial step towards full interoperability and any developers would be wise to follow the standard. The CAPE OPEN Laboratories continue the development of the standard.

Most design is now done using computational tools. Bogle and Cameron (2002) recently reviewed the tools available and how they are used throughout the design and development lifecycle. The market leaders are still the sequential modular simulators. Sequential Modular Packages commonly used in industry are based on calculating outputs from each in the order in which they appear in the flowsheet using modules for each unit of the flowsheet. If the flowsheet contains one or more recycles a stream must be guessed ('torn') and iterative methods are used to converge the calculated values to the guessed values. Most modules are written in FORTRAN, a high level computer language widely used in the Engineering and technical world. The calculation procedure is at the heart of the computational procedure used by these packages to solve the problem. However there are many other parts which make the whole package a convenient tool for the design engineer. The following are the most common elements: input interpreter, unit operation subroutines, physical property prediction subroutines, algorithm to select torn stream, recycle convergence block, costing databank, and output post-processor.

3.2. MODELLING SYSTEMS

We are defining modelling here as being able to incorporate and change the physical mechanisms of the system being modelled. Thus it must be possible to make a decision, based on the defined purpose of the model, about the length scale at which conservation equations are developed (lumped unit, differential fluid compartment, or even potentially at a molecular level) and to choose between alternative constitutive equations (such as driving force or rate based transport models) or physical assumptions (such as different molecular interaction models for thermodynamic prediction). Bogle and Ydstie outline the state of the art in model based design using complex models along with some examples.

True modelling systems are rarer. Significant progress can be made with generic systems such as Matlab or Mathematica. These systems are easy to use and allow the user to write in a language which is close to mathematical language. They also are able to draw on very powerful mathematical solvers once the model has been developed. They have solvers for algebraic and ordinary differential equation solvers and models with partial differential equations can be set up without difficulty.

They both have four weaknesses of significance for much modelling in Chemical Engineering systems.

1. It is difficult to link the programmes with the physical property prediction programs that are frequently used. This is important for model development since it is often necessary to compare overall predictions when different prediction models are used.

2. It is difficult to include logical or conditional statements. These statements are required when there are time dependent events or when the model has different regimes depending on the values of the variables. For example different flow regimes may occur with very different fluid mechanical predictive equations.

3. It is very difficult to put together a system of many models. This is a common requirement in Chemical Engineering systems where we are dealing with complex unit operations with ancillary units and when we wish to solve flowsheet models, with or without recycle.

4. The size of problem that can be solved is limited – both the computational overhead of running a general purpose system weighs down the computational execution but the systems become unreliable for large systems.

```
sol = NDSolve[{
      x'[t] = = (umax[t] (s(t)/s(t)+ks)) x[t] 91-
((p[t]/x[t])pxmax))) - x[t] dvol[t]/vol[t],
      s'[t] = = (-((umax[t]/yxs) (1 -
((p[t]/x[t])/pxmax) + m((prodrate[t]/x[t])/yps))
(s[t]/(s[t]+ks)) x[t] + gf[t]/vol[t]) - (s[t]
dvol[t]/vol[t]),
      p'[t] = = prodrate[t],
      x[0] = = x0,
      s[0] = = s0,
      p[0] = = p0,
            },x[t], s[t], p[t]}, {t, 0, tfinal}]
```

Figure 1. Part of Mathematica program to solve an ODE model of a fermentation system for substrate (s), cell concentration (x), and product rate (p).

In some cases it may only be necessary to concentrate on one part of the unit and there may be no need for physical property prediction. But using these very general purpose modelling systems definitely has limitations in modelling complex systems such as those involved in desalination.

The Chemical Engineering community has developed a number of specialist recent modelling systems which get over these problems. Aspentech has a product called Aspen Custom Modeller which supports model development.

A popular tool in the academic and industrial communities is gPROMS® of Process Systems Enterprise Ltd.. This system was developed specifically for Chemical Engineering systems. The model is introduced in a specific language which is close to the natural mathematical language. The system interprets this model and links together all the variables and equations to powerful mathematical solvers.

These systems, known as Equation Oriented packages, use a matrix representation of material and energy balance problems. This is used to set up a set of equations which can be solved numerically. From the equation set an occurrence matrix is assembled. This dictates the number of degrees of freedom which in turn dictates the number of specifications that can be made. Once a square system is obtained the design equations can be solved giving the solution to the design problem. These systems have advantages in that it is easier to set up and solve other types of problems such as dynamic simulation, optimization, and parameter estimation.

3.3. BRIEF DESCRIPTION OF THE gPROMS ® MODELLING LANGUAGE

The model developed in the present work has been implemented entirely in gPROMS®, developed in the early '90s (Barton and Pantelides, 1994; Oh and Pantelides, 1996). gPROMS® is a software package for modeling and simulating processes with both lumped and distributed parameters. A gPROMS model constitutes two types of modeling entity: *MODELs* (describing the physical and chemical laws that govern the behavior of the system) and *PROCESSes* (defining the operating conditions). They are accompanied by minor entities to describe the types of variables used or to define macro variables as variable STREAMs (made up of several simple variables), and some particular TASKs indicating internal or external actions to be modeled.

Logical operators like *IF* or *FOR* loops and logical *SELECTORs* are supported by the language as well in order to be able to simulate the non-continuous behaviour of the physical systems. Such a powerful representation for discontinuities in physical behaviour is also useful for simulating complex sequences of control actions and disturbances in the most general manner.

One of the key features of gPROMS® is the possibility of implementing *MODELs* at different levels, which may be included in a hierarchical structure, thus allowing the easy simulation of multi-stage systems. Another important feature is the use of a purely declarative language, where the order in which equations are written is irrelevant.

```
Model

EQUATION
$Mbr = Bin – Bout – Vap_rate – Non_cond_rate
Mbr = Vol_br*Dbr

CASE Evaporation OF
     WHEN present :
          Vap_rate*(Cp_br*(Tvap-Tbr)+Vap_heat) =
Bin*Cp_br* …
     SWITCH TO notpresent IF Tbr_in <
(Tvap+BPE+NEA)
     WHEN notpresent :
          Vap_rate = 0.0 ;
     SWITCH TO present IF Tbr_in >
(Tvap+BPE+NEA)+0.3 ;
END #CASE

SCHEDULE
SEQUENCE
     CONTINUE FOR 15000
     RESET
          MSF.FS(1).Tbr_in:=OLD(MSF.FS(1).Tbr_in)
- 10 ;
     END #RESET
     CONTINUE FOR 1000
     RESET
     MSF.FS(1).Tbr_in := OLD(MSF.FS(1).Tbr_in) +
10 ;
     END #RESET
     CONTINUE FOR 10000
END #SEQUENCE
```

Figure 2. Part of the gPROMS Model for the Desalination Plant showing equation declarations. $ indicates time derivative.

4. Dynamic Modeling of the MSF Process

Among conventional desalination technologies the Multi Stage Flash process has been the most widely used for more than 30 years (El-Dessouky and Ettouney, 2002). Its natural behaviour is that of a robust continuous process, working at steady-state conditions for long periods, until external disturbances or the control system act on the operations of the unit generating dynamic variations in operating conditions. In particular, start-up and shut-down procedures, leakages and component breakages, variations in feed conditions and power supply are typical examples of causes of non-continuous operations.

Coupling the MSF process with renewable energy sources could be feasible due to the low temperature pre-heating of brine required in industrial units. Conventional solar collectors easily reach temperatures up to 90°C which could be suitable for driving a small MSF unit. The oscillating behaviour of any solar source requires analysis of the response of the system to oscillating values of brine inlet temperature, in particular for the problem of designing suitable heat storage, in order to design for robust operations of the MSF unit.

The relevant literature contains several works on mathematical modelling of the MSF process. However few works are focused on the simulation of transient operations of real units. Moreover these works are often based on very restrictive assumptions. Among these, neglecting the presence of non-condensable gases and the blow through phenomenon across brine gates seem to be the most restrictive (Gambier et al., 2004).

In the present work preliminary results will be shown for the development of a dynamic model for the description of MSF plant operation at laboratory and industrial scale.

4.1. MODEL SET-UP

4.1.1. *Process description*

The elementary unit of the MSF process is a flashing chamber. Industrial units consist of several flashing stages (the number of stages in modern units usually varies between 18 and 24) each one characterized by temperatures and pressures decreasing stage by stage. The heated brine enters the first stage where a pressure below its vapour pressure exists; thus the flashing phenomenon occurs, releasing vapour and non-condensable gases which accumulate in the upper part of the chamber. The heat required for the evaporation is taken from the liquid and hence the brine is cooled stage by stage. Eventually vapour condensation or gas venting avoids gas accumulation inside each chamber providing the conditions for almost steady state operations. The brine passes from one stage to the subsequent stage through a brine gate which provides the pressure drop needed to generate the flashing.

A cold Recycled Brine stream is fed to the tube bundle condenser and is preheated through all the stages of the Heat Recovery Section and is eventually sent to the brine heater for final heating before entering the first flashing stage.

Although the model has been built adopting a quite general approach, in the present formulation some assumptions have been made in order to simplify its development. Some of these can be outlined as follows:

- vapour leaving the brine is considered salt free;
- both brine and vapour bulk inventories are considered perfectly mixed, thus a lumped-parameters model can be built;
- non-condensable gases are considered as inert gases dissolved in the brine and CO_2 equilibria have not been considered;
- the distillate duct has not been modelled and the condensed distillate is extracted from the stage and considered as an outlet;
- the brine heater has not been modelled, and inlet brine temperature is regulated as a variable to be set.

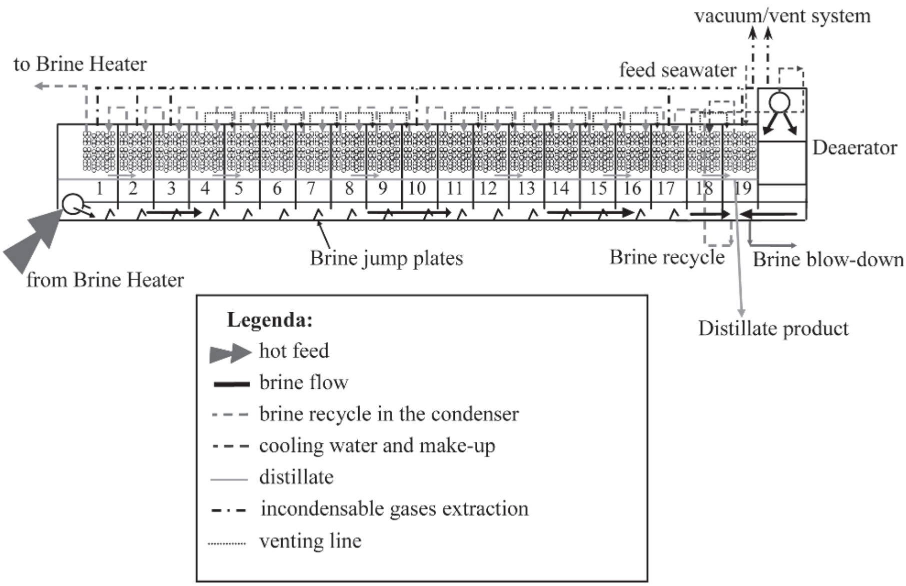

Figure 3. Sketch of a Brine Circulation MSF desalination unit.

Other geometrical and process simplifications have been assumed and will be presented in due course. A sketch of the process in its most commonly encountered configuration is shown in Fig. 3.

4.1.2. *Model equations*

In the present formulation of the model two different geometries were simulated.

The first one is a lab-scale unit with five flashing stages, reproducing a real lab-scale unit (Cipollina, 2005) presently operating at the Chemical Engineering Department of the University of Palermo (Italy). In particular the first and the last stages are the inlet and the outlet stages and they have a height of only 0.2m and no condensing tubes in the upper part of the stage. The vapour produced during flashing passes to the following stage through the venting line. The other three stages are 0.5 m high, while other geometrical details are described in Cipollina (2005).

The second formulation is an industrial-scale unit presently operating in Shuweihat (UAE) with 22 stages and whose geometrical details are reported in Cipollina (2004).

The model consists of a system of Differential Algebraic Equations describing mass and energy balances inside each stage of the unit. These are followed by several constitutive equations which account for the phase equilibria, heat exchanges and calculation of flow rates and all physical parameters in the system.

The model has a hierarchical structure. The lower model is the "Flashing Stage" and contains all the equations describing mass and energy balances, evaporation and condensation rates and non-condensables stripping rate in each chamber. The differential balance equations are:

Total Mass balance equations in the brine phase and in the vapour phase

$$\frac{dM_{br}}{dt} = B_{in} - B_{out} - Vap_{\_rate} - Non\_cond_{\_rate} \tag{1}$$

$$\frac{dM_{vap}}{dt} = Vap_{\_rate} + V_{in} - V_{out} - Cond_{\_rate} + Non\_cond_{\_rate} \tag{2}$$

Salt Mass balance equation in the brine phases

$$\frac{dM_{salt}}{dt} = B_{in} \cdot C_{br\_in} - B_{out} \cdot C_{br} \tag{3}$$

Non-Condensable Gases Mass balance equations in the vapour phase and in the brine phase

$$\frac{dM_{nncond}}{dt} = Non\_cond_{\_rate} + V_{in} \cdot Y_{in} - V_{out} \cdot Y \tag{4}$$

$$\frac{dM_{br\_gas}}{dt} = B_{in} \cdot X_{gas\_in} - B_{out} \cdot X_{gas} - Non\_cond_{\_rate} \tag{5}$$

Enthalpy balance equations in the brine phase

$$\frac{dE_{br\_tot}}{dt} = B_{in} \cdot E_{br\_in} - B_{out} \cdot E_{br} - Vap_{\_rate} \cdot E_{vap} \tag{6}$$

The definitions of variables are given in the Nomenclature section.

The above equations are followed by a number of constitutive (algebraic) equations in order to relate the differential variables to other model variables and to estimate physical parameters.

Evaporation, condensation and non-condensables stripping rates were calculated from balance equations coupled to equilibrium equations. Both evaporative and condensing processes can be typically affected by discontinuous behaviour, depending on the heat transfer equilibria established in the system. In order to ensure the model is close to reality, two *SELECTORs* and one *IF* statement were added in the single flash model, concerning respectively evaporation and condensation processes and release of non-condensable gases.

Two control loops were added in the lab-scale model, in order to control the brine level and the pressure in the last stage.

Finally, leakages have been modelled by adding a new equation to the flashing chamber model in order to introduce an inlet (of non-condensables) to each stage. The inlet flow rate is calculated by introducing a new variable (ALPHA_Leak) which accounts for the flow of the leakages. An equation similar to those used for the venting line is used to calculate the leakage which is related to the difference between the external pressure and the chamber pressure.

The higher level model is the “MSF unit” and incorporates several “Flashing Stage” models. Moreover it includes simple algebraic equations which allow for:

- calculation of the brine and vapour flow rates between stages;

- calculation of efficiency parameters (namely NEA and C_d), with a dependence on the pressure drop between stages, according to empirical correlations (Cipollina, 2005);
- the use of several closure relationships to equate mass flow rates between inlet/outlet streams of subsequent stages (including brine flow through the orifice, vapour through the venting line, and cooling water through condenser tubes).

Also concerning these relationships, the real behaviour of the unit can be typically discontinuous due to the presence of the *"blow through"* phenomenon, i.e. of vapour by-pass through the brine gates when the brine level is lower than the gate height (in real units, due to the turbulence of the flow, *"blow through"* may happen even when the brine level is higher than the gate). For this reason, brine flow rates through gates and flows of the vapour/gas mixture through the venting line are regulated by a *SELECTOR*, which allows for the calculation of the flow rates by properly describing the physical phenomenon when it occurs.

4.1.3. *Model implementation and numerical solution*

As said above, the model has been implemented in gPROMS®. The two levels *MODELs* were included in the same gPROMS® file for both the lab scale or to the industrial scale unit. Several different *PROCESSes* were also included in the same file in order to collect all the simulated cases for each model constructed.

Numerical convergence was generally reached quite easily with calculations taking less than 1 minute of computational time. However in some cases problems related to the action of *SELECTORs* and *IF* loops arose. In these cases (for example when a stage is empty and the blow-through phenomenon starts) the calculation is significantly slowed down due to the re-initialization of the numerical solver at each change in the model equations used.

Before starting the numerical solution a number of specifications must be assigned in the model in order to fix the operating conditions of the simulated case and the initial values of differential variables.

4.2. MODELING RESULTS & DISCUSSION

4.2.1. *Cases investigated, assignments and initial conditions*

In order to assess the generality of the mathematical model developed, the model was implemented for the two different geometries given above. Several test runs were conducted in order to analyze the model behaviour under different conditions. The first simulations were run on the industrial scale unit trying to simulate only simple cases of regime operations and some cases of start-up of the unit. However, a more comprehensive analysis was carried out with the lab-scale unit, where dynamic experimental data were available to qualitatively validate the model by comparison between experimental information and model results.

Most results were obtained to analyze the behaviour of an MSF unit in transient conditions and responding to different external disturbances. In particular, several simulations were carried out to analyze the achievement of steady state starting from different initial conditions, then the response of the system to different external disturbances was analyzed and discussed.

In presenting the results, attention will be focused on the model's capability for simulating the experimentally expected oscillatory behaviour of brine levels in the stages (Alatiqi, 2004), the presence of non-condensable gases, and blow through phenomena through brine orifices. Moreover, the potentialities of the model for describing the behaviour of a solar powered unit will be discussed.

4.2.2. *Modeling the industrial scale unit*

Simulation of operations quite close to the steady state (real operating conditions were provided by Cipollina, 2004) have shown first the capability of the model to simulate the simple case of almost steady state operations. This is in agreement with physical expectations, as shown in the Figs. 4 and 5, relating trends of temperatures and brine levels along the unit respectively.

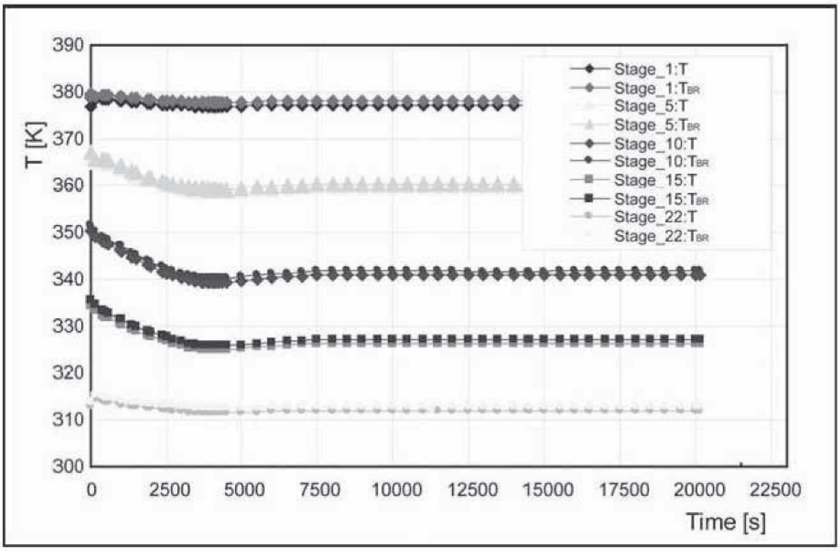

Figure 4. Brine and Vapour phase temperature trends in certain stages of the unit.

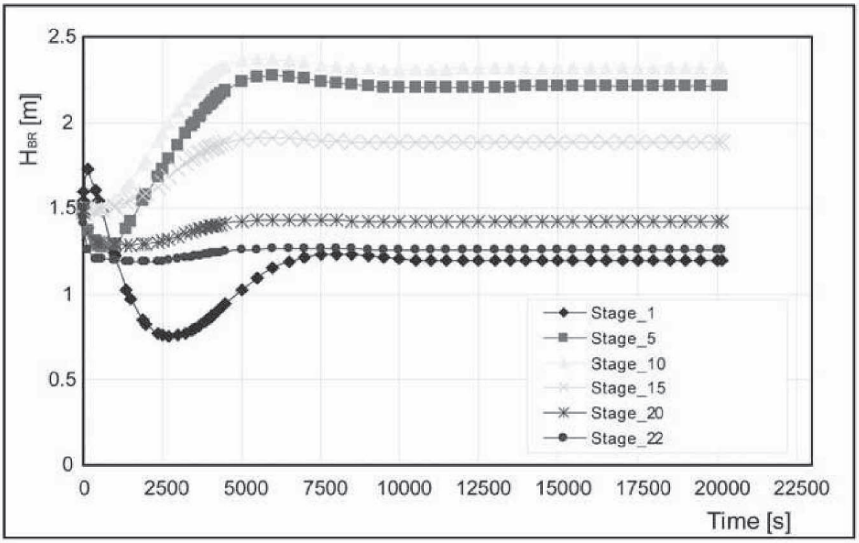

Figure 5. Brine level trends in certain stages of the unit.

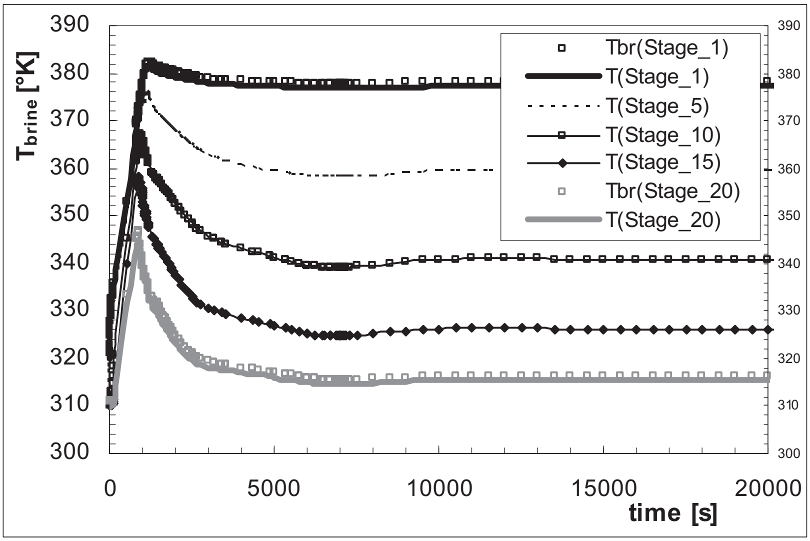

Figure 6. Temperature trends during start-up operations.

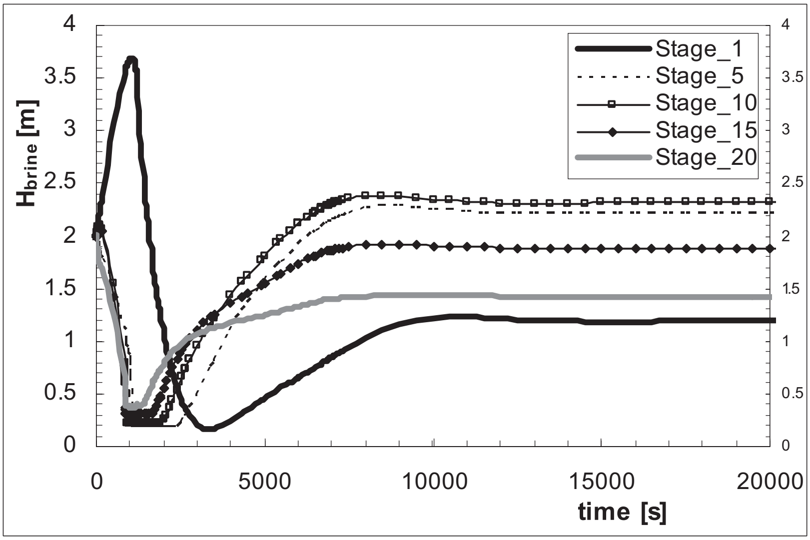

Figure 7. Brine level trends during start-up operations.

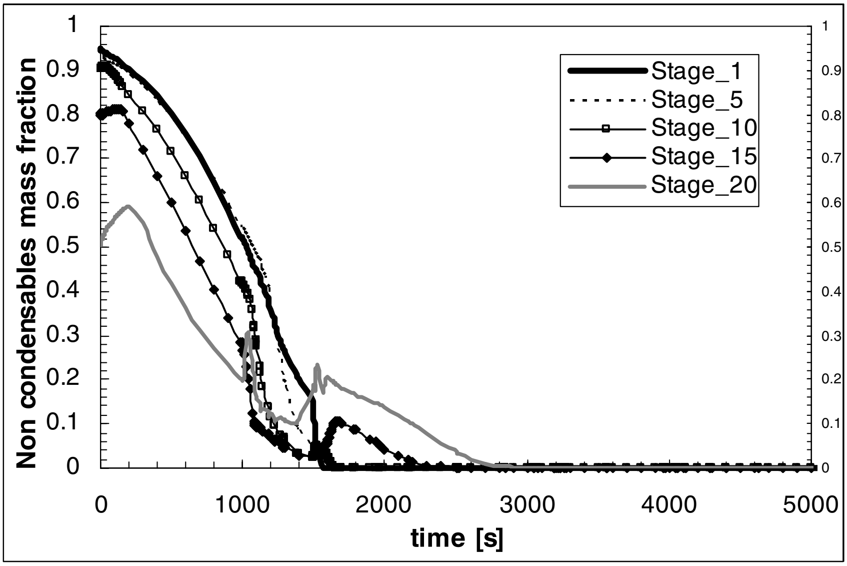

Figure 8. Variation in the mass fraction of non-condensables during start-up operations (first 5000s).

Also when attempting to simulate start-up operations, the model shows good agreement with expectations. In particular, following an increase in the inlet brine temperature the system responded with an increase in the temperatures of all the stages (Figure 6). Oscillatory behavior of brine levels was registered in the first part of the simulation, which eventually settled to the steady state values (Figure 7). Finally, the non-condensable gases mass fraction was also correctly shown to decrease rapidly (Figure 8) due to the effect of the venting system and to vapour formation.

It is worth noting that Figure 7 shows how the model is simulating the operating conditions with empty chambers, taking into account the *"blow-through"* phenomenon in the brine orifice, which is not currently taken into account in the state-of-the-art models.

4.2.3. *Modelling the lab-scale unit*

4.2.3.a. Achievement of steady-state from different initial conditions

The first simulations described the behaviour of the system starting from different initial conditions. In Figure 9 the effect of changing initial brine levels are reported, focusing on the trends of brine levels during the transient in all the stages. It is worth noting how, after the initial transitional behaviour, the system settles on steady state values equal to those achieved in the standard case, thus underlining that there is just one steady state which characterizes the unit once the operating conditions are fixed.

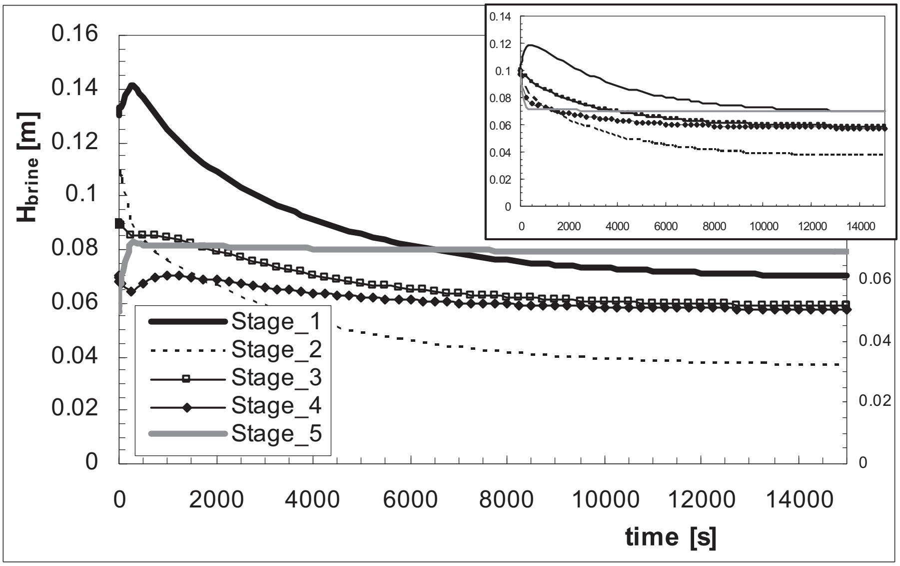

Figure 9. Comparison of trends in brine levels between the standard case (small inset in the upper part of the figure) and the case with different initial brine levels in the stages.

Similar trends were found for the other parameters, also when changing the initial temperature and pressure distribution, and the non-condensables mass fraction in the unit.

4.2.3.b. Effects of disturbances to the steady-state

The effects of a disturbance on the unit have also been studied in order to analyze the capability of the model to predict the system behaviour.

When the inlet brine temperature was increased by 10°K, an overall increase in flashing rate was expected. In fact, the model predicts an increase in pressure and, therefore a sudden decrease of all the brine levels (except for the last stage where the controller keeps the level at 7cm), generating *blow-through* across the brine orifices (Figure 10). Interestingly, the model describes the response of the system accounting also for the emptying of the chambers and for the blow through phenomenon (which is verifiable in real units) with behaviour which is as physically expected.

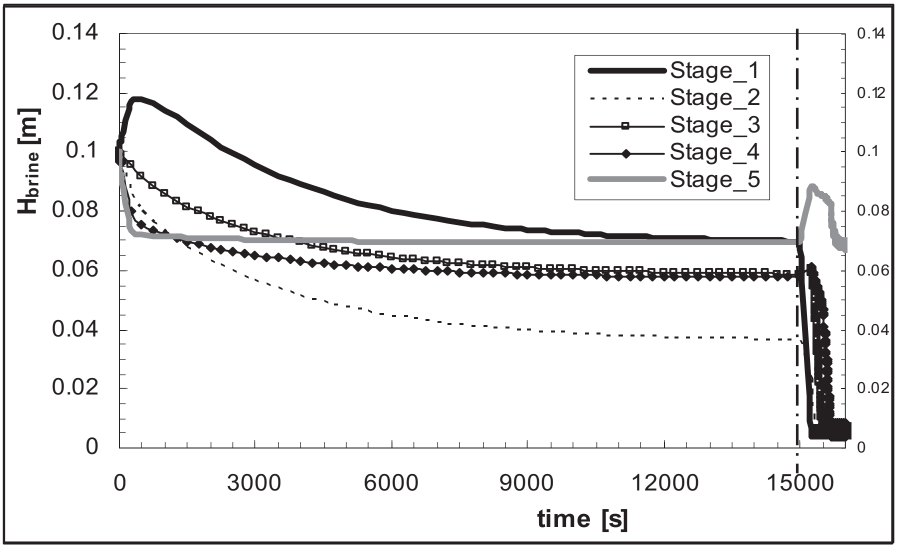

Figure 10. Trends in brine levels in the stages after a 10°K increase of inlet brine temperature.

The presence of a leakage from the third chamber was simulated as well, thus presenting a novel feature of the present model, since this has not been modelled yet in the works available in the literature where the presence of non-condensable gases is neglected. Leakages may be present in any unit working under vacuum conditions. They cause an increase in pressure and in non-condensables mass fraction inside the stage of interest and in all subsequent stages which may lead to unsatisfactory operation of the whole unit. Usually the presence of leakages is often balanced by an efficient venting system which purges all the non-condensable gases entering the unit through such leaks. Nevertheless when the leaking flow rate reaches a prominent value, the steady state operations may be significantly disturbed, given the possible increase in pressure in the chamber due to the new contact between the inside of the chamber and the surrounding environment.

In the simulated case, pressure and non-condensables increase from the third stage and the increase is then transmitted to the rest the unit, causing the variation in brine levels reported in Figure 11.

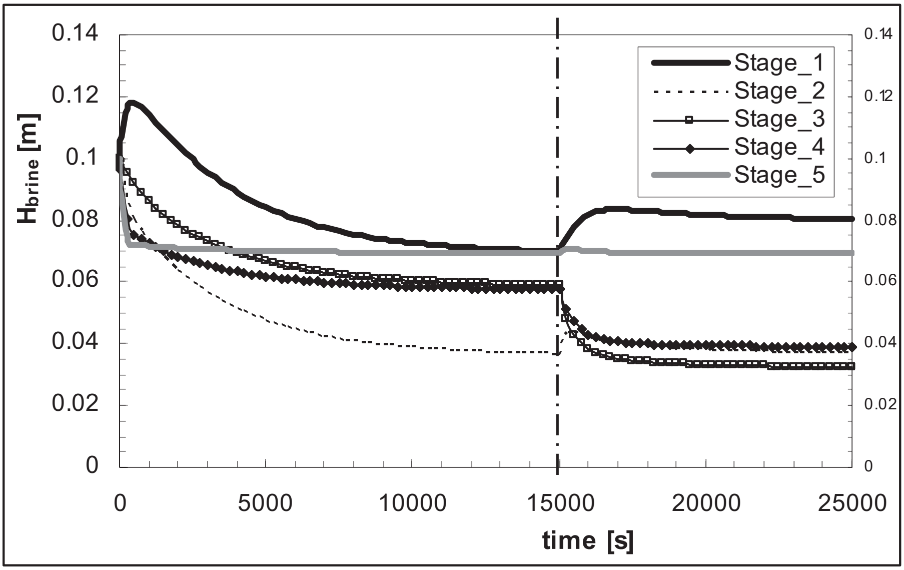

Figure 11. Trends in brine levels in the stages after the introduction of a leakage in the third stage.

Finally the same disturbances were simulated with pulsing behavior, maintaining the disturbance for only 1000s in the middle of steady state operations.

When the inlet temperature was increased by 10°K, emptying of the stages was registered as in the previous case, but restoring the original operating conditions leads back to the previous steady-state. Blow-through phenomena last for a while even after the disturbance was removed (Figure 12).

A proper description of the physical phenomenon is achieved when simulating a pulsed leakage also. The effect of increasing pressures from the third stage, thus decreasing brine levels in the subsequent stages, and is correctly predicted, as shown in Figure 13.

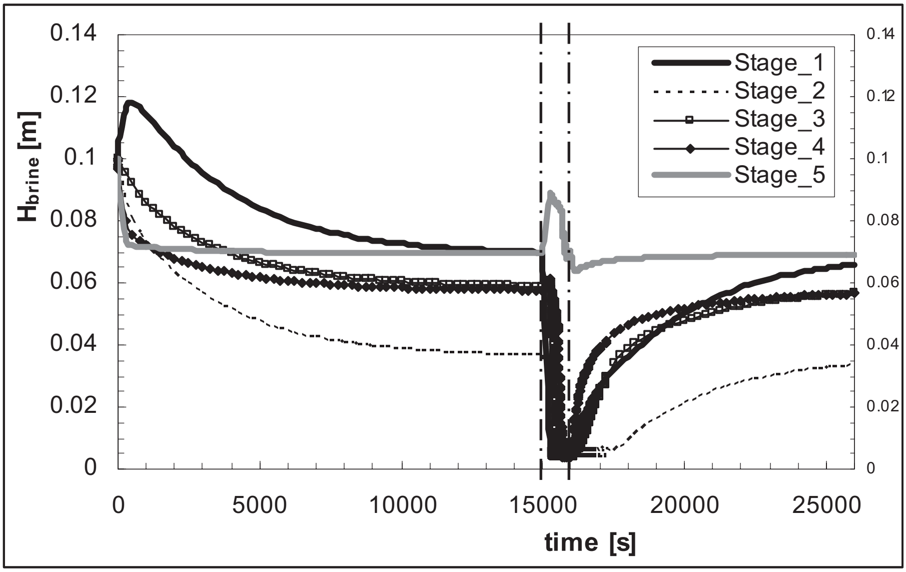

Figure 12. Trends in brine levels in the stages after a 10°K increase in inlet brine temperature for 1000s.

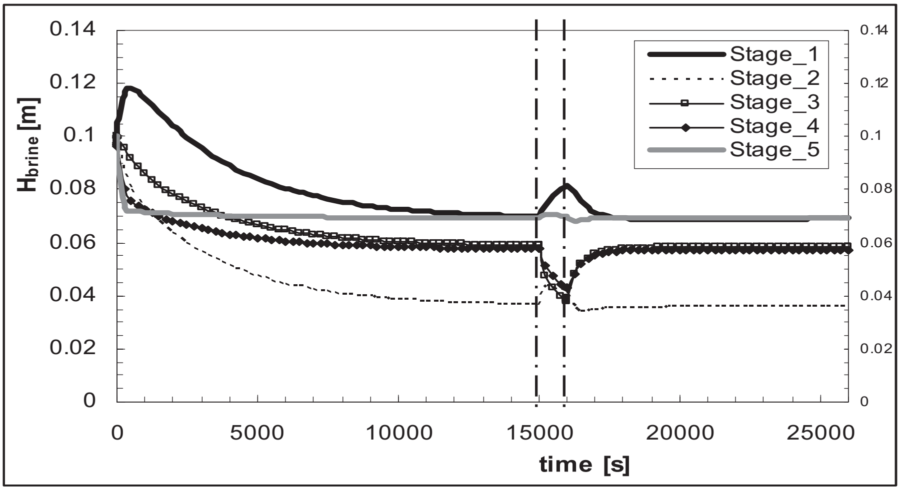

Figure 13. Trends in brine levels in the stages after the introduction of a leakage in the third stage for 1000s.

4.2.3.c. Response of the system to a sinusoidal inlet brine temperature behaviour

Finally, the model was tested to simulate the response of the system to oscillating behavior of inlet brine temperature, in order to simulate the operation of a solar powered system. In particular the choice of the amplitude of oscillations would be a fundamental parameter when designing such a unit in order to guarantee proper operations of the unit.

In Figures 14 and 15 the trends in brine temperatures and brine levels are reported for an oscillating amplitude of 4 °C over a whole day.

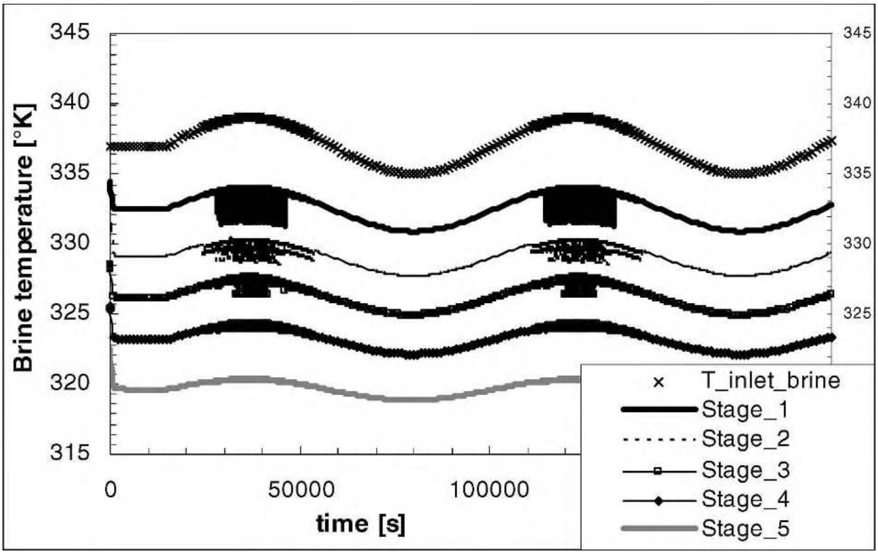

Figure 14. Trends of brine temperatures in the stages with an oscillating inlet brine temperature.

In this case, which is of course not the case of an industrial unit, even a small oscillation of 4 degrees of amplitude, gives rise to a significant oscillation of brine levels in the first stages, leading also to the blow-through in the gates.

A similar trend can be observed if raising the oscillations amplitude up to 10 degrees, obviously causing larger oscillations of brine levels.

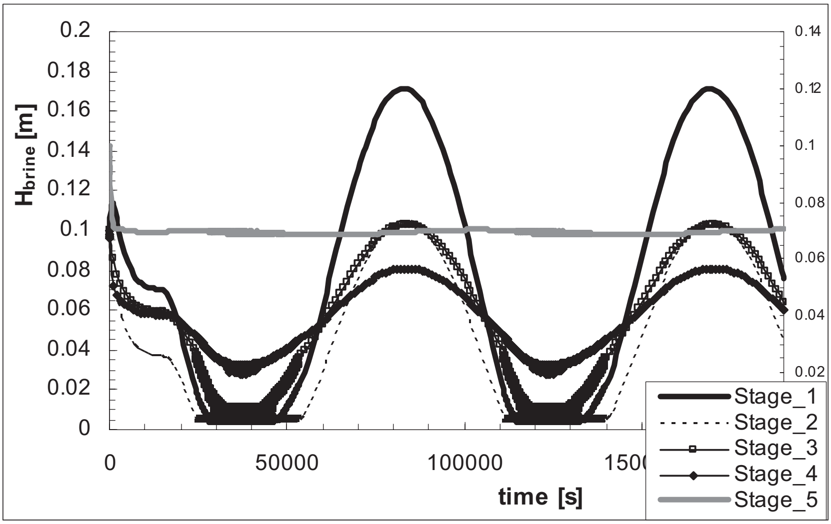

Figure 15. Trends of brine levels in the stages with an oscillating inlet brine temperature.

It is worth noting how similar results could be used both for the design of heat storage buffers which could reduce temperature oscillations but also for designing and optimizing a control system which could act for example on the venting line orifices in order to control the pressure distribution and therefore brine levels.

5. General Comments and Further Modeling Development

A novel model has been developed aimed at overcoming some of the weaknesses of existing published models. In particular an attempt was made to simulate the *"blow-through*" phenomenon inside brine orifices and the presence of non-condensable gases, always neglected in the formulation of existing published modelling works.

The use of gPROMS®, a software package for developing dynamic models, has allowed the development of a comprehensive physical model accounting for the main physical laws regulating the operations of a multi stage flash unit. Simulations were run both for lab-scale MSF geometry, and for industrial-scale geometry.

Simulations predicted the behaviour of both systems under several different transient operations. Brine levels have been found to be the most sensitive parameters, often forcing the simulation to stop because their physical limits were exceeded. This is confirmed by experimental measurements and other modelling works (Alatiqi, 2004; Tarifa and Scenna, 2001; Thomas et al., 1998).

The original formulation of the model has allowed the *“blow through”* phenomenon to be correctly simulated when brine levels decreased under the gate height. Moreover the presence of non-condensable gases in the model formulation enabled the simulation of leakages in one or more stages, thus providing original results for the behaviour of an MSF unit. Thus the model presents several new features which make its development and usage very promising for a comprehensive understanding and modelling of industrial Multi Stage Flash units. The final results have also shown the potential suitability of the model to simulate the transient operations of a solar powered MSF unit, where the system response to an oscillating trend in inlet brine temperature would be of crucial importance for the proper design and control of the unit.

Several actions to improve the model are planned in order to improve some model assumptions and, therefore, its reliability. Among these:

- Empirical correlations used in the model (for the calculation of NEA and C_d) may be modified or substituted with other correlations found in the literature, looking for the best match with experimental data. Moreover, some of the model parameters have to be tuned by comparison with experimental data, namely the venting line and blow-through discharge coefficients, ALPHA.
- Flashing and gas release rates could be modelled by more accurate descriptions of basic phenomena, accounting for turbulence, heat and mass transfer and bubble nucleation kinetics. A link between gPROMS® and CFD tools may be the key for further developments in this direction.
- In order to enable the model to completely simulate the behaviour of an industrial unit some changes need to be made to the present model formulation: the introduction of a Brine Heater and a De-aerator model, the additions of several equations to describe the brine circulation configuration, and the modelling of distillate ducts along the unit.

The new dynamic modeling capabilities available to Chemical Engineering researchers have been shown to provide an effective tool for the study of process systems with complex interacting phenomena and geometries.

NOMENCLATURE

ALPHA = vapour venting line discharge coefficient [m^2];
$ALPHA\_{Leak}$ = discharge coefficient used to estimate a leakage in a stage [m^2];
B_{in} = inlet brine flow rate [kg/s];
B_{out} = outlet brine flow rate [kg/s];
C_{br} = stage brine salt concentration [ppm];
C_{br_in} = inlet brine salt concentration [ppm];
C_{ond_rate} = tube bundle condensation rate [kg/s];
E_{br} = stage brine specific Enthalpy [J/kg];
E_{br_in} = inlet brine specific Enthalpy [J/kg];
E_{br_tot} = total brine Enthalpy [J];
E_{vap} = stage vapour/gas specific Enthalpy [J/kg];
H_{brine} = brine level in the stage [m];
H_{gate} = brine gate height [m];
M_{br} = stage brine mass [kg];
M_{br_gas} = non-condensables content in the brine phase [kg];
M_{nncond} = non-condensables content in the vapour/gas phase [kg];
M_{salt} = salt brine content [kg];
M_{vap} = stage vapour/gas mass [kg];
$N_{on\_cond\_rate}$ = stripping rate of non-condensables during the flashing [kg/s];
V_{in} = inlet vapour/gas flow rate (through the venting line) [kg/s];
V_{out} = outlet vapour/gas flow rate (through the venting line) [kg/s];
X_{gas} = non-condensables mass fraction in the stage brine [-];
X_{gas_in} = non-condensables mass fraction in the inlet brine [-];
Y = non-condensables mass fraction in the stage vapour/gas phase [-];
Y_{in} = non-condensables mass fraction in the inlet vapour/gas phase [-];

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A METHODOLOGY TO PREDICT OPERATION OF A SOLAR POWERED DESALINATION UNIT

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Abstract. The aim of our research is to develop humidification-dehumidification desalination technique for arid regions that are suffering from shortage of potable groundwater. The specific objective of the current study was to present a methodology to predict operation of a solar powered desalination unit using the Solar Multiple Condensation Evaporation Cycle principle. The corresponding dynamic models developed from the thermal energy and mass balances represent better the real behavior of the system and can be used to investigate the effect of various parameters on the performance of the desalination unit. Suitable modular software is developed to provide adequate computational facilities for simulating, sizing, designing and optimizing this kind of desalination unit.

Keywords: Solar energy, water desalination, modelling, simulation, software.

1. Introduction

Since most arid regions have high solar energy resource, the use of solar energy in brackish water or seawater desalination displays an interesting opportunity, or even the only way to offer a secure source of fresh water. The most widely used solar desalination system is a simple solar still, in which the brackish water is heated, evaporated and then condensed. In fact,

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the brackish water acts as a heat absorber and an evaporator, while the glass cover acts as a condenser. Based on the experimental and mathematical model results, it was concluded that the best performance of the solar still is achieved when the following conditions are satisfied (Maalej, 1991):

- high intensity of insolation,
- full insulation,
- minimum wind velocity.

Under these conditions, a maximum solar still efficiency of approximately 50% is obtained and the daily solar still production is about 3-4 $1/m^2$ (Maalej, 1991; Delyannis et al., 2001; Kalogirou, 1997). Theoretical analyses of a simple solar still were developed by Dunkle (1961). Dunkle confirmed that the mass transfer rate depends on the temperature difference between the water surface and the glass cover. In order to increase this temperature difference some researchers (Mathioulakis and Belessiotis, 2003; Kumar and Tiwari, 1996; Lawrence and Tiwari, 1990; Tiwari et al., 1996; Yadav and Jha, 1989; Yadav, 1993; Yadav and Prasad, 1995) studied the effect of coupling the solar still to a flat plate solar collector. Another possibility to increase the temperature difference between the water surface and the glass cover is to reduce the glass cover temperature. The temperature difference could be increased by adding a condenser to the still (Al-Kharabsheh and Yogi Goswami, 2003; EI-Bahi and Inan, 1999; Fath and Elsherbiny, 1993; Khalifa, 1985; Saatci, 1984).

The other type of solar powered water desalination unit is based on SMCEC principle (Solar Multiple Condensation Evaporation Cycle) as is the case in this paper. For this type of unit as shown in Figure 1, there are three different sections: solar collectors, an evaporation tower and a condensation tower. All three stages are set-up in three independent compartments. This makes the overall system efficiency higher than the still distiller described above. The solar collector is the main component of the solar-powered desalination unit. In fact, its characteristics represent an important factor to the operation and efficiency of the unit. It has an absorber of copper material with its upper surface painted matt black to increase the absorptivity of the system. The absorber in which the fluid circulates in a forced convection and in one direction is covered with a single glass of high transmissivity to solar radiation. All these parts are fitted inside an external case. The undersides of the absorber and the side casing are well insulated to reduce heat losses to ambient air.

The evaporation tower produces the water vapour. Thorn trees are utilised to increase the water spray and improve evaporation. The condensation chamber contains polypropylene condensation plates through which the salty water circulates for preheating. The thermal insulation of the condensation and evaporation chambers is achieved by the plates of polypropylene which cover the whole internal surface of the chambers and protect the external insulating styrofoam layer against corrosion. More details concerning the operation principle are presented in (Ben Bacha et al., 1999; Ben Bacha et al., 2001). The performance of the desalination unit depends mainly on the weather conditions, design and operating parameters. However, to estimate the optimum values of these parameters in different weather conditions using full experiments is costly and time-consuming. Therefore, the development of a simulation model offers a better alternative and has proven to be a powerful tool in evaluating the performance of the system. Based on previous considerations, this requires the availability of suitable software which should be totally modular in nature and should provide adequate computational facilities for simulating, sizing, designing and optimizing this kind of desalination unit.

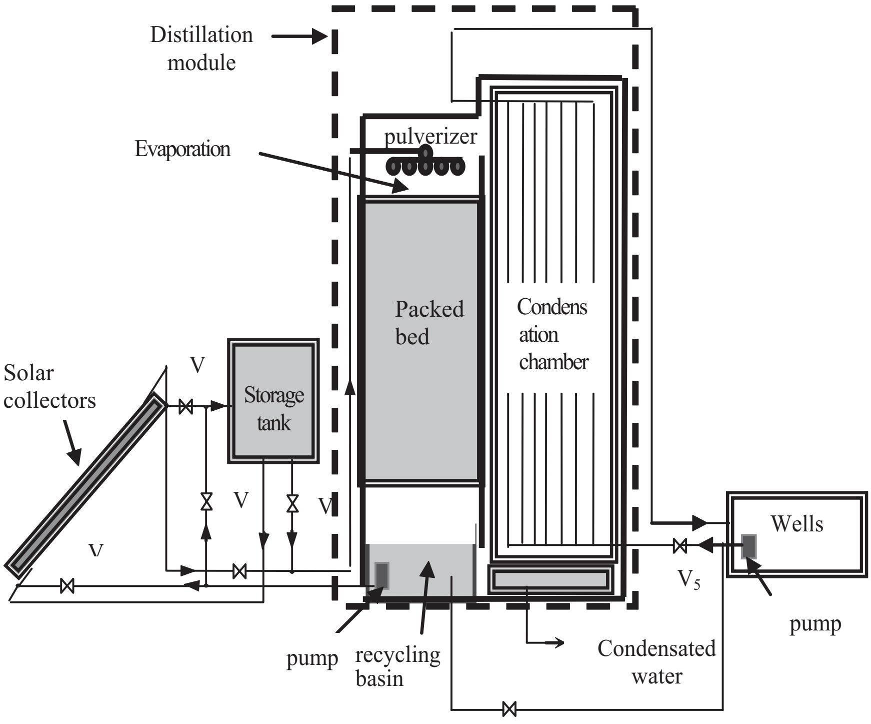

Figure 1. SMCEC-based desalination station. V

This paper is presented as follows: in section 2, the dynamic model of each stage is developed using thermal energy and mass balances. These models allow a good description of the real process and monitoring of the spatial distribution and time evolution of the various parameters. Section 3 is dedicated to present software developed to size and to simulate the SMCEC desalination process. The prediction of the operation of the desalination unit is discussed in the last section.

2. Development of the Mathematical Model

2.1. SOLAR COLLECTOR

The solar collector can be viewed as a multivariable system with several input and output signals. Seawater or brackish water debit mf(t) and water temperature Tfe(t) represent the input signal. Both solar radiation I(t) and ambient temperature Ta(t) are considered perturbations that would affect the solar collector due to their random behavior. The fluid temperature Tfs(t) is an output signal. The thermal balance for the fluid and the absorber for a slice of the collector with a width l, a length dx, and a surface $dS = l*dx$ for a time interval dt, yields the following model (called two temperatures model):

$$\begin{cases} \dfrac{\partial T_f}{\partial t} = -v\dfrac{\partial T_f}{\partial x} + c_1(T_c - T_f) \\ \dfrac{dT_c}{dt} = a_1(f(t) - T_c) + b_1(T_f - T_c) \end{cases} \quad (1)$$

with: $v = L\dfrac{m_f}{M_f}$, $a_1 = \dfrac{SU'}{M_c C_c}$, $b_1 = \dfrac{Sh}{M_c C_c}$, $c_1 = \dfrac{Sh}{M_f C_f}$,

$f(t) = \dfrac{BI(t)}{U'} + T_a(t)$: The ambient condition function.

For the model developed in a previous work (Ben Bacha et al., 2003) both fluid and absorber temperatures are considered the same throughout the absorber. In this case, the thermal balance of the system formed by the absorber and the fluid for a slice of the collector with a width l, a length dx and a surface $dS = l*dx$ for a time interval dt gives the following model (called one temperature model):

$$\frac{\partial T_f}{\partial t} = \frac{1}{b}\left(-m_f a \frac{\partial T_f}{\partial x} - T_f + f(t)\right) \quad (2)$$

with: $a = \dfrac{C_f}{U'l}$, $b = \dfrac{(M_f C_f + M_c C_c)}{U'Ll}$, $f(t) = \dfrac{BI(t)}{U'} + T_a(t)$

The obtained mathematical model for the solar collector allows the determination, for variable solar intensity levels and ambient temperature, of the fluid instantaneous temperature at any point of the collector as a function of the command, geometrical, and physical parameters (flow rate, collector area, material, and inclination angle of the collector). It should be noted that, the fluid temperature and flow rate at the collector outlet are the two parameters with the most significant impact on the unit production as they are the input parameters of the evaporation chamber.

2.2. EVAPORATION CHAMBER

The mathematical model of the chamber is based on thermal and mass balances. The balances are considered for a given element of volume with a height of dz. The obtained model is a set of equations with partial derivatives with respect to space and time, ordinary differential equation and algebraic equations. The model is based on some assumptions (Ben Bacha et al., 2003), different heat transfer coefficients and mass transfer coefficients as listed in (Ben Bacha et al., 2001). The variations of the water temperature (Tl), air temperature (Tg), air humidity (Xg), temperature at the air-water interface (Ti) and the saturation humidity (Xi) are expressed in the following set of equations:

Water phase :

$$m_l C_l \frac{\partial T_l}{\partial t} = -LC_l \frac{\partial T_l}{\partial z} - h_l a(T_i - T_l) \quad (3)$$

Air phase :

$$m_g C_g \frac{\partial T_g}{\partial t} = -GC_g \frac{\partial T_g}{\partial z} - h_g a(T_i - T_g) \quad (4)$$

$$m_g \frac{\partial X_g}{\partial t} = -G \frac{\partial X_g}{\partial z} + k_g a(X_i - X_g) \quad (5)$$

Air-water interface :

$$(X_i - X_g) L_v k_g = h_l (T_l - T_i) + h_g (T_g - T_i) \quad (6)$$

$$X_i = 0.62198 \frac{P_{ws}}{1 - P_{ws}} \quad (7)$$

where $m_l = \varepsilon_l \rho_l$, $mg = \varepsilon_g \rho_g$ with P_{ws} being the saturation pressure given by Dunkle(1961), El-Bahi (1999) and Fath (1993):

$$\mathrm{Ln}(P_{ws}) = -6096.938\frac{1}{T_i} + 21.240964 - 2.71119\mathrm{x}10^{-2}T_i + 1.67395\mathrm{x}10^{-5}T_i^2 + 2.43350\mathrm{Ln}(T_i)$$

2.3. CONDENSATION CHAMBER

The thermal and mass balances of the condensation chamber are established for the cooling water of the condenser, the humid air and the air-condensate interface on an element of volume of height dz. The variations of the cooling water temperature (Tc), air temperature (TG), air humidity (XG), temperature at the air-water interface (Tic), the saturation humidity (Xic) and the flow rate of the condensed water are expressed respectively as:

Water phase :

$$m_C C_C \frac{\partial T_C}{\partial t} = -D_C C_C \frac{\partial T_C}{\partial z} - UA(T_{iC} - T_C) \quad (8)$$

Air phase :

$$m_G C_G \frac{\partial T_G}{\partial t} = -G C_G \frac{\partial T_G}{\partial z} - h_G A(T_G - T_{iC}) - L_v k_G A(X_G - X_{iC}) \quad (9)$$

$$m_G \frac{\partial X_G}{\partial t} = -G \frac{\partial X_G}{\partial z} + k_G A(X_G - X_{iC}) \quad (10)$$

Air-condensate interface:

$$(X_{iC} - X_G) L_v L_G = h_G (T_G - T_{iG}) + U(T_C - T_{iC}) \quad (11)$$

$$X_{iC} = 0.62198 \frac{P_i}{1 - P_i} \quad (12)$$

where $m_G = \varepsilon_G \rho_G$, $m_c = \varepsilon_c \rho_c$, and P_i is the saturation pressure.

Following the water balance $dW_C = G dX_G$, the flow rate of the condensed water is:

$$dW_C = k_G A(X_{iC} - X_G) dz \quad (13)$$

Here, the process of condensation is slow enough to assume that dW_c can be that at the steady-state condition.

3. Software Developed

All mathematical models have been tested and validated (Ben Bacha et al., 2003). These models permit the sizing and the prediction of the solar collectors, the evaporation tower and the condensation tower. The numeric simulation of the desalination unit models allows the study of the relation among the different control parameters of the unit that would optimize its production. For the unit behavior analysis, the sizing and the design of such systems, it is highly desirable and much more flexible to leave the choice of any system configuration entirely up to the designer. Or, the complex sizing and simulating of the process requires trained people using the appropriate tools for reviewing the different functioning case and design of the station. Based on previous considerations, suitable software is developed. The computational tools incorporated in the software include three main parts: (i) the simulation of typical SMCEC station; (ii) the sizing of a new station; (iii) the sizing of the station components such as thermal exchanger, circulating water pump and packed bed.

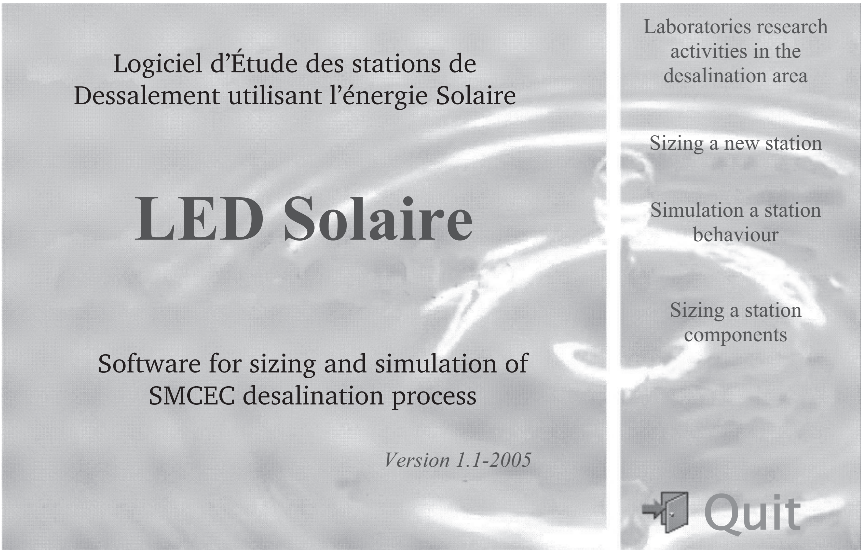

Figure 2. Main page.

Any of the three parts of this software can be easily accessed by the user through a simple menu as shown in Figure 2. The first part allows the simulation of the typical SMCEC water desalination station for different data that can be accessed and charged by the user. It provides the distillate water production and the system performance in the various stages of the station.

Through the second part, the user has the possibility of sizing a new desalination station for a desired production of distilled water. The user can size each stage alone or the global station. The third part concerns the sizing of three main station components which are tubular exchanger, circulating pump and packed bed.

4. Operation Prediction

The software developed allows the simulation of four possibilities of functioning modes according to the season of the year and climatic conditions. Functioning modes 1, 2 and 3 are proposed to be used on winter days (low insulation) (Figures 3, 4 and 5). In the modes 1 and 2 brackish water is preheated in the condenser by exchange of heat with the vapour at condensation. Concerning mode 3, water not evaporated is collected in a basin at the bottom of the evaporation tower and then injected in the solar collector. These configurations allow the reduction of the consumption of thermal energy necessary for heating the water in the solar collector.

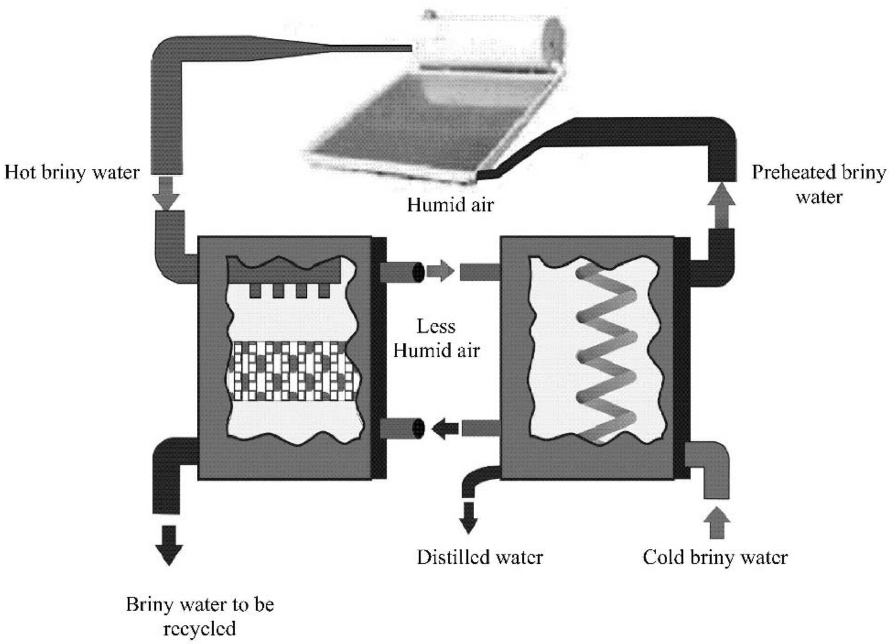

Figure 3. Operating mode 1.

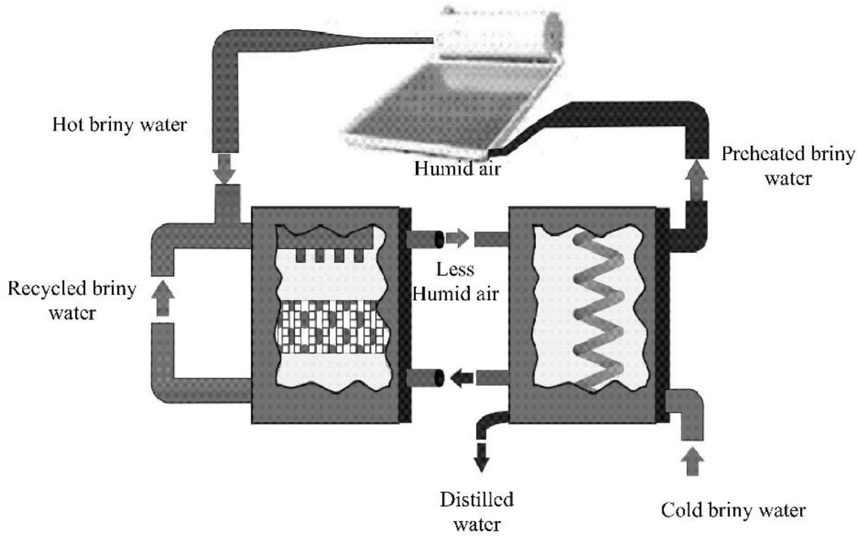

Figure 4. Operating mode 2.

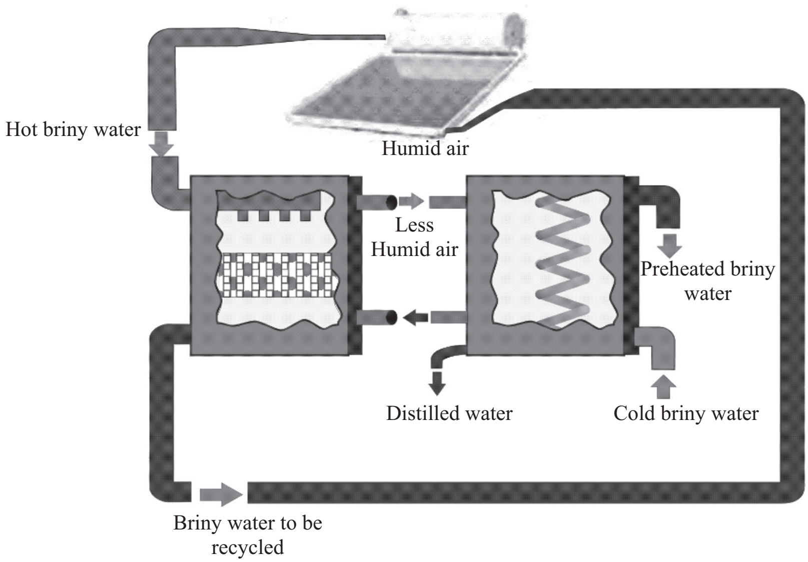

Figure 5. Operating mode 3.

Mode 1 is the nominal mode of operation. Functioning mode 2 called recycle mode. The recycling is needed to recuperate the amount of heat stored in the water which did not evaporate. This water is then mixed with the water coming from the solar collector. The result is high hot water debit which guarantee the optimal operational temperature and water debit at the evaporation tower entrance. Functioning mode 3 has two advantages; it allows heat recuperation from the heat stored in the water which did not evaporate and it permits to use low water temperature at the entrance of condenser. Functioning modes 4 is proposed to be used on sunny days (high insulation) (Figure 6).

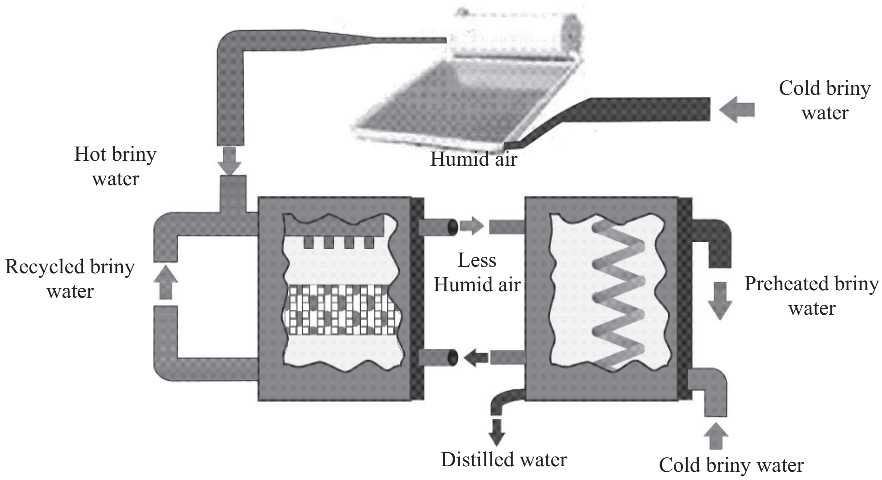

Figure 6. Operating mode 4.

A set of simulation scenarios, with functioning modes 1 and 2, are carried out to predict the operation of a prototype desalination unit. Figure 7 indicates that the amount of water Xg2 in the humid air at the top of the evaporation tower increases significantly as the water temperature (Tl2) at the evaporation tower inlet increases.

Figure 8 shows that the air temperature at the top of the evaporator (Tg2) varies linearly as a function of the water temperature at the evaporator inlet (Tl2). That is, the increase of the hot water temperature at the entrance of the evaporation tower produces more heat inside the installation. Increasing the amount of distillate water in the condensation tower requires a high humid air temperature with significant water content, a low cooling water temperature and a significant air debit.

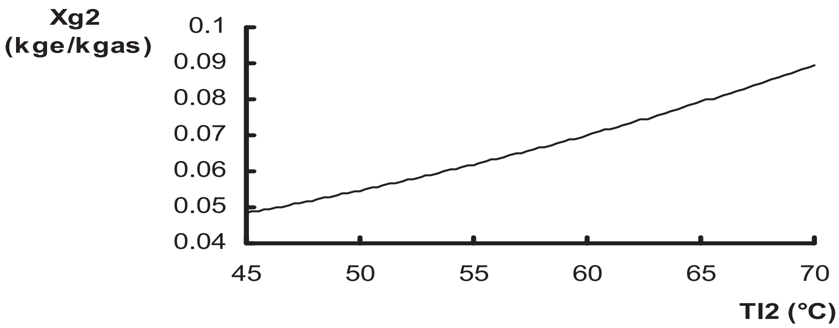

Figure 7. Impact of water temperature at the evaporation tower inlet on the air humidity (top of the evaporation tower).

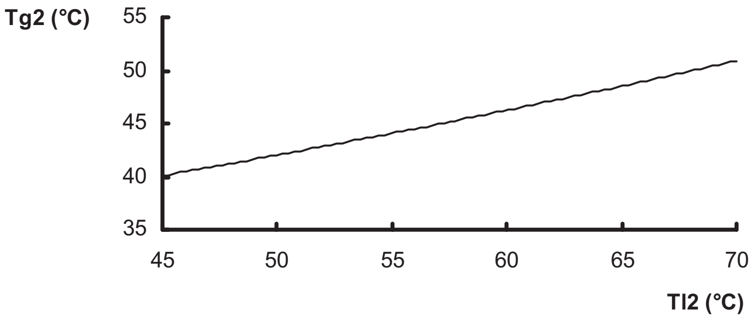

Figure 8. Impact of water temperature at the evaporation tower inlet on the air temjperature (top of the evaporation tower).

Figures 9 and 10 display respectively the estimated condensation rate (Wc) for eight hours of operation with the functioning modes 1 and 2. The graph 10 shows the increase in the production of the condensation rate due to the recycling technique (mode 2).

Figure 11 predicts the production of the distilled water for a pilot desalination unit.

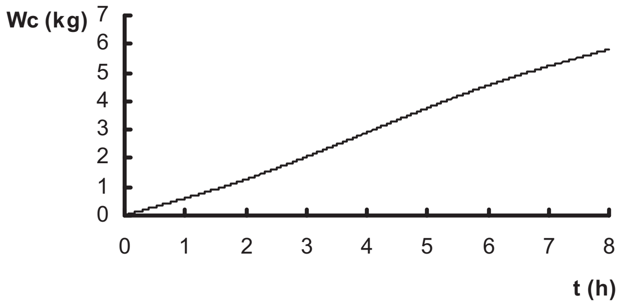

Figure 9. Variation of the condensation rate: Operating mode 1 (nominal mode).

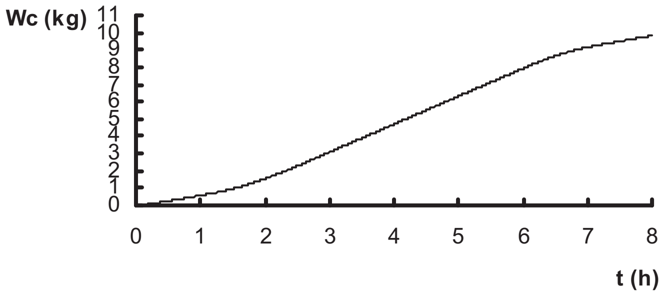

Figure 10. Variation of the condensation rate: Operating mode 2 (recycle mode).

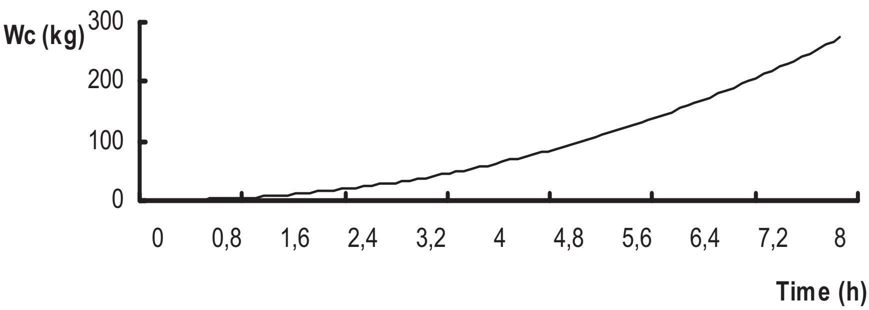

Figure 11. Variation of the distilled water produced for a pilot unit.

5. Conclusions

A methodology to predict operation of a solar powered desalination unit is proposed in this paper. The models developed could be used for further investigation and optimisation of the installation and for the estimation of the amount of produced distilled water of the desalination unit. Suitable modular software is designed and developed to provide adequate computational facilities for simulating, sizing, designing and optimizing this kind of desalination unit.

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OPTIMIZING COUPLING SMALL DESALINATION UNITS TO SOLAR COLLECTORS: A CASE STUDY

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Abstract. The south Mediterranean area is suffering from lack of drinking water. However, brackish water is abundant in these regions. Desalination of such water can be a solution to provide the needs of the local populations (less than 10 m^3/day). Different solutions for brackish water desalination have been developed and many prototypes have been built and tested. Bourouni et al. (1999) developed a water desalination plant based on Aero-Evapo-Condensation Process (AECP). A prototype was built and tested in the region of Kebili in the south of Tunisia. A geothermal brackish water source was used to feed the unit. Promising results were found, since the cost of water was reduced to 1.2 USD per cubic meter of fresh water (Bourouni et al, 1999). The present study shows that the geothermal source can be replaced by solar preheated water. The efficiency of the whole system can be improved by using air flat-plate solar collectors to preheat the air entering the evaporator of the AEC system. Warm air has a higher evaporative capacity than ambient air, and thus, the evaporation of brackish water will be faster and more efficient. In this paper we present a methodology to obtain the best configuration of coupling solar energy to the desalination unit and to optimize the surface collectors used to preheat water and air. TRNSYS simulations are held to predict the performances of the new design of the system. A life cycle cost analysis of the new system design is held to evaluate the cost of a cubic meter of fresh water produced by this innovative process. Different configurations of the plant are studied by detailed simulations. For a small unit producing 3 m^3 of fresh water per day, the cost obtained is as low as 1.58 USD per cubic meter of fresh water produced.

Keywords: Desalination; Solar energy; Water cost; Optimization; Simulations.

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1. Introduction

In the rural regions of the south Mediterranean countries, the use of solar energy for power supply can be very interesting. In fact the conventional power supply of these regions (fuel, electricity, etc.) is very expensive due to the dispersion of the population. Furthermore solar radiation is important. Hence, solar collectors can be used for domestic or agricultural purposes. These regions also suffer from water supply problems although the availability of important underground waters resources. Unfortunately a great part of these resources is salt. Another promoting exploitation of this renewable energy is brackish water desalination.

Solar distillation represents one of the oldest techniques and is successfully used for the production of fresh water from brackish/saline water, in many parts of the world. In the last decade, extensive research has been carried out by different institutions worldwide to develop an efficient means of utilising solar energy for water desalination. Small plants, based on multi-effect humidification process (MEH) were constructed and tested in different countries. In these plants, heat is recovered by air circulation between the humidifier and the condenser using natural draft or forced draft circulation (Al Hallaj et al. (1998) and Garg et al. (2002)).

Al Hallaj et al. (1998) studied a closed air cycle humidification and dehumidification process used for water desalination using solar energy. The circulated air by natural or forced convection was heated and humidified by the hot water obtained from a flat plate solar collector or from an electrical heater. Two units of different sizes were constructed from different materials. The productivity of these units was found to be much higher than those of the single-basin stills. The authors showed that the effect of air velocity was only noticed at low operating temperatures. Outdoors experiments showed that the mass of the unit proved to be another factor that negatively affects the unit performance. A delay of 3 h was noticed between sunrise and the start of production of fresh water. It was noticed that most of the energy received in these early hours is used as sensible heat to warm up the large mass of the unit, which was about 300 kg. Nighttime operation could increase the unit production and serve to keep the unit at elevated temperature, which enables unit production to start earlier the next day.

Gräter et al. (2001) carried out an experimental investigation on a four-effect still for hybrid solar/fossil desalination of sea and brackish water in typical conditions. Different operation modes and configurations of the test facility were examined: heat recovery, natural and forced convection in the distillation chambers (effects). The obtained results show that heat recovery from the outlet mass flows of concentrate and distillate has only a small effect on distillate output but the gained output ratio (GOR) increased considerably. The use of blowers and intermediate screens, installed inside the distillation effects, lead to a distillate yield increased by more than 50% and GOR by 60% compared to results of a configuration without heat recovery and blowers. This reduces the specific thermal power requirement and thus the required solar collector area and boiler capacity.

Bourouni et al. (1998) developed an innovative desalination prototype, functioning by Humidification and Dehumidification process, using low temperature energy (solar or geothermal). The experiments showed that this process is very encouraging, in fact a cost less than 1.2 USD/m^3 of distilled water has been obtained using geothermal energy. Whereas, when water is heated by solar collectors, the cost increases to 1.58 USD/m^3. The authors showed that one of the parameters governing the unit performance is the humidifier inlet air temperature. Both experimental and numerical results showed that the production of the unit increases linearly versus this parameter. In the previous investigations, the inlet air temperature was not controlled. In fact, the used configurations correspond to a closed cycle air between the humidifier and the dehumidifier or to an open cycle. Hence, the inlet air temperature was imposed by the performances of the dehumidifier and the ambient temperature.

In order to increase the inlet air temperature in the unit, a solar air collector, placed upstream the humidifier, can be used. In this paper we analyse the feasibility of this coupling and the advantages of this configuration.

The solar air collector is modelled with the software TRYNSIS in order to determine the energetic contribution of each component in the system. Some experiments carried out on the air flat collector allowed the validation of the numerical results. After that, the proposed model is coupled to the one developed by Bourouni et al. (1998) for the AECP desalination unit. This work allows us to obtain a complete model on the whole installation (desalination unit and solar collectors). Several simulations carried out on the complete model allow the influence of the solar collector surface on the distilled water quantities to be analysed.

The second objective of this paper is to design, in an optimum way, the solar system in order to minimise the distilled water cost. The additional water quantities obtained thanks to the solar air collectors are determined and their unit cost compared to those obtained with geothermal and solar energy. This allows reaching a conclusion about using solar air collectors for air preheating.

2. Installations Presentation

The prototype is presented in Figure 1. It includes a humidifier tower (1), a condenser (2) and a solar air collector (3). Two tanks (4), under the evaporator, and (5) under the condenser, contain respectively salt and distilled water. The two exchangers are linked by a pipe (6) 0.2 m in diameter, allowing the circulation of humid air from the humidifier to the condenser.

Solar energy incident on the solar collector arrays (3), heats up the air sucked to the humidifier by a blower (7). At the top of this tower, the hot brackish water (geothermal or preheated by solar collectors) is pumped inside tubes in polypropylene. At the bottom, the cooled brackish water is recovered in a storage tank (8).

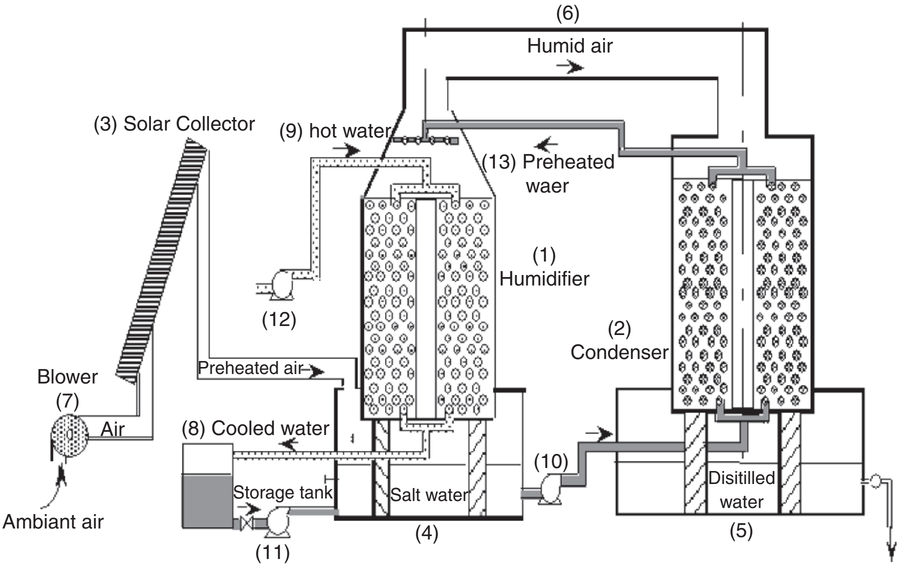

Figure 1. Presentation of the prototype functioning by the Aero-Evapo-Condensation process. (1) Humidifier; (2) Condensor; (3) Solar collector; (4) salt water tank; (5) distilled water tank; (6) pipe; (7) ventilator; (10) (11) and (12) pumps; (13) nozzle.

Heated brackish water (9) moves down the tubes. Its temperature at the entrance is about 65°C. The preheated air moves up in the space between the tubes. The cold salt water in the tank (4) at ambient temperature is sucked up by the pump (10), to the condenser (2). In this exchanger the water moves up inside the tubes. At the condenser outlet, salt water is preheated to 50°C. The liquid is introduced through spray nozzles (13) into the top of the humidifier and falls from tube to tube. Liquid films flow and evaporate on the outside surfaces of the tubes. The humidified hot air from humidifier is drifted towards the condensation tower by forced convection.

In the condenser (2), the humid air moves down through the space between the tubes. On contact with the cold tube walls, we have a film condensation, coupled with latent heat restitution to the salt water circulating inside the tubes. Finally, the distilled water is recovered in the tank (5).

3. System Modelling

The solar system to be modelled can control only the temperature and the velocity of the air injected in the desalination unit. For this reason, we have considered all the other inlet parameters of the desalination plant constant (Inlet hot water temperature $T_{in.fc}$, hot water flow rate m_{fc}, etc.). These parameters are taken at their optimum values, (Bourouni et al., 1998).

Inlet film temperature : $T_{in..f}$ = 45 °C; Linear mass flow : Gamma = 0.025 kg/m.s; hot liquid inlet temperature : $T_{in.fc}$ = 65 °C and hot liquid mass flow : m_{fc} = 100 l/h.

The only varying parameters to consider in the present modelling are the ones that depend on the meteorological conditions and the performance of the solar collector, which are the air temperature and velocity at the inlet of the desalination system. In order to model the global system, we have considered the variation of the evaporated water quantity as a function of these parameters.

Simulations were carried out using the environment conditions of Tunis. Results were obtained each hour throughout the year.

The comparison of the numerical results and experimental data obtained on the air solar collectors highlighted the reliability of simulations.

4. Numerical Results

4.1. INVESTIGATION OF THE PLANT PERFORMANCES

Since the plant performances depend on the ambient air temperature, the variation of water production during the year was investigated. In Figure 2, the monthly amounts of distilled water are plotted for different solar collector surfaces. These results were obtained for an air mass flow of m_{air} = 0.3 kg/s.

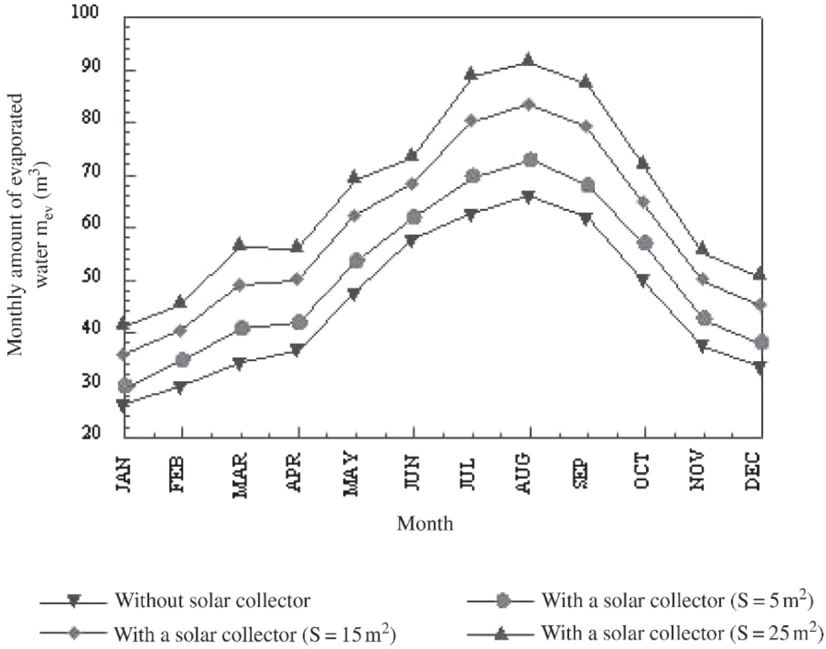

Figure 2. Variation of the monthly evaporated water for different solar collector surfaces.

An inspection on this plot reveals a significant variation of the unit performance between winter and summer. Evaporation rate reaches its maximum in August (65 m^3 when no collector is used) and its minimum in January (25 m^3) and the same for any used surface collector. Data obtained showed an improvement in the evaporator performance when the surface of solar collector increases. This increase is almost constant (4% per m^2 of surface collector) for all months.

4.2. INFLUENCE OF THE SOLAR COLLECTOR AREA

Figure 3 represents the variation of the annual evaporated water versus the collector surface. This figure shows a significant increase of the unit performance when the surface collector increases. In fact the unit capacity can be increased by about 10 m^3/year when the solar collector surface increases by 1 m^2.

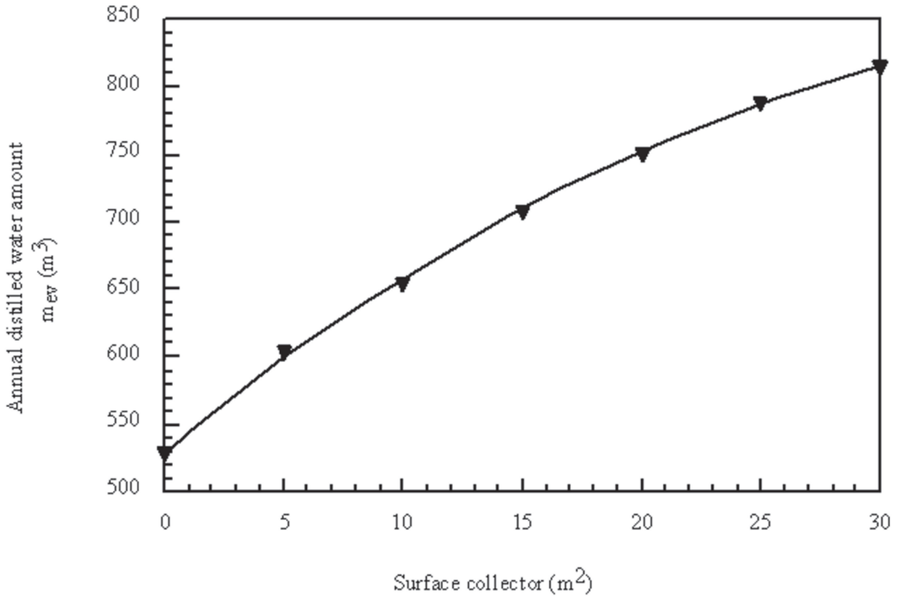

Figure 3. Variation of the annual evaporated water amount versus the solar surface collector (m_{air}=0,3 kg/s).

5. Economical and Technical Analyses

The AECP desalination unit was experimented in two test sites in the south of Tunisia. In the first the unit is coupled to a geothermal spring, whereas in the second site solar collectors are used to preheat the water (Bourouni et al., 2002). In the first case, the authors show that for a project with lifespan of N=20 years, the unitary cost of water is about 1.2 USD/m^3 This cost includes the investment, the energetic consumption and other fixed costs. On the other hand, when solar collectors are used for heating water, the authors obtained an optimum cost of 1.58 USD/m^3. In this paper, we investigate the variation of this cost when an air solar collector is added to the system.

The unitary cost of the water can be obtained by the equation 1:

$$C_u(S_i) = \frac{N\ m_{ev,a}\ C_u + C_{collector}}{N\ m_{ev,a}(S_i)} \tag{1}$$

$C_u(Si)$: unitary cost for the surface collector S_i (in USD/m^3)

C_u :	unitary cost when no air solar collector is used (in USD/m^3)
$C_{collector}$:	total cost of the solar collector (in USD)
$m_{ev,a}$:	annual water quantity obtained when no air solar collector is used (in m^3)
$m_{ev,}(S)$:	annual water quantity obtained when an air solar collector with a surface S_i is used (in m^3)
N :	Lifespan of the installation (in year)

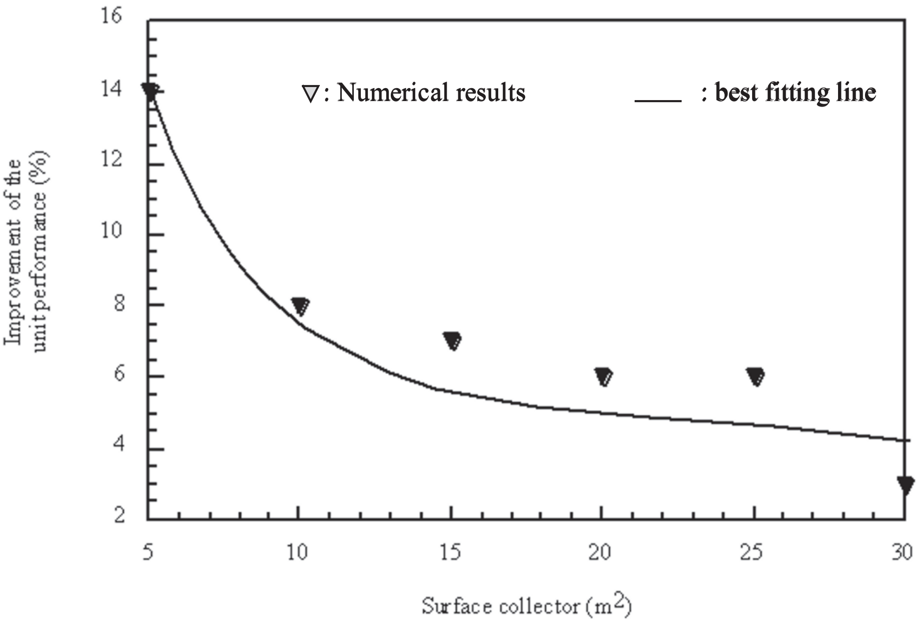

Figure 4. Variation of unit performances versus the solar collector surfaces (m_{air} = 0,3 kg/s).

The variation of the unit performances versus the solar collector area is plotted in the Figure 4. This result shows that the use of a collector with 5 m^2 leads to an efficiency improvement of 14% compared to the case "without surface collector", while increasing the surface from 5 to 10 m^2 the efficiency increase is of about 8% only. However, any increase of the collector surface over 20 m^2 do not improve significantly the productivity of the unit.

The total unitary cost versus the solar collector surface is plotted in the Figure 5, and this for the two cases (using solar or geothermal energy for heating water). The curves show that the water cost decreases when the surface collector increases until 25 m^2. After this the variation of the unitary cost is not significant. Hence, we can conclude, according to pervious results, that the optimal surface to be used for the solar collector is 25 m^2.

For this surface a cost of 0.82 USD/m^3 is obtained in the case of geothermal energy and 0.98 USD/m^3 in the case of using solar collectors.

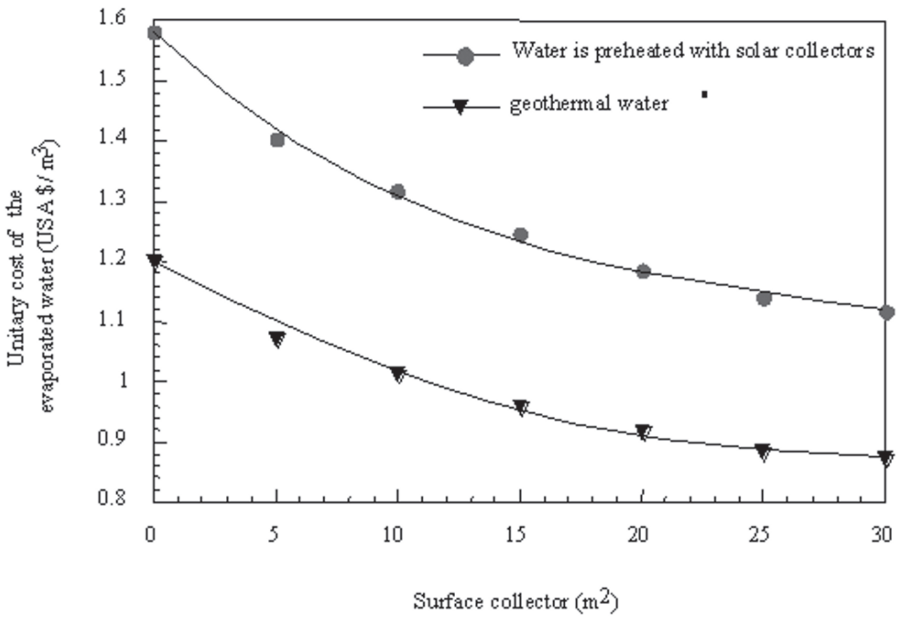

Figure 5. Variation of the performance improvement versus the solar surface collector (m_{air}=0,3kg/s).

6. Conclusions

The development of small desalination units presents an interesting answer to decentralised water demand, which is the case of remote rural regions in developing countries. However, in these distant regions, electric energy is almost inexistant and the supply of fossil energy is very expensive and difficult. Hence, the developed desalination plants should function with a renewable energy source such as solar energy, very abundant in these countries.

In this paper, the efficiency of a system containing a small innovative desalination plant functioning by AECP (Bourouni et al., 2002) coupled to solar collectors has been analysed. The first objective of this investigation is to present a solar system compatible with the AECP unit in order to maximise the global installation return. Previous results (Bourouni et al., 1999) showed that the unit performance increases versus the inlet air temperature. In this paper authors investigate the technical and economical improvement of the unit when air solar collectors are used.

The solar system is modelled in order to determine the energetic contribution of the different components. The elaborated model is coupled to the one that Bourouni et al. (1998) realised for the AECP desalination unit. This allowed to analyse the influence of the surface solar collector on the produced fresh water quantities.

The second objective of this work has been to design in an optimum way the solar system in order to minimise the unitary cost of the fresh water. For this reason, several simulations corresponding to different possible configurations are carried out. In the first case, the use of geothermal energy for preheating water is considered. In the second case solar collectors are used. The surface of air collectors optimising water quantities and costs is 25 m^2 for both cases. The first configuration gives an optimum cost of 0.82 USD per cubic meter of fresh water for an average daily production of 2.2 m^3/d, while the second configuration gives an optimal cost of 0.98 USD per cubic meter of fresh water.

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USING A SIMULATION PROGRAM TO OPTIMIZE THE OPERATING CONDITIONS OF A SOLAR DESALINATION PLANT FOR MAXIMUM PRODUCTION

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Abstract. The subject of this paper is to optimize the operating parameters of an actual solar desalination plant in operation and maximize its annual water production. The plant is located in Abu Dhabi, UAE, it consists of a field of evacuated tube collectors, a heat accumulator of the thermally-stratified type and a multiple-effect seawater (MES) evaporator of the vertical stack type. A simulation program "SOLDES" was used to find the influence of each of the selected operating parameters on plant production. Solar radiation and other weather data for Abu Dhabi were used in the simulation runs. The results of the program were validated against the actual plant data and the agreement was found to be good. The selected plant operating parameters found to have an effect on plant water production were the heating water flow to the evaporator, the collector bypass valve open temperature and the frequency of monthly collector cleanings. The aim is to maximize monthly water production by setting these operating parameters to their optimum values. For this purpose monthly correlation equations were established by running the program at different values of each parameter and using the least square technique. The resulting monthly second-degree polynomial were optimized using the steepest ascent method.

Keywords: solar, MES, simulation, optimization, real operations.

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1. Introduction

A solar desalination plant does not operate at steady state for any length of time due to the continuous variation in the energy source supplying it (solar energy) as well as variation in other weather conditions such as ambient temperature and relative humidity. This situation results in a solar plant operating at different loads thus producing different amount of water at different times of the day and different seasons of the year. In order to maximize the annual production of water by the plant, its operating conditions have to be adjusted on a monthly (or seasonal) basis so as to make sure that the plant is always producing the maximum amount of water possible. A proper understanding of the complexity of the operating conditions of a solar plant demands that its operation be simulated mathematically on an hour-by-hour basis so that the influence of the different operating parameters on water production can be properly predicted. The availability of the simulation program SOLDES was designed to aid in designing new solar desalination plants and also for predicting daily operating conditions.

In this paper, this simulation program was utilized to optimize the operating conditions of an actual solar desalination plant for maximum water production. The plant is the Abu Dhabi solar desalination plant located in Umm Al Nar, near the city of Abu Dhabi, UAE. The aim is to find the operating conditions that yield the maximum annual water production.

2. The Solar Desalination System Considered

Figure 1 is a schematic diagram of the solar desalination system under investigation[1,2] and Figure 2 shows a picture of the plant. A field of evacuated tube collectors is used to provide thermal energy required by a multiple-effect, vertically-stacked (MES) seawater evaporator. A heat accumulator is provided between the collector field and the evaporator in order to allow the evaporator to achieve continuous running throughout day and night and during overcast periods.

The collector field has a bypass line to allow the fluid discharged from the field to return back for further heating when the fluid temperature is too low. Two motorized valves are used in the collector field to control the temperature of water entering the heat accumulator, one valve installed in the bypass line and the other in the supply line to the accumulator. When one valve is open the other will be closed. A temperature sensor (RTD) installed in the discharge line of the collector field monitors the water temperature leaving the collectors and if it is below a set point the bypass valve will be open and the accumulator supply valve will be closed. If the temperature is above the set point, the bypass valve will close and the supply valve will open. This will ensure that the water temperature entering the accumulator tank will always be above a set point.

The operation of the solar collector pump is controlled by a controller which provides a startup (when pump is shutdown) or shutdown (when pump is operating) signal to the pump depending on the intensity of prevailing solar radiation measured by a solar sensor. After sunrise, as soon as the solar radiation intensity reaches a certain value (which depends on the water temperature at the bottom of the accumulator) the controller sends a startup signal to the pump to begin pumping water through the collectors. Just before sunset and as soon as the radiation intensity reaches another low value, the controller sends a shutdown signal to the pump to stop operation.

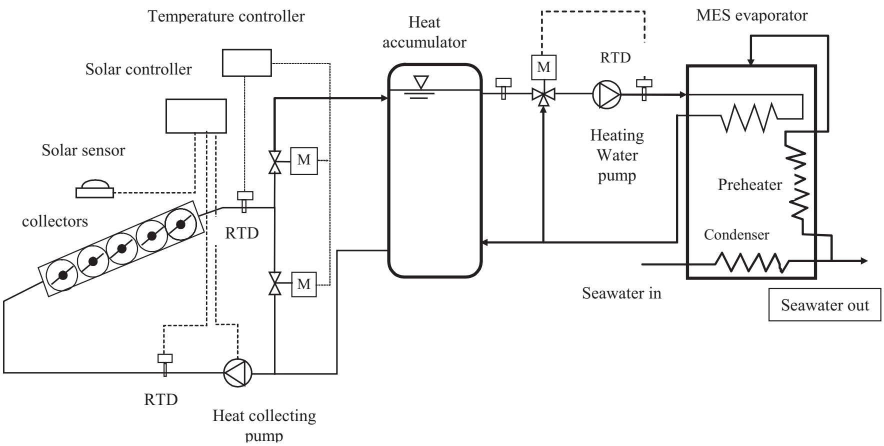

Figure 1. Schematic of the solar desalination system.

The heat accumulator used in this system is a thermally stratified water tank. By virtue of density variation between the top and bottom layers, the higher temperature water is located in the upper region of the accumulator tank while the lower temperature water occupies the lower region. The lower temperature water is drawn from the bottom of the tank and pumped through the collector field by the heat-collecting pump. The hot water returning from the collector field is forced to flow to the top of the tank. The hot water from the top region of the accumulator is drawn from this region by another pump – called the heating water pump -which supplies this water to the first effect of the multiple-effect evaporator. As this water flows through the tube bundle of the first effect, it will cool down thus providing the thermal energy required by the evaporator. The return water from the first effect flows to the bottom of the accumulator tank. The MES evaporator has a number of effects that can be varied by the designer according to the desired performance ratio and top brine temperature. Each effect, with the exception of the first, consists of a tube bundle where vapor is generated in the previous effect flows through the tubes. The first effect, as was mentioned earlier, has heating water from the accumulator flowing through the tubes. In addition to the effects, the evaporator has a number of feed water pre-heaters - equal to the number of effects minus one- and a condenser. The absolute pressure to be maintained in the final condenser is designed to be 50 mm Hg. The pressure to be maintained in each effect varies from slightly below atmospheric in the first effect to about 50 mm Hg in the last effect.

Figure 2. A picture of the Abu Dhabi solar desalination plant.

Seawater is used to condense the vapor generated in the last effect. Part of the discharged warm seawater leaving the final condenser returns to the sea, while the other part constitutes the evaporator feedwater. The feedwater flows through all the 17 pre-heaters before being admitted to the first effect.

3. Validating the Results of the Simulation Program “SOLDES” with Data from the Abu Dhabi Solar Desalination Plant

A computer program was developed to simulate the operating performance of existing and proposed plants and also to help in the preliminary design phase of new solar plants similar to the Abu Dhabi plant. The program was written in Fortran language and was fine-tuned using actual data from the plant. The program was named “SOLDES” and included mathematical models of the basic components of the plant as well as controllers for the solar collector field and the evaporator operation. A model of the dust effect on collector performance is also included. The program carries an hour-by-hour calculation of various plant operating parameters such as the hourly amount of heat collected, amount of heat supplied to evaporator, amount of distillate produced, etc. The program input consists of site climatic data such as solar radiation and ambient temperature and seawater temperature as well as system design data such as collector field absorber area, heat accumulator capacity and evaporator capacity. Site location coordinates (latitude and longitude) are also input to the program. The output of the program consists of, among other information, the daily amounts of solar energy falling on collector field, amount of heat collected, heat supplied to evaporator and distillate produced.

In order to check the validity of program SOLDES[4], the actual operating data of the Abu Dhabi solar plant during one month of continuous operation was selected for comparison with simulation results. The selected month was January 1985. The reason why 1985 year was selected for this validation is that the plant was then in a clean condition with no evaporator tube fouling or collector vacuum level deterioration detected. Although the plant has operated for many years afterwards, its performance level was somewhat below the 1985 level.

The daily solar radiation on a tilted surface with the same tilt angle as the collector absorber plates for January is shown in Figure 3. For the month of January, large fluctuations in solar radiation is observed due to cloud cover.

A comparison between the measured and simulation values of the daily heat supplied to the accumulator for this month is shown in Figure 4. It can be seen that both measured and simulation results follow closely the fluctuations in the measured solar radiation and that the program is clearly able to predict these fluctuations very well.

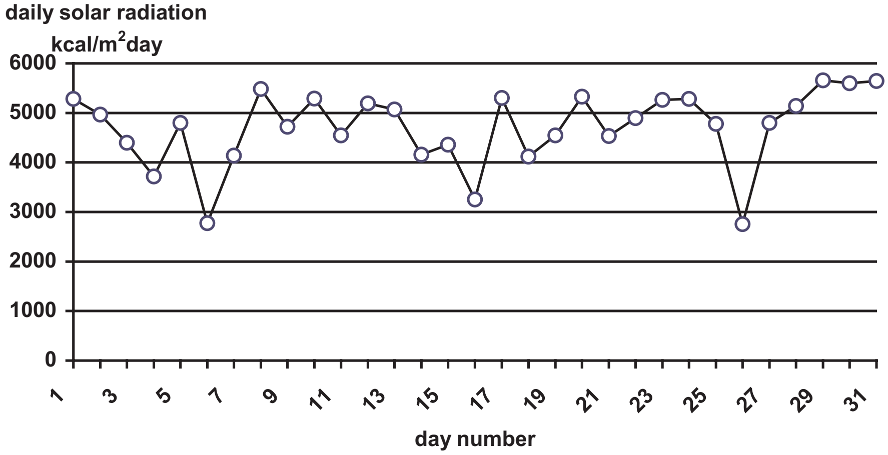

Figure 3. Daily solar radiation for January.

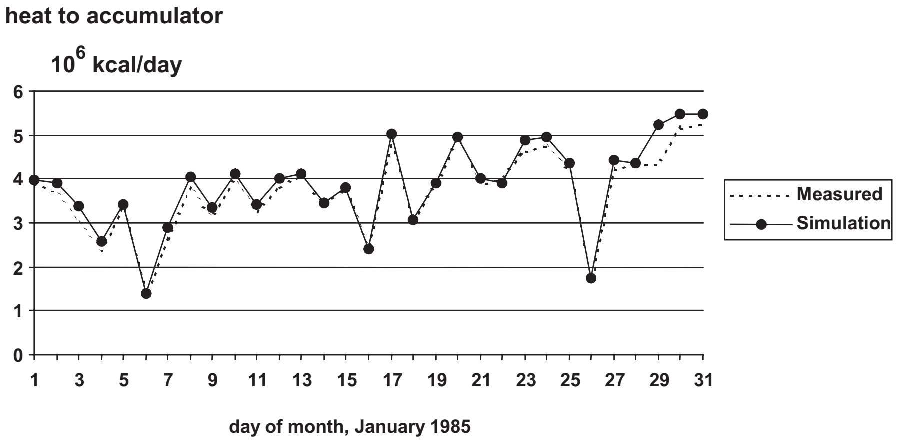

Figure 4. Daily heat supply to accumulator: comparison between measured and simulation results for January.

Figure 5 shows the measured and predicted water production. The simulation program predicted that the plant will be shutdown three times during this month (on the 4th, 7th and 17th) due to insufficient amount of heat in the accumulator. This is what exactly happened in reality where the plant was in automatic shutdown during these three days and no distillate was produced.

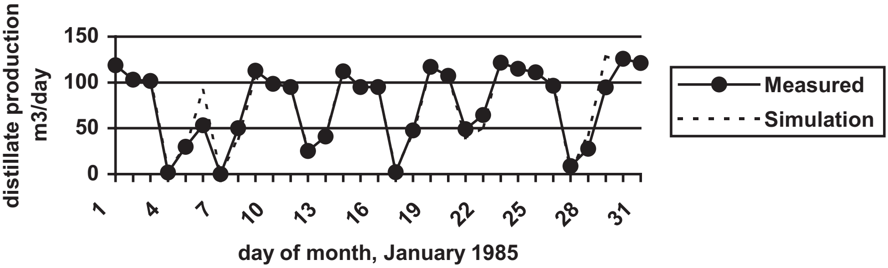

Figure 5. Comparison between measured and simulated distillate production, January.

The measured and simulation values of the evaporator daily-average specific heat consumption (SHC) in kcal of heat supplied per kg of water produced for January is shown graphically in Figure 6. Days during which the evaporator was running continuously (no shutdown due to insufficient accumulator charge) had a specific heat consumption of about 40 kcal/kg of distillate whereas days in which the evaporator was automatically shutdown due to insufficient accumulator heat demonstrated high SHC values. This is attributed to the fact that whenever an evaporator starts up from cold after an automatic shutdown, heat has to be absorbed by the evaporator to bring its temperature to normal operating levels before it can starts any water production. This amount of heat which is added to the evaporator without producing any distillate results in a high SHC during days with automatic shutdown.

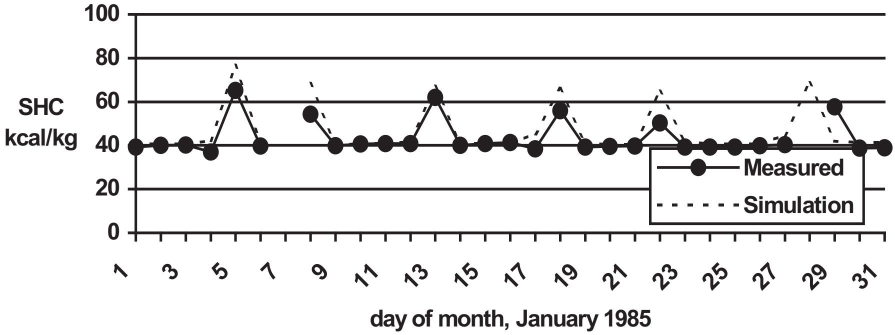

Figure 6. Daily average evaporator specific heat consumption (SHC) for January.

A comparison between the measured values and calculated values of the total heat supply to accumulator and the total distillate production during

January is shown in Table 1. The error in predicting the monthly heat supply to the accumulator is shown to be 4.3% for January and the corresponding error for the distillate production is 2.1%.

TABLE 1. Comparison between measured and calculated values of heat supply to accumulator and distillate production for January

		January 1985
Heat supplied to heat accumulator kcal/month	Simulation	120,100,000
	Measurement	115,100,000
	Percent error	4.3%
Distilled water production m^3/month	Simulation	2,390
	Measurement	2,340
	Percent error	2.1%

4. Monthly Production Maximization Procedure

4.1. THE OPERATING PARAMETERS CONSIDERED

The heating water flow rate (HWF), the collector field bypass open temperature (BPT) and the frequency of collector cleaning (N) are the three main parameters that affect the average product flow rate of the evaporator over a certain period of time. High heating water flow results in a high instantaneous product flow rate but this flow rate cannot be maintained over a long period of time due to the rapid discharge of the heat accumulator. This results in frequent automatic shutdown of the evaporator due to the drop of the heating water temperature below the set-point value which usually corresponds to 60% of the full-load evaporator capacity. The shutdown period will depend on weather conditions and in particular on the solar radiation intensity. On the other hand, if the heating water flow is too low, the instantaneous product flow rate will be low but the evaporator will maintain its operation for longer periods of time without automatic shutdown. A monthly optimum heating water flow rate has to be used so as to maximize the monthly water production of the evaporator.

The collector field bypass valve operation is controlled by a temperature sensor attached to the heat-collecting return piping. The bypass valve operation is shown schematically in Figure 7. The open/close temperature of the bypass valve can be set every month. When the temperature of the water returning from the collector is lower than the preset value, the flow of water is recirculated back to the collector inlet as shown in part (a) of the figure. When the temperature of the water returning from the collector is higher than the set point value, the bypass valve is closed and the accumulator inlet valve is open as shown in part (b) of the figure. A high bypass temperature during winter months with low ambient temperatures can result in a high collector piping heat loss to the environment and a reduction in the net amount of heat supplied to the accumulator.

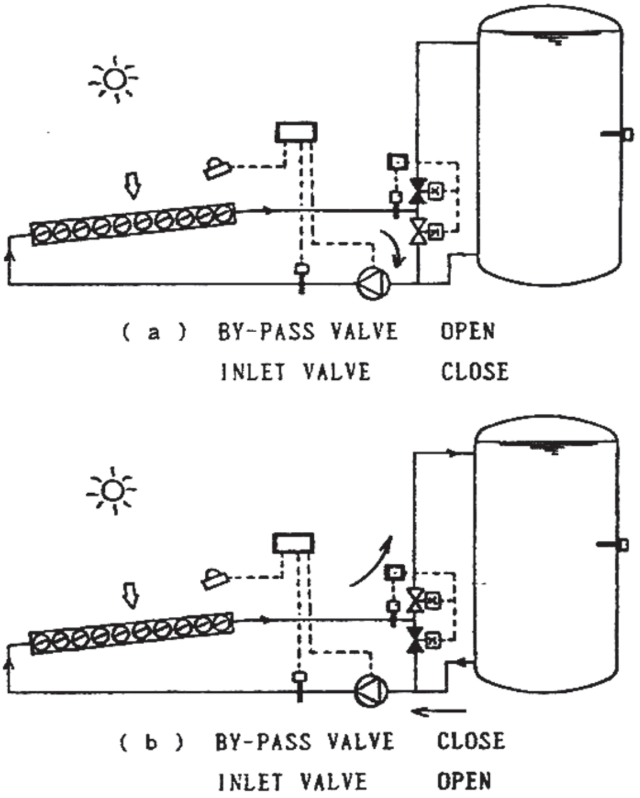

Figure 7. Bypass valve operation for the solar collector field.

A high-pressure water spray was used to remove the dust accumulated on the collectors. Using a pump having a discharge pressure of 50 atmospheres and a water flow rate of 18 liters per minute flowing through a fan-shaped nozzle, most of the dust and dirt deposited on the surface of the glass tubes were removed. The frequency of collector cleaning is an important factor affecting the net amount of water produced by the evaporator over a given period of time[5,6]. The net amount of water produced by the evaporator is defined as the total amount of water produced minus the amount of water used for washing the collector field. Each time the collector field was washed, a measured amount of 6.3 m^3 of water was consumed. Operating the plant with a low frequency of collector cleaning results in dust deposition on the collector glass tubes which results in a low transmittance of solar radiation through the glass tubes and a low amount of collected heat. A low amount of collected heat results in low evaporator water production. On the other hand, a high frequency of collector cleaning results in high transmittance and a correspondingly high water production but the net water production might drop due to excessive water used for cleaning the collector field. Therefore, an optimum cleaning frequency has to be established in order to maximize the net water production.

In order to find the monthly optimum operating conditions that would yield the maximum monthly water production, the simulation program SOLDES was run for different values of the heating water flow, bypass temperature and collector cleaning frequency using the base solar radiation values for 1985. The heating water flow rate was allowed to vary between 12.0 m^3/hr and 20.0 m^3/hr. The operating conditions of the plant that were maintained throughout these test runs are shown in Table 2.

TABLE 2. Operating conditions for the simulation program SOLDES

Operating parameter	Value
Collector absorber area	1862 m^2
Heat collection water flow rate	83.6 m^3/hr
Frequency of solar collector cleaning	Once a month
Storage tank initial temperature distribution	60/60/60/74/74/74/74
Maximum brine temperature	68°C
Seawater flow rate	36.7 m^3/hr
Feedwater flow rate	17.5 m^3/hr
Evaporator startup temperature	Heating water temp. corresponding to 80% load
Evaporator shutdown temperature	Heating water temp. corresponding to 60% load

Open and close of the collector field bypass operation is controlled by a temperature sensor attached to the heat collecting return piping. In the SOLDES program, the open/close temperatures of the bypass valve can be set every month. When the return collector temperature is lower than the preset value, the bypass valve is opened to allow the heating water to re-circulate through the collector field for further heating. When the temperature is higher than the preset value, the bypass valve is closed and the flow is allowed to enter the heat accumulator. The monthly open bypass temperature was allowed to vary between 60°C and 75°C and the optimum monthly value corresponding to maximum production was established using the simulation program. The monthly closed bypass temperature was set 4°C above the open bypass temperature.

In the input file of the SOLDES program, the days when the collector field is cleaned are specified by the letter “C” and the other days are specified by the character “*”. The frequency of collector cleaning can therefore be as low as once per month or as many as daily cleaning. The frequency of collector cleaning can be specified for each month of the year so as to take care of the seasonal variation in dust deposition.

4.2. DEVELOPMENT OF MULTIPLE REGRESSION EQUATIONS

As mentioned above, the monthly water production was assumed to depend on three operating factors (independent variables): the heating flow rate, the bypass open temperature and the number of collector cleanings per month. The number N_c of all possible combinations of factors to be performed is given by

$$N_c = n^k \tag{1}$$

where n is the number of levels and k is the number of factors. The levels are the number of values each factor is allowed to have. In the case of a four-level factorial experiment in which each factor is fixed at four levels and all combinations of k factors are used, we deal with a 4^k full factorial design[7]. In the case of four levels and three factors, the number N_c of all possible combinations is 64. This means 64 simulation runs are to be carried out for each month of the year. The three factors are the heating water flow rate, HWF, (designated x_1), the bypass open temperature, BPT, (designated x_2) and the number of collector cleanings per month, N (designated x_3). The monthly water production (designated y) is used as the dependent variable.

In order to develop multiple regression equations relating the monthly water production to the three independent factors x_1, x_2 and x_3, the following estimate equation is used:

$$\hat{y} = a\, f_1(x_1)\, f_2(x_2)\, f_3(x_3) \tag{2}$$

where $f_i(x_i)$ is any function of x_i. According to Brandon’s method[8], a correlation is first developed between y and x_1 using least square technique using samples of simulation results with constant values of x_2 and x_3. Thus we find that

$$\hat{y}_{x_1} = f_1(x_1) \tag{3}$$

Now a new sample is built up by dividing by $f_1(x_1)$:

$$y_1 = y / f_1(x_1) \tag{4}$$

This quantity is no longer dependent on x_1, and solely determined by the parameters x_2 and x_3. Therefore one may write

$$\hat{y}_1 = a\, f_2(x_2)\, f_3(x_3) \tag{5}$$

Using new samples of y_1 and x_2, another correlation line is obtained depicting the dependence of y_1 on x_2:

$$\hat{y}_{x_2} = f_2(x_2) \tag{6}$$

The correlation coefficients are again obtained by least square method and a sample of the new quantity is built up

$$y_2 = y_1 / f_2(x_2) = y / [f_1(x_1) f_2(x_2)] \tag{7}$$

This quantity is independent of two factors x_1 and x_2, and can be found from the following regression equation:

$$\hat{y}_2 = a\, f_3(x_3) \tag{8}$$

This procedure is repeated until the sample of y_3 is obtained

$$y_3 = \frac{y_2}{f(x_3)} = \frac{y}{f_1(x_1) f_2(x_2) f_3(x_3)} \tag{9}$$

This quantity is independent of all the three factors x_1, x_2 and x_3, and is defined by the coefficient of the original equation

$$\hat{y}_3 = a = \frac{1}{n} n \sum_{i=1}^{n} y_{3i} \tag{10}$$

where *n* is the sample size.

In order to obtain the monthly optimum operating point (optimum values of HWF, BPT and *N*) which corresponds to a maximum water production, the steepest ascent method is used[9].

5. Results

One correlation equation for each month was obtained using the results of 64 computer runs using the standard operating condition given above. For January, for example, the equation is given below:

$$y = 11.1748 + 0.571849 \times x_1 - 0.018339 \times x_1^{\ 2} - 0.350084 \times x_2 + 0.00229845 \times x_2^2 - 0.071811 \times x_3 + 0.00625788 \times x_3^2$$

Figure 8 shows the effect of the heating water flow rate on the January water production for optimum values of the bypass temperature and using a one collector cleaning (carried out on the first day of the month). It is clear from this figure that, under the operating conditions used, the maximum production for this month takes place when the heating water flow rate is set at 16.5 m^3/hr. The water production of the evaporator increases by increasing the heating water flow rate, but by increasing the flow rate there is more probability of prolonged evaporator shutdown due to rapid accumulator discharge, particularly during relatively cold months like January. These shutdowns are automatic and take place as soon as the accumulator temperature drops below the set value. With frequent prolonged shutdowns, the monthly water production is obviously expected to be low. An optimum heating water flow rate has therefore to be established for each month.

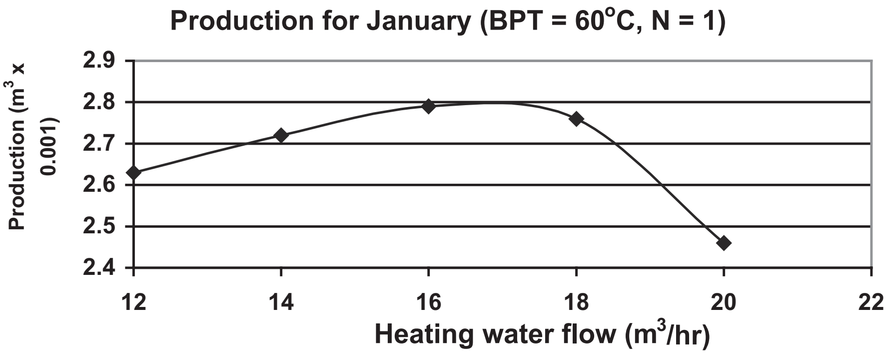

Figure 8. Effect of heating water flow (HWF) on January production. Bypass temp. (BPT) = 60°C and number of cleanings (*N*) = 1.

The effect of the bypass temperature on the January production is shown in Figure 9 for a constant heating water flow of 16m^3/hr and a single collector cleaning carried out on the first day of the month. Under these operating conditions, the maximum production for this month can be obtained using a bypass temperature of 60°C which is the lowest set-point value for the plant. A high set-point value during winter months with relatively low daily global solar radiation and lower ambient temperatures results in a reduction in the amount of heat supplied to the accumulator and consequently less water production by the evaporator. Even though the collector efficiency is higher during winter months due to low ambient temperature, the low daily global radiation accompanied by the larger collector piping heat loss contribute to the low heat supplied to the accumulator during winter months.

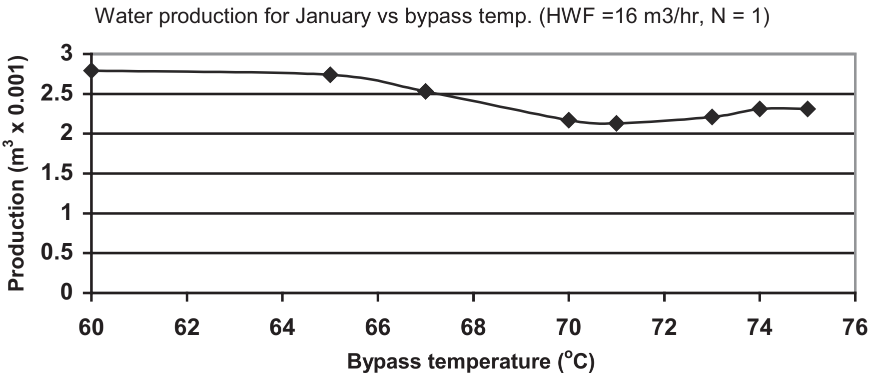

Figure 9. Effect of bypass temperature on water production for January.

Figure 10 shows the influence of variation of the number of collector cleanings and heating water flow rate on the January water production assuming a bypass temperature of 60°C.

The monthly optimum operating conditions and the corresponding maximum monthly production are summarized in Table 3. The hourly global solar radiation and ambient air temperature data for the reference year (1985) are used in the simulation program SOLDES to obtain the following results. It can be seen that the highest monthly water production occurs during April and the lowest in December. The optimum heating water flow was found to be 16m^3/hr for all months of the year. The bypass temperature ranged from 60°C during January and February to 70°C for all other months except March. The optimum number of collector cleanings changed from one during winter months to as high as 8 (for July) in the summer.

The solar radiation data of years other than 1985 are likely to be different from that of the reference year (1985). In order to find the sensitivity of the optimum operating points to variation in the solar radiation data, several simulation runs were conducted using a set of solar radiation data which is 10% higher and 10% lower than that of the reference year.

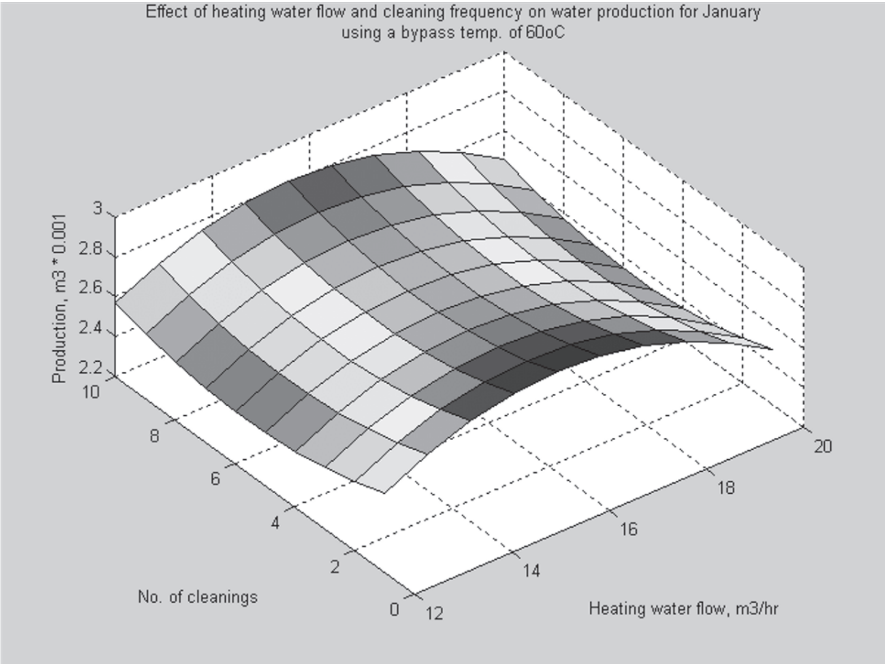

Figure 10. Effect of the number of collector cleanings and heating water flow for January using a bypass temperature of 60°C.

TABLE 3. Optimum operating condition for maximum production.

Month	*HWF (m^3/hr)*	*BPT (Bypass temp. ^oC)*	*N (no. of cleanings)*	*Production (m^3/month)*
January	16	60	1	2790
February	16	60	1	3530
March	16	65	1	3680
April	16	70	1	3810
May	16	70	3	3790
June	16	70	4	3760
July	16	70	8	3500
August	16	70	4	3590
September	16	70	2	3790
October	16	70	2	3790
November	16	70	3	3210
December	16	65	1	2610

The sensitivity of the optimum operating points for January is shown in Table 4 which indicates clearly that although the monthly water production is quite sensitive to variation in the solar radiation intensity, the optimum operating points are relatively insensitive to such variations.

TABLE 4. Sensitivity of optimum operating point to variation in solar radiation for January

Year	Heating water flow, m^3/hr	Bypass temperature, ^oC	No. of cleanings	Water production, m^3
Reference year (1985)	15.6	60	1	2836
Reference year plus 10%	15.6	60	1	3197
Reference year minus 10%	15.8	60	1	2324

6. Conclusions

Based on this study, the following conclusions can be made:

- It is essential to establish an hour-by-hour simulation program in order to set the main plant operating parameters to their optimum values for monthly maximum water production.
- The program should incorporates the extent of dust influence on collector performance (which is a site-dependent phenomena) in order to establish the optimum number of collector cleaning necessary in each month of the year.
- Although the solar radiation data for the reference year (1985) was used in the program, the influence of variations in the solar radiation intensity from year to year was found to have a strong influence on water production but only a small influence on the optimum operating parameters of the plant.
- In Abu Dhabi, the frequency of collector cleanings during summer months was found to be higher than the corresponding values during winter months.

Acknowledgement

The author is grateful to Dr. Darwish M.K. Al Gubaisi for his unfailing help and support during the research program in solar desalination at the Abu Dhabi Water and Electricity Department.

NOMENCLATURE

N_c	number of possible combinations of variable parameters;
N	number of levels for each parameter;
k	number of variable parameters (factors);
HWF	heating water flow (m^3/hr) – also referred to as x_1;
BPT	bypass temperature (°C) – also referred to as x_2;
N	number of collector cleanings per month – also referred to as x_3;
y	monthly distillate production, m^3;
SHC	specific heat consumption, kcal/kg distillate.

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DE-CENTRAL WATER AND POWER SUPPLY INTEGRATING RENEWABLE ENERGY – TECHNICAL AND ECONOMIC PERFORMANCE PREDICTION

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Abstract. Supported by MEDRC and the CEC, European experts in desalination, renewable energy and computational analysis in scientific collaboration with partners from Jordan and Algeria are transforming the computational systems analysis environment ***RESYSproDESAL*** into a capacity for feasibility assessment analyses on de-central water and power supply, integrating renewable energy in MENA countries. Starting from the internet version of ***RESYSproDESAL***, accessible via www.RESYSpro.net, relevant systems analysis capacity is built at MENA water authorities and engineering institutes. The scope of desalination technologies comprises BWRO, SWRO, ED, HDH, MVC, MED and Solar Still, the included sources of renewable energy are wind, photovoltaic, and solar thermal energy collection through flat plate, evacuated tube and parabolic trough systems. The typical stages of systems analysis are: ***Design and dimensioning, modeling of part load operation, simulation of time series performance, and evaluation of life cycle cost.*** The feasibility assessment by ***RESYSproDESAL*** is based on input about local infrastructure, climate, load profile and economic boundary conditions. Case studies with the facility done by the local partners in MENA identify opportunities for reliable and competitive integration of renewable energy utilisation with medium and small scale water treatment processes.

Keywords: MENA, Sea Water, Brackish Water, Desalination, Photovoltaic Power, Wind Power, Solar Thermal Energy, System Integration, Hybrid Systems, Performance, Economics

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1. Introduction

A Specific Support Action (SSA) within the 6th Framework Programme of the European Commission is transforming the systems analysis environment ***RESYSproDESAL*** into a capacity for feasibility assessment studies on de-central water and power supply integrating renewable energy in MENA countries.

Apart from European experts in desalination, renewable energy and computational analysis, the project consortium includes scientific partners from Jordan and Algeria representing typical users of the tool. Starting from the MEDRC-sponsored public internet version of ***RESYSproDESAL*** , accessible free of charge via www.RESYSpro.net, the development aims at the establishing of capacity at water authorities and engineering institutes in MENA for the performance of feasibility and engineering studies on local solutions for de-central water and power supply. The scope of desalination technologies so far includes BWRO, SWRO, ED, HDH, MVC, MED and Solar Still, the included sources of renewable energy are wind, photovoltaic, and solar thermal energy collection through flat plate, evacuated tube and parabolic trough systems.

The MENA partners are concerned with capacity building for ***RESYS-proDESAL*** use at their institutes and with dissemination of knowledge and results to water authorities and industries in their countries. Exemplary studies on selected cases in these countries are done to demonstrate capacity and to test the flexibility of the tool.

The main objective of the action is the creation of a facility which is capable to identify opportunities for reliable and competitive integration of renewable energy use with conventional power supply to medium and small scale water treatment processes.

2. The Challenge: De-central Simultaneous Water and Power Supply

Most Middle East and Northern Africa (MENA) countries are facing growing problems of water supply. Impressive efforts are dedicated to the implementation of large scale equipment with the well proven cost-effective MSF-, MED- and RO-technologies for central sea water desalination at coastal sites or brackish water desalination near inland cities. However there are many technically neglected places remote from the countries' centres of water and power production.

Typically such settlements of a few hundred people with no clean underground water depend on long distance transport of water by truck with high risk due to limited reliability of driver, vehicle and fuel supply as well as hygienic deficiencies of equipment. The true cost of such methods of supply is often not evaluated by the responsible authorities. If grid connection is not near enough the village may have a simultaneous problem of water and power supply.

The inhabitants of such places deserve safer and cost-effective solutions to satisfy their needs for an acceptable standard of living. Water and power production should be implemented on site, employing appropriate technologies and making best use of local resources of energy, material and labour. Sustainable solutions include local public-private partnership, making local contractors directly responsible to customers for the effective and affordable supply of water and power.

3. The Concept: Engineering for Water and Power Points

Starting from their own experience with innovative projects on the powering of water pumping and desalination from renewable energy in arid countries like Algeria, Chile, Jordan, Libya, Morocco and Namibia, the project consortium is developing engineering methods and software tools for the technical and economic performance analysis of de-central integrated water and power point systems. The scientific expertise on solar engineering and systems integration is complemented by co-operation with specialists from desalination and wind energy industries.

The range of desalination technologies comprises Reverse Osmosis (RO), Electrodialysis (ED), Multiple-Effect-Humidification (MEH), Mechanical and Thermal Vapour Compression (MVC, TVC), and Multiple-Effect-Distillation (MED). The range of power generation technologies includes Wind Energy Conversion (WEC), Photovoltaic Electricity Generation (PV), Solar Thermal Process Heat (STH), Solar Thermal Power Generation (STP) and all conventional power generation in hybrid combinations with renewable energy conversion.

The challenge of such systems analysis and engineering stems from the necessarily integrative character of the solutions (Figure 1): Usually only the simultaneous water and power production and the hybrid utilization of conventional and renewable energy sources are promising, reliable and cost-effective solutions. Sustainable solutions in this context aim at

- participation of local water and power authorities in planning and implementation
- participation of local labour and local (small) entrepreneurs in public private partnership (contracting),
- use of local resources for material and energy,
- protection of local environment.

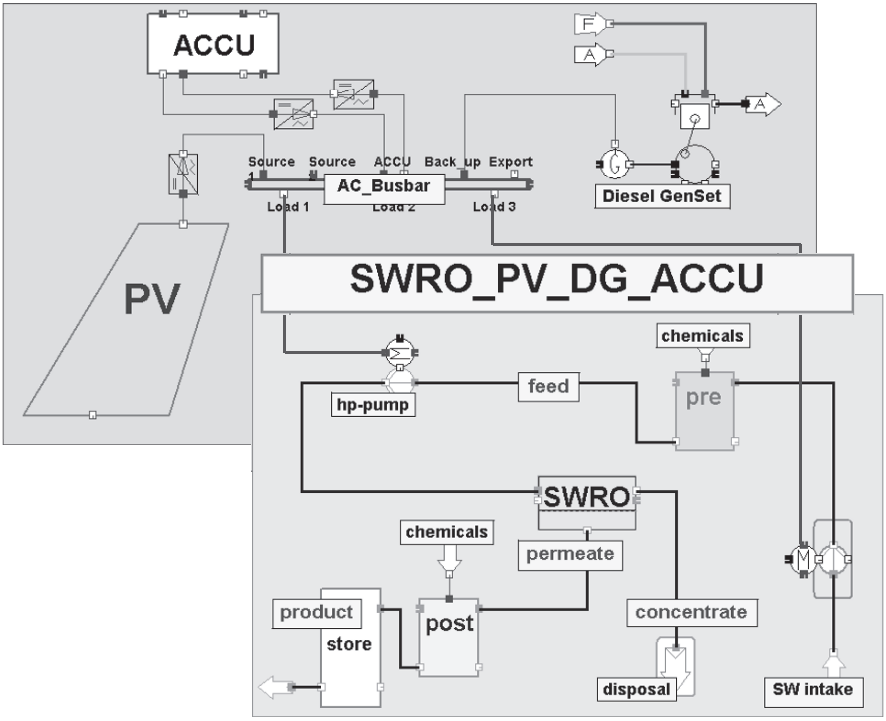

Figure 1. Integration of SWRO with Hybrid Energy Supply (PV and Diesel Generator).

4. The Tool: RESYSproDESAL

The general process modeling package ***IPSEpro*** is the heart of the systems analysis environment ***RESYSproDESAL***. ***IPSEpro*** is an equation solver with an open framework comprising several purpose-built modules. The basic modules are the Process Simulation Environment ***PSE*** and the Model Development Kit ***MDK***. The extension module ***PSEconomy*** is the techno-economic analysis tool which allows detailed evaluation of life cycle cost for different technical process configurations under varying economic scenarios. The specific technical and economic details of the process are contained in so-called model libraries which are created and extended with ***MDK***. With this approach it is possible for end-users to develop very detailed but still adaptable solutions without the need to get into time-consuming high-level programming.

The special model library ***RESYSproDESAL*** covers a wide range of technologies for energy conversion and sea- and brackish water desalination with emphasis on energy supply from renewable sources. Cost data are allocated to system components contained in the library as functions of size and capacity. They are based on market information, and cost parameters as well as functional relationships can be updated at any time.

The economic assessment is performed through a complete through-life cycle cost analysis, which includes the total capital cost of the plant, the cost of fuel, O&M costs and the expected revenues from the sale of power and water at different operating conditions. Varying economic scenarios, including anticipated inflation and fluctuations in fuel prices and product revenues, can be taken into account. ***PSEconomy*** generates different profitability measures like net present value (NPV), internal rate of return (IRR) and product through-life costs, which can be used for economic assessment.

Via ***PSExcel***, that allows the use of ***IPSEpro*** models inside Microsoft's spreadsheet program MS-Excel, the process simulation is linked to time dependent energy balancing (e.g. annual performance evaluation). The interaction of the three components ***IPSEpro*** , ***PSExcel***, and ***PSEconomy*** is schematically shown in Figure 2 and further details from the development of the tool were published by Rheinländer in 2003[1].

5. Component Modeling: Examples RO and WEC

Reverse Osmosis (RO) is a good example for the modeling of a physical process by IPSEpro. The model includes the flow and separation processes in a single pressure vessel (Figure 3).

The model for the RO process in one pressure vessel, SWRO (Figure 3), has been developed using ***IPSEpro's*** Model Development Kit (***MDK***). The box shaped icon of unit SWRO shows a symbolic membrane and connectors to three streams: feed, concentrate and permeate. The process is modelled by a set of physical equations for the determination of

- mass balance between feed, permeate and concentrate
- effective salinity of feed on membrane surface
- osmotic pressure (difference) as function of salinity of feed
- net driving pressure difference on membranes
- recovery (of water) as function of specific flux density of permeate
- salinity of permeate as function of effective salinity of brine and salt rejection quality of membranes

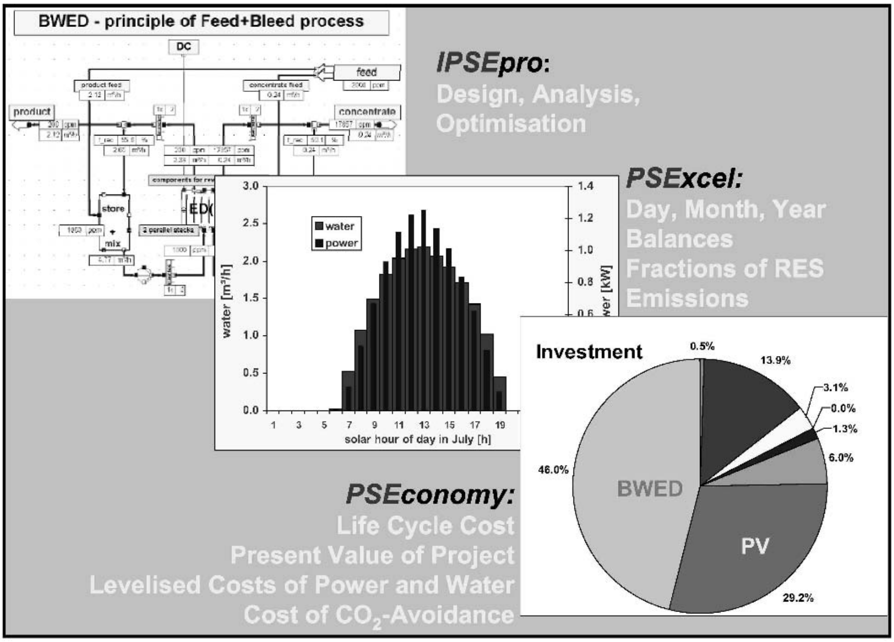

Figure 2. The components of ***RESYSproDESAL*** : ***IPSEpro***, ***PSExcel***, and ***PSEconomy.***

Excluding pre- and post-treatments the minimum configuration of a Sea Water RO system (Figure 4) comprises

- pressure vessels
- headers for feed, concentrate and permeate to and from pressure vessels
- high pressure pump with pump motor
- power recovery by e.g. pressure exchange (PX)
- booster pump for partial feed flow through pressure exchange

The quality of the membranes and the design of the pressure vessels is reflected by parameter values specified from manufacturer's data or equipment testing.

- number of vessels (e.g. 120)
- number of membrane elements per vessel (e.g. 6)
- salt retention (e.g. 99.3 %)
- specific flux per unit of net driving pressure (e.g. .215 g/s/m²/bar)
- concentration polarisation (e.g. 1.092)
- specific osmotic pressure (e.g. .7621 bar/1000ppmTDS)

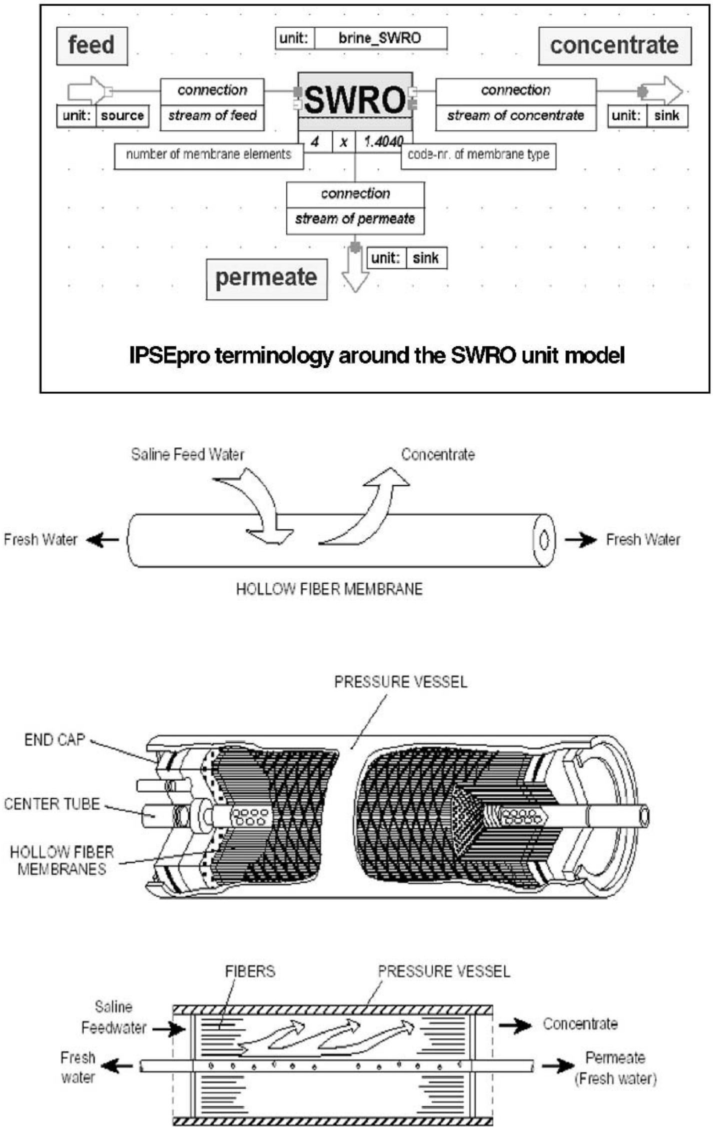

Figure 3. Pressure Vessel with Hollow Fibre Membrane Assembly[2] and Icon of Unit for RO Pressure Vessel in Model Development Kit.

plant		
n_vessels	120	
nominal capacity	129599	m³/d
availability	0.90	
actual capacity	277.78	m³/h
recovery	0.473	
PX-efficiency	0.95	
hydropower rec	0.52	
spec. power	3.05	kWh/m³

SWRO_unit		
process in	pressure	vessel
n_elements	6	
nominal capacity	50.00	m³/h
nominal feed	5.14	m³/h
nominal recovery	0.45	
retention R	0.993	
water perm. WPC	0.2150	g/s/m²/bar
salt perm. SPC	0.0295	g/s/m²
conc. polaris. cp	1.092	
fouling	0.92	
dp_osm_spec	0.7621	bar/1000ppm
dp_osm	45.24	bar
dp_osm_max	60.21	bar
ndp	19.84	bar
load	1.02	
recovery	0.45	
permeate produced	2.31	m³/h
actual capacity	6000	m³/d

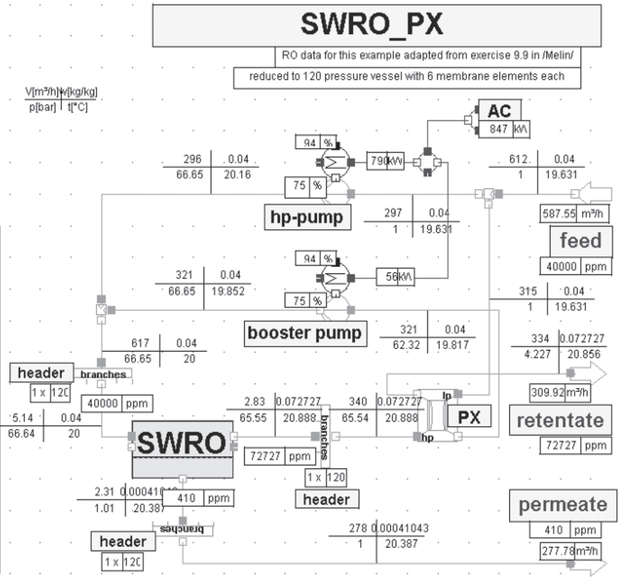

Figure 4. ***IPSEpro*** scheme for basic SWRO system (no pre- and post-treatment considered).

The quality of the power supply and recovery system is specified by the corresponding isentropic, mechanical and electrical efficiencies of pumps and motors. Rather conservative values assumed for these efficiencies lead to the realistic value of about 3.05 kWh/m³ specific energy consumption in the case of the example process shown in Figure 4 for the desalination of sea water of 40000 ppm salinity at a recovery rate of 47.3 %. Hydropower recovery is calculated with 52 % achieved by the pressure exchanger. In case of brackish water for feed the system would include a bypass for the blending of the permeate with saline feed water up to an allowed salinity aiming at a reduction of power consumption.

The modeling of wind energy conversion (WEC) basically includes (Figure 5):

- computation of the wind speed at hub height from values measured at standard height (10 m) or other by the logarithmic wind profile function and
- determination of WEC power output from wind speed at hub height by the power-curve of the engine as given by the manufacturer.

The logarithmic wind profile function considers the roughness height of the surrounding ground surface.

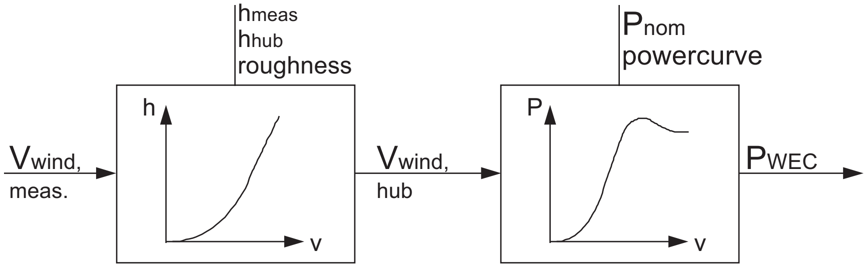

Figure 5. Modeling of Wind Energy Conversion in ***RESYSproDESAL.***

6. System Integration

Developing further the example from the previous paragraph, the basic SWRO system has to be completed with the pre- and post-treatment units, tanks for feed and product and the power supply system. To secure minimum water supply during O&M periods two parallel identical RO streams should be implemented. If renewable energy sources are involved, the power supply is probably an integrated system for the hybrid use of renewable and conventional energy sources (Figure 6).

For the management of the power loads and sources, the balance of plant (BOP) of such a system should include a busbar for the AC power balance. The model unit of the AC-busbar is equipped with connectors for three loads and different power inputs from grid connection, Diesel generator set, Wind energy converter (WEC), and Photovoltaic Generator (PV). Another two connectors are provided for the charging and discharging of an accumulator (ACCU). The purpose of the ACCU may be limited to short term energy storage (for minutes only), mainly to protect a Diesel engine from fast fluctuations of the output from wind energy conversion, or it may be used for the storage of excess output from the renewable energy sources[3].

The system integration example for a daily desalination capacity of 240 m^3 shown in Figure 6 combines the Diesel power station for a village grid with wind energy conversion, including a small capacity ACCU for smoothing power input fluctuations.

In this example similar membrane characteristics as mentioned in Figure 4 are set and process simulation for desalination of sea water with 4 % salinity under nominal operation conditions yields 30 % recovery rate, at a specific power consumption of 3.5 kWh/m^3. The power demand at nominal output of 240 m^3/d is 39 kW. Both the WEC (nominally 200 kW) and the Diesel GenSet (330 kW) are oversized for the task, but design maximum of wind speed is available for only few hours per year and the GenSet is designed to supply up to 300 kW power to the village.

7. Performance Simulation

From involving a randomly non stationary energy source like WEC the need for simulation of time dependent performance arises, either based on classified wind speed hours (Weibull-distribution) or time series of weather data. This is done by linking ***IPSEpro*** via ***PSExcel*** with spread sheet computation in ***RESYSproDESAL***. Parameter values like hourly average of wind speed are transferred from the spread sheet into the IPSEpro project, and the results e.g. the hourly average of WEC power are returned from there into ***RESYSproDESAL***.

Other frequencies of quasi-stationary process simulations are possible and the spread sheet can be employed for further evaluation like daily or annual sums, averages and minimum/maximum values.

The example of energy performance in Figure 7 visualizes the contribution from WEC to a constant power load of 60 kW of a desalination system during a typical day in July. From the 13th to the 19th hour excess power from WEC (up to 51 kW) is supplied to the village. During night and morning power from the Diesel engine is required. These fluctuations are within the part load range acceptable for the 300 kW Diesel GenSet, if the village grid is equipped with load control.

8. An Example from a MENA Country: SWRO+RES in Libya

A good example of a typical application of these tools is the design study and performance analysis done for the General Electricity Company of Libya (GECOL) on a demonstration plant for Sea Water Reverse Osmosis Desalination Powered by Renewable Energy Sources on the Libyan coast of the Mediterranean Sea[4,5]. The technical configuration of the system in principle is shown in Figure 6.

In this case the Integrated Power and Water Point (IPWP) will supply up to 300 m^3/d and 240 kW electricity to a village. For the RO-power demand of 60 kW a 275 kW wind turbine is integrated with a 300 kW Diesel GenSet.

The engineering analysis of this scheme produces all required information like component efficiencies, part load characteristics and specific power consumption of water production. The process simulation for desalination of sea water with 4.3 % salinity under nominal operation conditions yields 57 % recovery rate at a specific energy consumption of

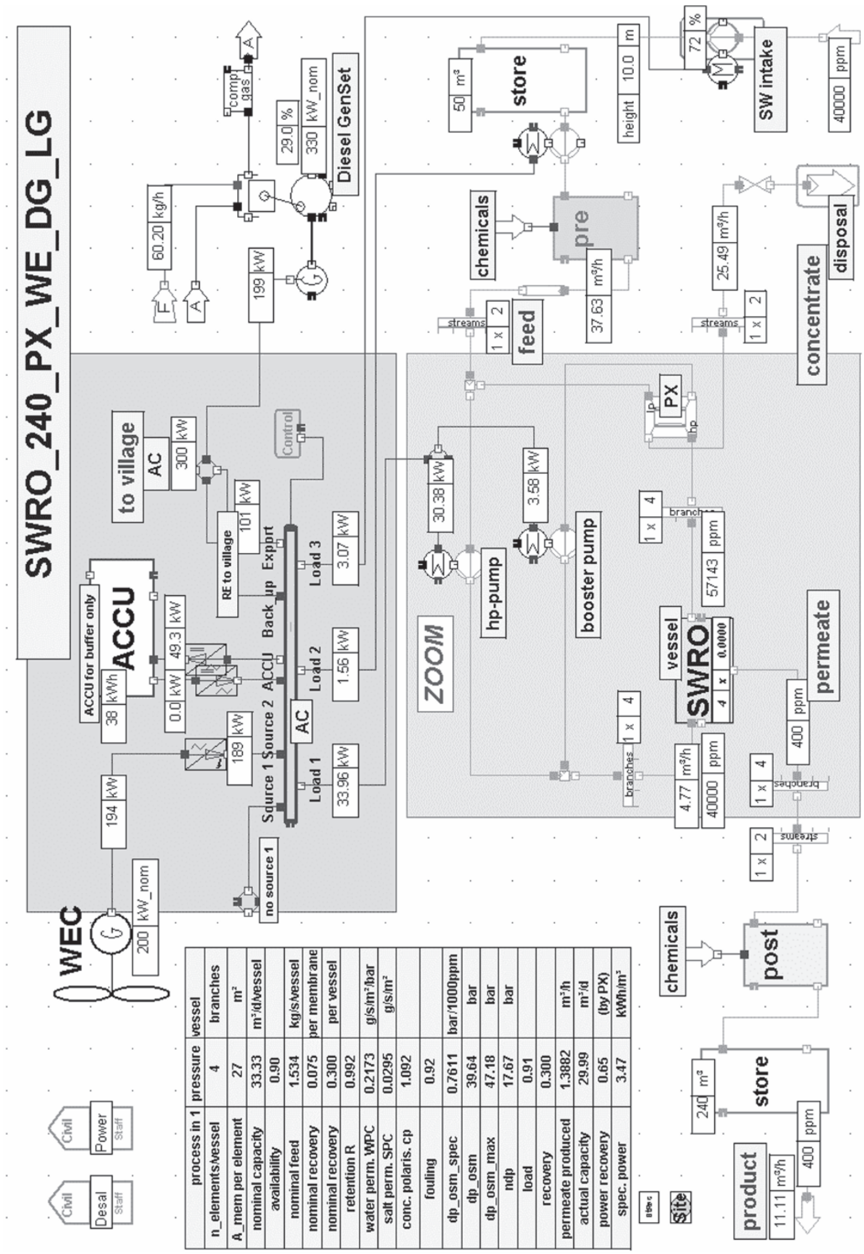

Figure 6. Integration of SWRO with Power Supply from Conventional and Renewable Energy Sources.

	July	21st	31	4848														
hour(s)	t_amb °C	V_Wind m/s	Irradiance kW/m²	WEC P/P0 ---	perm_1 g/s per ves.	perm_2 0	HP_p_1 bar	HP_p_2 bar	sal._1 ppm	recov_1 ---	sal._2 ppm	recov_2 ---	P_RO_tot kW(AC)	P_RO_1 kW(AC)	P_RO_2 kW(AC)	P_aux. kW(AC)	P_PV kW(AC)	P_wind kW(AC)
1	24.6	4.61	0.000	0.13	0.87	0.87	77.07	77.07	376	0.57	376	0.57	60.0	25.8	25.78	8.44	0.00	30.00
2	24.5	4.70	0.000	0.13									60.0	25.8	25.78	8.44	0.00	31.40
3	24.5	4.59	0.000	0.12									60.0	25.8	25.78	8.44	0.00	29.58
4	24.5	4.54	0.000	0.12									60.0	25.8	25.78	8.44	0.00	28.83
5	24.3	4.35	0.000	0.10									60.0	25.8	25.78	8.44	0.00	25.78
6	24.9	4.15	0.014	0.09									60.0	25.8	25.78	8.44	0.00	22.55
7	25.6	4.02	0.080	0.08									60.0	25.8	25.78	8.44	0.00	20.48
8	26.5	4.12	0.258	0.09									60.0	25.8	25.78	8.44	0.00	22.04
9	27.5	4.40	0.454	0.11									60.0	25.8	25.78	8.44	0.00	26.53
10	28.7	4.95	0.644	0.16									60.0	25.8	25.78	8.44	0.00	35.60
11	29.8	5.53	0.792	0.23									60.0	25.8	25.78	8.44	0.00	46.53
12	30.5	6.10	0.881	0.28									60.0	25.8	25.78	8.44	0.00	60.14
13	31.0	6.76	0.910	0.36									60.0	25.8	25.78	8.44	0.00	81.63
14	30.9	7.28	0.823	0.44									60.0	25.8	25.78	8.44	0.00	101.68
15	30.5	7.45	0.720	0.46									60.0	25.8	25.78	8.44	0.00	108.61
16	29.6	7.52	0.584	0.45									60.0	25.8	25.78	8.44	0.00	111.43
17	28.5	7.50	0.425	0.43									60.0	25.8	25.78	8.44	0.00	110.38
18	27.4	7.22	0.244	0.39									60.0	25.8	25.78	8.44	0.00	99.28
19	26.3	6.61	0.075	0.35									60.0	25.8	25.78	8.44	0.00	76.33
20	25.7	5.99	0.000	0.28									60.0	25.8	25.78	8.44	0.00	57.38
21	25.3	5.46	0.000	0.21									60.0	25.8	25.78	8.44	0.00	45.05
22	25.0	4.93	0.000	0.15									60.0	25.8	25.78	8.44	0.00	35.26
23	24.7	4.66	0.000	0.13									60.0	25.8	25.78	8.44	0.00	30.73
24	24.7	4.50	0.000	0.12	0.87	0.87	77.07	77.07	376	0.57	376	0.57	60.0	25.8	25.78	8.44	0.00	28.18
maxima:	31.0	7.5	0.9	0.46	0.87	0.87	77.07	77.07	376	0.57		0.6	60.0	25.8	25.8	8.4	0.0	111.4
daily sum:		132	6.90	5	75	75							1440	619	619	202	0	1265
monthly sum:		4090	214	168	2325	2325							44642	19182	19182	6277	0	39227
unit;fraction:		m/s*h	kWh/m²	---	m³	m³							kWh	0.43	0.43	0.14	**0.00**	**0.88**

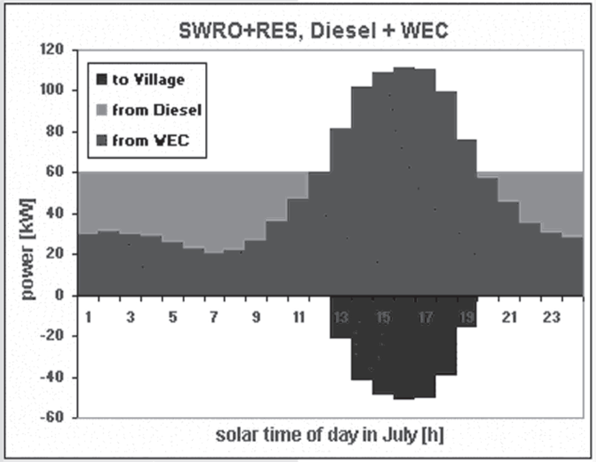

Figure 7. Simulation of power supply performance for typical day in July.

4.8 kWh/m³ (pumping included). The power demand at nominal output of 300 m³/d is 60 kW. Both the WEC (200 kW) and the Diesel GenSet (300 kW) are oversized for the task, but design maximum of wind speed is available for only few hours per year and the GenSet is designed to supply power (240 kW) to the village as well.

With respect to the energy performance of the integrated system the engineer and the water and power producer are looking for

- daily profiles of power supply performance (e.g. diagram inserted Figure 7)
- monthly contributions form renewable and conventional sources to the required energy supply (Figure 8)
- annual fraction of renewable contributions (Figure 8, right bar)

In Figure 8 the power supply to the constant consumption by the desalination process only is balanced with the power supply. The non-stationary demand of the village is absorbing the excess wind energy conversion (as recognized from the example of a day in July in Figure 7). Controlled Diesel power generation is complementing village supply. Here the yearly wind energy fraction of power for RO was predicted at 77%.

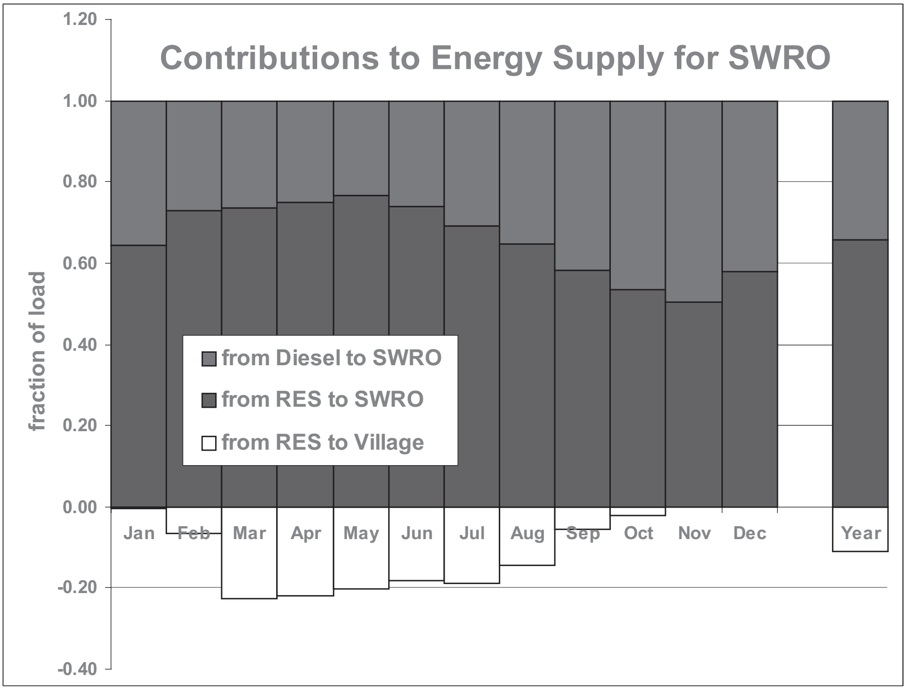

Figure 8. Monthly contributions to energy supply for SWRO.

An economic life cycle analysis is linked to the technical performance prediction, and the computation for specified project (component) life, discount rate, local fuel, and other local economic boundary conditions the computation yields:

- investment cost (global and specific)
- annual O&M cost and cost of consumables (fuel or external power)
- life cycle cost and present value of the project (e.g. in Figure 9)
- levelised electricity cost (for fossil part only as well as for power mix from renewable and fossil sources)
- levelised water cost

The key results finally obtained from the analysis of the example IPWP presented here are (assuming 20 years project life and loan period, 6 % discount rate, 25 €¢/kg opportunity fuel cost assumed):

1,777,000 Euro	total initial investment
245,000 Euro	annual cost of O&M, fuel and consumables
5,039,000 Euro	total present value of total IWPP project
.092 Euro/kWh	levelised electricity cost for power from Diesel GenSet system
.243 Euro/kWh	level. el. cost for power from WEC system
.115 Euro/kWh	level. el. cost for power mix from fossil and renewable sources
2.24 Euro /m³	levelised water cost

For the small system, including more than 50 % energy contribution from a renewable source at a remote site, the levelised water cost of 2.24 Euro/m³ is realistic and affordable.

9. Outlook

Keeping pace with the rapidly growing need for de-centralised supply of water and power to remote settlements and industrial sites in MENA, demands for easy and fast engineering and planning tools for the technical, economic and environmental analysis of integrated systems for water and power, including extensive use of locally available renewable sources. Easily transportable and mountable package system solutions are required with flexible combinations of desalination and power generation processes well adapted to the site conditions and the local resources for material, energy and labour.

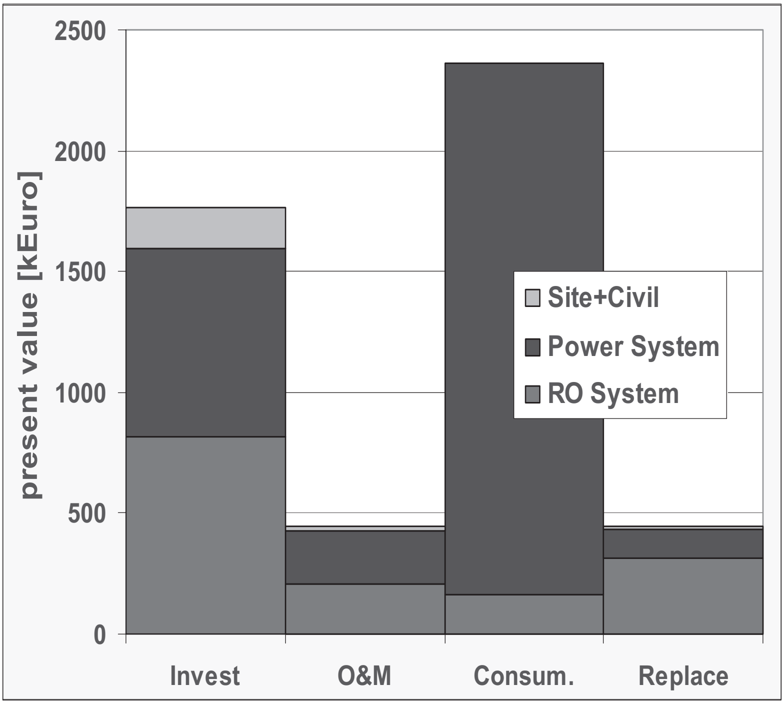

Figure 9. Breakdown of present value for total water and power supply to village.

The flexible systems analysis environment ***RESYSproDESAL*** already thoroughly proven in the field of thermal power engineering, allows us to obtain realistic results in the domain of water desalination when applied to the analysis and planning of integrated water desalination and power generation projects. The engineer and the project developer are supplied with complete information on design, performance, cost and environmental impact. The medium-term goal of software development is the establishing of an expert system service to public authorities and private engineering firms for the quick evaluation of water and power point project feasibility, selection of appropriate technology and optimal design, all under specific site conditions.

For a first glance on the development status and the potential of application of the tool we suggest a visit (free of charge) to the website

www.RESYSpro.net,

where the expert in desalination may study selected examples for elementary plant configurations. Within certain limits the user may here select a site and adjust several parameters in these examples to obtain a technical and economic pre-feasibility result for his project. This may help to compare plant concepts and to do a preliminary selection among suitable technologies. This will save cost and time on the way to a detailed engineering solution by specialists to be contracted for the task later.

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MOROCCAN POTENTIALITIES OF RENEWABLE ENERGY SOURCES FOR WATER DESALINATION

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Abstract. Morocco is characterised by a semi arid climate and the decrease of the available surface water has a strong impact on the renewable resources of ground water. Without additional unconventional water sources, the water deficit will keep growing, even if more dams are built in the future, since they alone will not mobilise more water by capita. The obligation to use other non conventional water resources such as desalinated water or waste water reuse and the need for a more rigorous policy of water management and planning becomes a necessity. However Morocco has a large potential of wind and solar energy sources that could be used in the sea water desalination. The paper presents the experiences of the use of renewable energy sources in desalination in Morocco and an economic analysis of wind powered desalination in the south of Morocco.

Keywords: Desalination; renewable energies; potential; Morocco; economic analysis.

1. Introduction

Morocco is characterised by a semi arid-climate. The average rainfall over the last 60 years was about 150 billion m^3 of which almost 80%

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evaporates. The useful rain, 30 billion m^3, is found as surface water (22.5 billion m^3) and as underground water (7.5 billion m^3).

Moreover the rainfall is characterized by temporal and geographical disparities. It is lower than 300 mm per year in the south and it can exceed 700 mm per year in the north. In five months, the north of Morocco gets 90% of the rainfall, but the south gets a lot less. Some northern regions get up to 2000 mm rainfall per year, whereas some southern regions don't get more than 40 mm per year; fifty times less. Figure 1 gives the annual rainfall average card of Morocco.

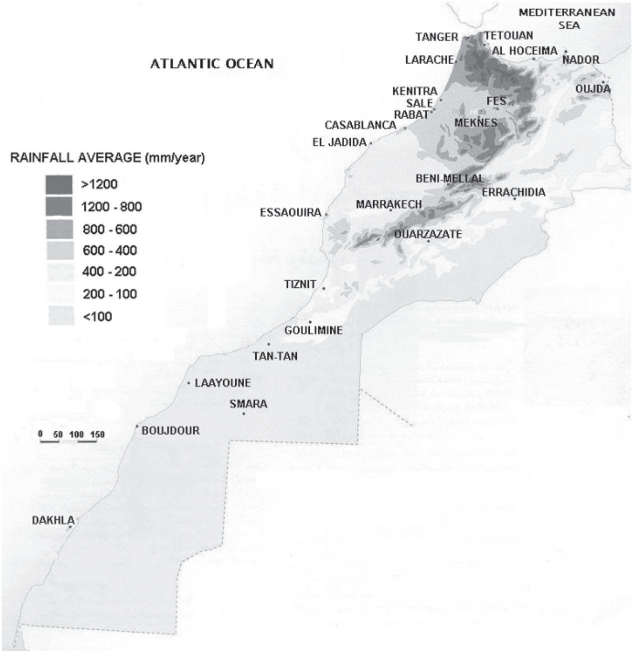

Figure 1. Annual rainfall average card of Morocco (Source: State Secretariat of Environment).

To overcome the temporal and geographical disparities, a policy of construction of dams and the transfer of water to arid regions has been adopted since the 1960's. Today Morocco has about 103 dams for approximately 16 billion m^3. In spite of these efforts, the availability of water decreases with the years. The availability of water was 3500 m^3/capita/year in Morocco in 1960, and 900 m^3/capita/y in 2004. In 2020 it will be just about 500 m^3/capita/year. This is related mainly to the climatic changes and to the dry periods which have occurred regularly for several years leading to a reduction in rainfall of more than 5% and consequently to a reduction in the availability of water of about 20%. The demographic explosion over the last three decades and growing urbanisation due to rural migration because of long periods of drought, together with a long neglectful policy, have greatly contributed to overexploitation and deterioration of water quality. Morocco had more than 80% of rural population just after independence but today it has reduced to only 45%. Intense irrigation and dams silting (which causes a loss equivalent to that of one dam per year) play an important role in the reduction and pollution of water resources.

The policy of careful planning and vigilant management adopted by Morocco since 1980 gave satisfactory results for a few years, but has reached its limits since 2000. Without additional unconventional water sources, the water deficit will keep growing, even if more dams are to be built in the future, as they will not mobilise more water per capita. The use of other non-conventional water resources such as desalination or waste water reuse and the application of a more rigorous policy in water management and planning become necessities.

Desalination has made great progresses in spite of the relatively high cost per cubic meter of produced water. Morocco has access to sea water along a coastline of more than 3500 km and has a big potential of brackish water. Considerable efforts were made in the South with the construction of several desalination plants in particular by the National Office of Potable Water (ONEP) and the Cherifien Office of Phosphates (OCP). The national production capacity by desalination today exceeds 30,000 m^3/day and will increase rapidly. The ONEP continuously launches invitations to tender for the extension of existing installations and for the construction of new installations in the South of the Country. The largest installation of more than 80,000 m^3/d is planned for Agadir town in 2020 (probably before). At the beginning of 2006, OCP started a new installation at Layoune in the south of Morocco with a capacity of 4000 m^3/d. An invitation for the first part of a big new installation (60,000 m^3/d) in the south of Casablanca (Jorf Lasfar) will be tendered in 2006.

However, in spite of the 3500 km of coastline in Morocco, the use of desalination remains limited to the southern regions due to the high energy cost per cubic meter. Indeed desalination remains an intensive energy technology and consequently an expensive alternative process especially for developing countries like Morocco that don’t produce fossil fuels. The increase in oil prices since last year will be disadvantageous for this technology.

The volatility of international energy prices and the increasing concern to regional and global pollution problems has intensified an interest in the application of renewable energy sources for all energy uses, including desalination

As far as renewable energies are concerned, solar and wind sources are among the most viable alternatives to fossil energies. As a matter of fact wind energy has progressed over the last two decades, while solar energy has still many technical and economical problems to overcome before getting to be widely adopted. In this paper, only solar and wind energies will be considered.

2. Renewable Energy Systems for Desalination

Renewable Energy Systems (RES) convert the natural energy source into thermal, electric or mechanical energy. Their applicability and cost depend on local conditions and type of application. In desalination processes the main problem is the coupling of renewable energy sources and desalination technology. The RES are characterised by intermittent and variable intensity; whereas desalination processes are designed for continuous steady state operation.

RES for desalination processes are divided in two main types: "direct methods" and "indirect methods". The former involve a single unit incorporating both the RES and desalination process in one device. It has a single structure and does not require sophisticated technical construction or operation procedure. "Indirect methods" conversely consist of conventional RES and desalination plant kept separated.

A sketch of a simple solar still is reported in Fig. 2.

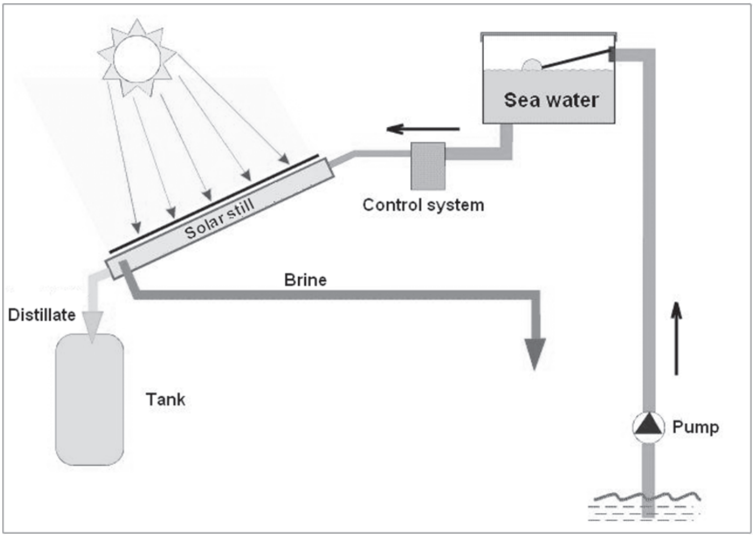

Figure 2. Principle of desalination by solar still.

The direct method uses only solar energy as a renewable energy source. The oldest and most simple device for solar desalination is the solar still:

sea water is pumped into the unit where it is heated by solar irradiation which penetrates the glass or transparent plastic cover. The ascending steam condenses on the cold cover and the distillate runs into a collecting trough. The rate of production is 2 to 5 l/d per square meter of glass surface; the heat consumption is about 1500 kWh/m^3 (700 kWh/m^3 of evaporation heat plus heat losses).

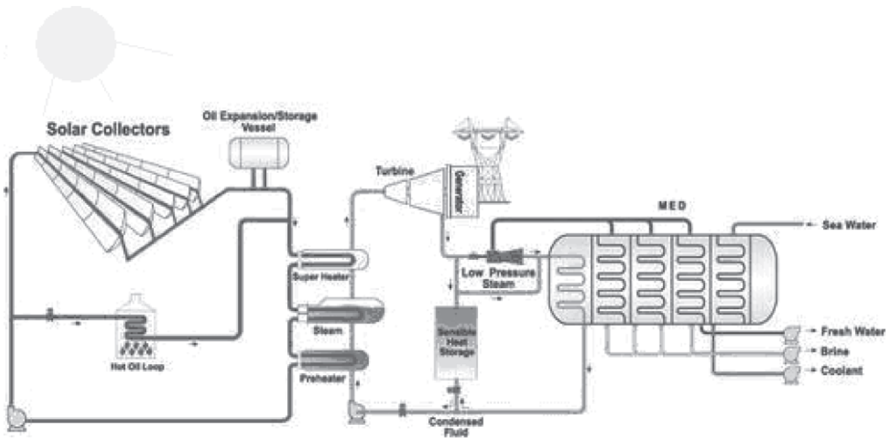

Figure 3. Scheme of a solar field coupled to a MED system.

The more recent indirect methods use thermal or electrical energy.

The thermal indirect methods use solar energy. Solar thermal distillation plants include a field of solar collectors or salinity gradient solar ponds, where a thermal fluid or sea water is heated. The solar field may consist of flat or parabolic trough collectors, according to the desired water temperature.

The distillation unit may be either a multistage flash distillation (MSF) or a multi-effect distillation (MED). There are experimental devices and field units being tested in various locations across the world. An example of Solar MED unit is sketched in Fig. 3.

In the case when renewable energy sources are converted into electricity, the coupling can be made with reverse osmosis, electro-dialysis and mechanical vapour compression desalination processes.

3. Solar and Wind Turbine Technologies for Electricity Production

In small power plants, photovoltaic cells are commonly used to convert solar radiations into electricity. Studies concerning their combination with RO and VC are numerous[1,2] and most of them have been demonstrated[3,4].

However, the continuous high cost per unit of solar power generation limits its use in medium and large-scale power.

The recent progress made in a Dish/Stirling technology[5] opens the field to study its use for sea water desalination. Dish/Stirling systems are small power sets which generate electricity by using direct solar radiation. The system involves two independent technologies, namely the concentration of solar radiation and its use as a heat source in a Stirling engine which serves as prime mover for an electricity generator[5,6]. The Dish/Stirling system basically consists of the following components shown in Figure 4:

- Parabolic solar concentrator,
- Solar heat exchanger (receiver),
- Stirling engine with a generator
- Tracking system.

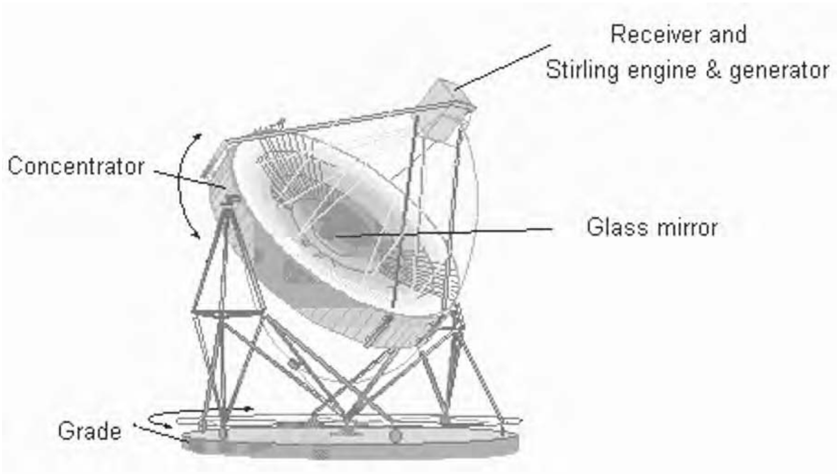

Figure 4. Scheme of a Dish/Stirling system[6].

Compared to the Otto and Diesel internal combustion engines, the Stirling engine depends only on external heat supply, with no preference on the type of heat source (solar energy, thermal waste, external combustion of gas or biomass, etc.)[6]. Hydrogen and helium are both used for heat transfer and working fluid in this kind of system.

For many years, wind energy was considered the least promising renewable energy. However, the situation has changed, and the current technology of wind turbines has today become the world's fastest growing energy source. By the end of the year 2004, a wind capacity of 47,616 MW was operational worldwide.

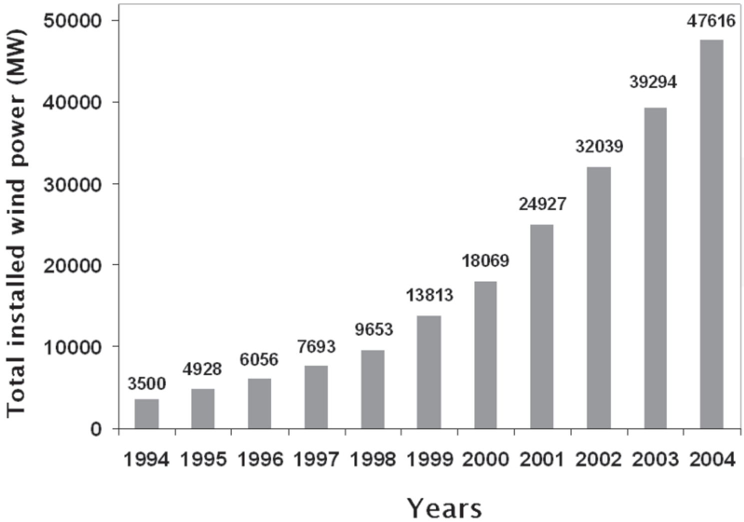

Figure 5. Evolution of the world total installed wind power.

4. Renewable Energy Potential in Morocco

Morocco has a large potential of wind and solar energy sources. The exploitation of these two energies is a very old practice. The exploitation of wind power was started on an industrial scale a few years ago in the North of the Country. Several studies were undertaken to extrapolate these experiments to the regions with important regular wind, especially in the South.

Immense solar potential is well distributed in Morocco throughout the year. But because of the well known constraints, its use was limited to a small scale, particularly domestic use. Several studies are underway in various research laboratories to contribute to the reduction of these constraints.

Solar radiation in Morocco is very high. Figure 6 shows the annual average of daily solar irradiation on a horizontal surface [7].

The assessment of the wind capacity in Morocco is shown in Figure 7, with the location of the largest wind sites, mainly in the north and near the south coast (TanTan, Laâyoune, Dakhla) [8,9]. The average wind speed is over 7 m/s in these areas.

After the first unit was installed in the Tetouan region with a 54 MW wind capacity, it was planned to increase this national capacity nearly six-fold by 2005. New projects totaling 320 MW are slated in the Tangier, Taza, Essaouira and Tarfaya regions [10].

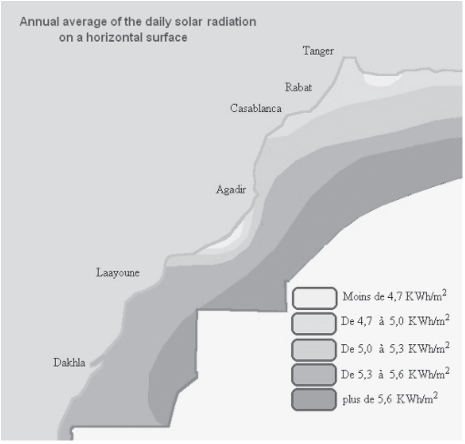

Figure 6. Annual average of the daily solar radiation on a horizontal surface in Morocco[7].

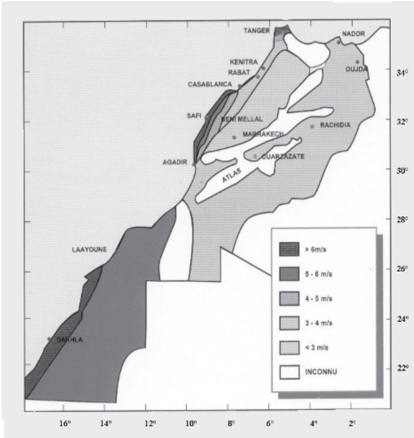

Figure 7. Distribution of the mean wind speed at 9 m above the ground (m/s) [8].

5. Experiences in the Use of Renewable Energy Sources in Desalination in Morocco

In water production, the great use of wind power is for water pumping and generally is limited on a small scale.

However, ONEP has launched a project in the South of the Country for a desalination plant powered by wind turbines. The capacity of the plant will be of 110 l/s and will be achieved in two phases: 70 l/s in 2006 and 40 l/s in 2010. The installed wind power will be 8.5 MW in the first phase and will reach 13.5 MW in the second.

ONEP carried out research in collaboration with national and international organizations on the exploitation of wind power in the production of drinking water especially by desalination.

The use of solar energy in water production remains on a study scale and sometimes on a pilot scale. Most of these studies are carried out exclusively by ONEP in collaboration with research organisms.

An experiment was carried out in the region of Marrakech on the use of solar energy for water pumping. The cost obtained with the use of solar energy was 0.25 €/m^3.

The study by ONEP on the use of solar energy for the desalination of sea water by MSF for a plant of 1500 m^3/d, came to the conclusion that operating and investment costs are far too high. Energy consumption was estimated at 90 kWh/m^3 and the surface of the solar pond at 11000 m^2. The use of solar energy in desalination must be limited to the very small plants.

Other studies were carried out on the use of other forms of energy in the production of drinking water by desalination such as gravitating energy or nuclear energy. The operating and capital costs were generally higher than those of fossil energies.

6. Economic Analysis of Wind Powered Desalination in the South of Morocco

The cost of desalinated water was calculated for three towns in the south of Morocco: Tan-Tan, Laayoune and Dakhla, using the method of Levelized Water Cost (LWC)[11].

The cost was estimated for two sea water desalination processes: reverse osmosis and mechanical vapor compression powered by wind turbines. Electric connection to the grid is available, so that the grid can be used to power the plant when RES are not available. This alternative was then compared to the baseline which consists of the grid-only configuration.

The desalination processes studied in this paper were designed to produce 1,200 m^3 per day of water, the daily consumption of almost 10,000 inhabitant-equivalent. Table 1 gives technical characteristics of the two processes studied desalination.

TABLE 1. Technical characteristics of the two desalination systems

	Reverse Osmosis	**Mechanical Vapour Compression**
Number of desalination units	5	2
Hourly nominal unit water production (m^3/h)	10	25
Daily nominal water production (m^3/d)	1200	1200
Specific energy consumption (sea water) (kWh/m^3)	5	8
Total nominal power (kW)	250	400
Annual energy consumption (MWh/y)	2190	3504
Lifetime (years)	20	20

Depending on the wind potential of a given region, the installed power of wind turbines will be chosen in order to deliver an annual energy production equivalent to the annual energy consumption of the desalination system. ALWIN software was used to determine the expected annual energy yield of a wind turbine based on wind resource assessment[8].

The baseline water cost per cubic meter was evaluated at 0.91 € for the RO and at 1.26 € for the MVC. The taken grid electricity price was 0.08 €/kWh.

Table 2 outlines the estimated water cost for the grid-wind turbine configuration and for the three towns. MVC is the system with the highest LWC both in the baseline and in the alternative due to its high energy consumption. Dakhla has the lowest water cost and Tan-Tan has the highest. Table 3 shows the wind potential of the three towns.

TABLE 2. Alternative water cost and Grid Wind Turbine/Grid Ratio for the three towns

Towns	Water Cost (€/m^3)		Grid Wind Turbine/Grid water cost Ratio	
	Reverse osmosis	Vapour compression	Reverse osmosis	Vapour compression
Tan-Tan	0.83	1.13	0.91	0.89
Laayoune	0.74	0.98	0.81	0.78
Dakhla	0.64	0.82	0.70	0.65

TABLE 3. Wind potential of the three towns.

Towns	Mean annual wind speed (m/s)	Wind speed measurement height (m)	Annual kWh prod. by installed kW*	Required wind installed capacity (kW)	
				RO installation	VC installation
Tan-Tan	5.1[8]	9[8]	2040	1080	1720
Laayoune	5.7[12]	15[12]	2840	780	1240
Dakhla	8.4[12]	10[12]	5180	430	680

*Data obtained by using the ALWIN software.

A typical water cost breakdown, for two towns (Tan-Tan and Dakhla), for the grid-only and the grid-wind turbine configurations is given in figure 8. In the grid-only configuration, the highest share corresponds to electricity consumption for both RO and VC. In the Grid-Wind Turbines configuration, the highest share corresponds to the desalination investment cost for RO and VC in the case of Dakhla. This share decreases from high wind potential region (Dakhla) to a low wind potential one (Tan-Tan). The wind turbine investment cost becomes the highest share for the VC in the case of Tan-Tan (low wind potential region).

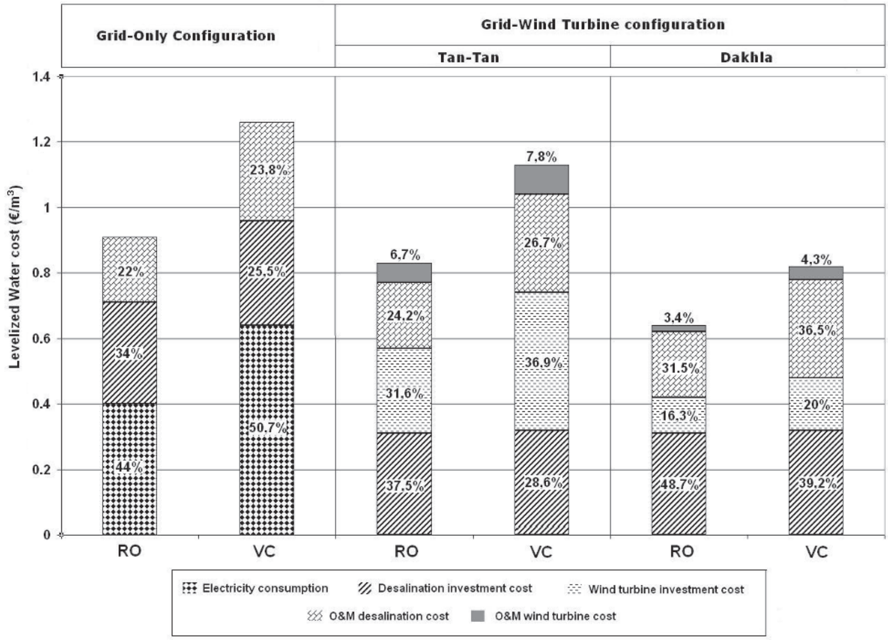

Figure 8. The Levelized Water Cost breakdown.

Two conclusions emerge from this economic analysis study:

- As an energy source, the grid-wind turbine seems to be the most promising solution for the three towns based on the results of the study and on the expected increase of the grid kWh cost and the expected decrease of the wind electricity price.
- As a desalination process, the RO clearly offers the cheapest cubic meter of desalinated water. The energy consumption of MVC still remains high.

7. Conclusion

The interest for renewable energies has become a global strategic priority for all countries. The volatility of international energy prices and the increasing concern about regional and global pollution problems are at the basis of this tendency. As far as renewable energies are concerned, solar and wind sources are among the most viable alternatives to fossil energies.

Morocco has a large potential of wind and solar energy sources. Many efforts are being made towards the development of technologies to use these renewable energy sources. The long coastline of Morocco offers great potential to couple the renewable energy sources and desalination processes to produce drinking water which would be an ideal solution to the decrease in water availability and to the problem of water shortage.

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SOLAR ENERGY UTILISATION OPPORTUNITIES IN BULGARIA

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Abstract. The solar potential of Bulgaria as well as opportunities for its utilisation through both thermal and photovoltaic installations is presented in this paper. The present solar power usage and ideas for energy efficiency and utilisation of renewable energy sources are shown. The fresh water resources of this country are estimated compared with the resources of other European countries and eventual future need of desalination is discussed in the work.

Keywords: solar energy potential, solar energy utilization, fresh water resources.

1. Introduction

There are two main challenges for the world's energy industry as it enters the 21st Century. The first is to meet the expected exponential growth in demand for energy services, in particular in developing countries where today 1.6 billion people do not have access to commercial energy. The second is to deal with the global, regional and local environmental impacts resulting from the supply and use of energy. The future prospect of all forms of energy depends most critically today on two factors - environmental policies, especially with respect to greenhouse gas emissions, and future fossil fuel prices. Overall, it appears that the dominance of the main commercial fossil fuels - oil, gas and coal - will continue for the foreseeable future.

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There has been considerable interest recently in the topic of renewable energy. This is primarily due to concerns about environmental damage (especially acid rain and global warming) resulting from the burning of non-renewable fossil fuels. However, investing in renewable energy is controversial for several reasons. First, not all scientists agree on the degree of environmental damage that can be attributed to fossil fuels. Second, fossil fuels are relatively abundant and cheap energy sources, and have contributed significantly to economic growth. Abandoning inexpensive fossil fuels for more expensive renewable energy sources will have major economic ramifications.

Developing countries represent about 80% of the world's nations, and in general have the highest solar radiation intensity and longest hours of sunshine, one of the most important among natural renewable energy resources (RES). The average daily solar radiation intensity in these countries is 6 kWh/m^2 and the average sunshine is more than 8 h/day, compared with the global average of 2.5 kWh/m^2 and sunshine of 3h/day. But compared with the developed countries, only a few have introduced renewable energy in their national programmes. In most of developing countries the annual budget for RES is lower than 1 million USD.

2. Solar Power Usage

2.1. BASIC FACTS ABOUT SOLAR ENERGY

Solar energy is produced in the core of the sun. In a process called nuclear fusion, the intense heat in the sun causes hydrogen atoms to break apart and fuse together to form helium atoms. A very small amount of mass is lost in this process. This lost matter is emitted into space as radiant energy. Less than 1 percent of this energy reaches the earth, yet it is enough to provide all of the earth's energy needs. The sun's energy travels at the speed of light, almost 300,000 km/s, and reaches the earth in about 8 minutes. Capturing the sun's energy is not easy, since solar energy is spread out over such a large area. The energy a specific land area receives depends on factors such as time of the day, season of the year, cloudiness of the sky, and proximity to the equator.

One primary use of solar energy is home heating. There are two basic kinds of solar heating systems - active and passive. In an active system, special equipment (such as solar collectors) is used to collect and distribute the solar energy. In a passive system, the home is designed to let in large amounts of sunlight. The heat produced from the light is trapped inside. A passive system does not rely on special mechanical equipment.

Another primary use of solar energy is producing electricity. The most familiar way is using photovoltaic (PV) cells, which are used to power toys, calculators, and roadside telephone call boxes. The other primary way to produce electricity is using solar thermal systems. Large collectors concentrate the sunlight onto a receiver to superheat a liquid, which is used to make steam to power electrical generators.

TABLE 1. Advantages and disadvantages of solar energy

Advantages of Solar Energy	Disadvantages of Solar Energy
• Unlimited supply • Causes no air or water pollution	• May not be cost effective • Storage and backup are necessary • Reliability depends on availability of sunlight

2.2. SOLAR ENERGY POTENTIAL OF BULGARIA

The Republic of Bulgaria is a middle-sized South-Eastern European country situated in the centre of the Balkan peninsula with a total territory of 110,994 km^2 (slightly larger than Tennessee) including land area of 110,634 km^2 and water area 360 km^2. It is the oldest surviving state in Europe which has kept its original name, since 681 AD.

Bulgaria has optimum climatic conditions: great solar activity March - October > 7 kWh/m^2 per day and duration of solar lighting > 14 h/day, so the technological possibilities for the utilisation of solar power in this country cannot be neglected (Table 2).

TABLE 2. Solar energy resources of Bulgaria

Region	Average duration of solar lighting, March - October, h	Average duration, October - March, h	Annual resource, $kWh/m^2.y$
Central-East	< 1640	< 400	1450
North-East	up to 1750	400-500	1500
South-East, South-West	> 1750	> 500	1550

Bulgaria is located at the upper border of the so-called "solar belt" of the world. As a result the total annual solar intensity in the capital of this Country, Sofia, is equivalent to the solar intensity of Madrid, Spain[1], and similar to those in Athens, Greece, and in Sicily, Italy (Figures 1, 2).

Figure 1. Solar energy potential of Bulgaria.

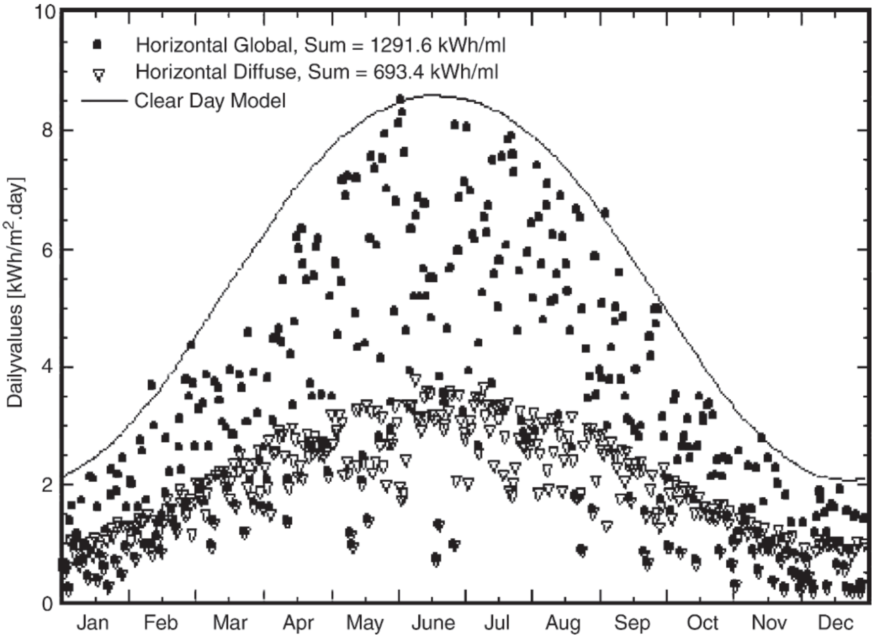

Figure 2. Meteorological data for Sofia.

Depending on the duration of the solar shining and the total annual or monthly solar radiation received on 1 m^2 horizontal surface of the country[2], the territory of Bulgaria could be conditionally separated into three zones (Figure 3), namely:

Zone A - encompassed regions in South-East (SE) Bulgaria, part of the South Black Sea coast region, the rivers Struma, Mesta and Maritza valley. The duration of the solar shining here is over 2,200 h/y and the total solar radiation received on horizontal surface is over 1,500 kWh/ m^2 per year.

Zone B - included regions in the Danube River plain, Dobrudja region, Trace lowland, small part of South-West Bulgaria and Stara Planina mountain regions. The duration of the solar shining in this zone varies from 2,000 to 2,200 h/y and the summed up solar radiation received on horizontal surface varies from 1,450 to 1,500 kWh/ m^2 per year.

Zone C - covers the remaining part of the country territory but mainly its mountains, where the duration of the solar shining is less than 2,000 h/y and the summed up solar radiation received on horizontal surface is less than 1,450 kWh/ m^2 per year.

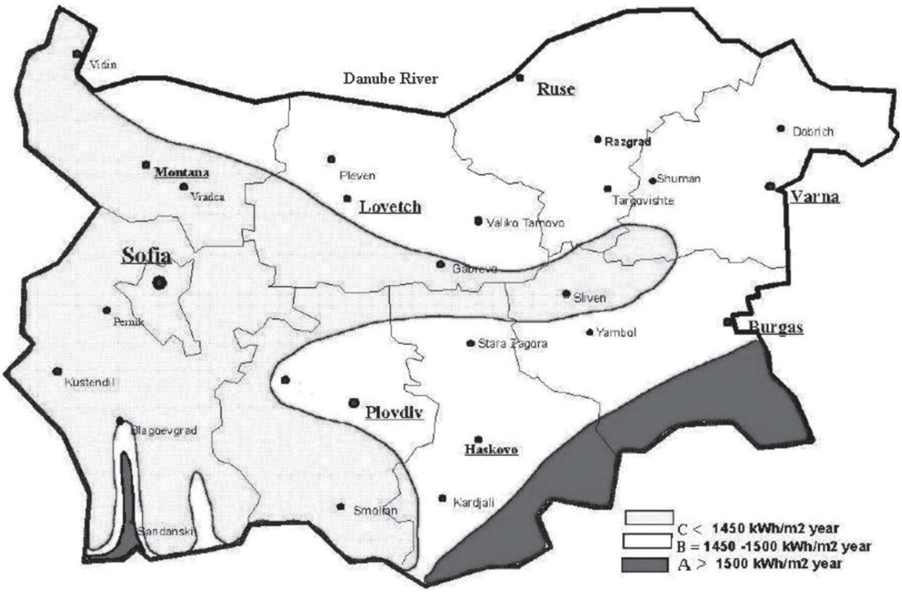

Figure 3. Theoretical Solar Energy Potential of Bulgaria.

2.3. SOLAR ENERGY UTILISATION IN BULGARIA

The main users of solar energy in Bulgaria are solar thermal systems for hot water of residential, public and agricultural objects, passive solar systems for heating, systems for drying of wood material and agricultural products. Electrical production by thermal transforming of solar energy has no potential application at the moment. At present other applications of solar energy such as solar cooling, solar pools[3], desalination and decomposition of water are only theoretical due to the particular conditions of this country.

Many research matters carried out in Bulgaria[4,5] show that the most effective method for solar heating in buildings is applying passive solar systems. Technical, economic, social and environmental analyses, conducted over the past decade support this attitude. The major impediments to increasing market penetration of passive solar systems are a long pay back period (10- 15 years) and a lack of available information and experience data. Conventional economic analysis, on the other hand, would be distorted if we do not take into account some additional conditions: the hidden environmental and health costs associated with fossil fuels (generally they do not include these costs in energy prices); subsidies of many conventional energy carriers[6]; long life time of passive solar systems (50 years and more) and a large economic, environmental and social effect in a use phase. Therefore, passive solar systems have some special advantages as a solar technology and for purposes of space heating these may have significant potential.

Two predominant approaches of passive solar heating are in using - indirect and direct gain systems. All other categories are subsets within these two approaches. The direct gain systems use a transparent wall to allow solar radiation to enter the space requiring heating[7-9]. The indirect gain systems combine the function of collector and storage as a part of building structure.

At present in Bulgaria there are 20 MW heat power capacity by solar thermal installations and there are no PV installations except for a few research/demo versions, like the example in the South-Western University in Blagoevgrad (Figure 4), in the Bulgarian Academy of Sciences, etc.

Solar heating technology is almost fully mature. Considerable increase in solar thermal collectors is also expected. Solar heating is competitive compared to electrical water heating. The passive usage of solar power could have the main share in decreasing the usage of power for heating and cooling in buildings.

Energy consumption in the household and services sectors could be considerably decreased by improving the general energy intensity and by widespread usage of RES, mainly solar energy in renovated (maintained) or in brand new constructed buildings. It is important to take a global approach and to unite the measures for rational usage of energy (building casing, heating, illumination, and air conditioning and cooling) when using RES technologies.

Generation of electric power from solar PV is one of the contemporary super-modern renewable power technologies. Solar PV, in spite of rapidly decreasing prices, remains very dependent on preferential conditions.

Figure 4. Solar PV and thermal collectors on the roof of the South-Western University “Neofit Rilsky” in Blagoevgrad, Bulgaria.

The idea for decentralized power generation, using PV electrical systems, is very interesting. The reduced losses from power transmissions, as well as the preservation of the environmental status will be a decisive argument for their economic efficiency.

2.4. DEMO SOLAR PROJECTS IN BULGARIA

The main part of the installed PV solar systems is the result of demo projects financed by the EU through the programmes Copernicus, Tempus, Phare, etc.:

- 1.5 kW grid-connected PV system and a thermal solar system with heat
- accumulator tank (Figure 5) in the Laboratory for Alternative Energy Sources of the South-Western University "Neofit Rilsky" in Blagoevgrad.

- 1.5 kW PV system for pumping out of water and 10 kW grid-connected PV system (in construction) in the Central Laboratory for Solar Energy and New Energy Sources at the Bulgarian Academy of Sciences.
- 3 kW PV system in the Education Centre for Renewable Energy Sources at the University of mining and geology in Sofia.
- A demo version hybrid system in the Technical Universities in Sofia and Varna.
- 10 kW grid-connected PV system (in construction) in the Technical University, Gabrovo.

In most of these installations monitoring and data collection for system working in the climatic conditions of Bulgaria is carrying out.

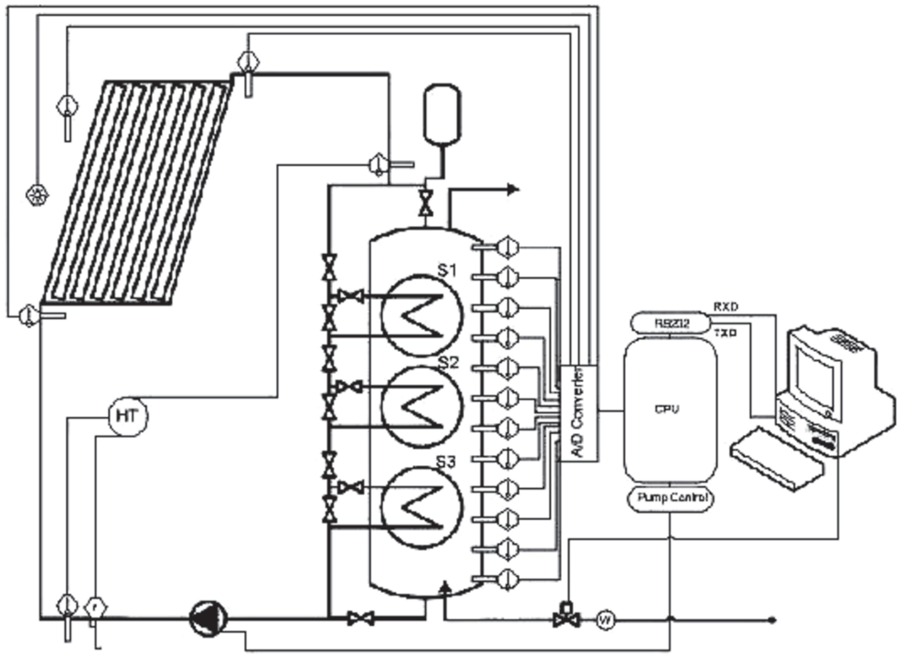

Figure 5. Sketch of the solar thermal system and heat accumulator tank with stratified layers supplied electrically by the PV system at the SWU "Neofit Rlisky" in Blagoevgrad, Bulgaria.

Besides these demo-version systems other solar systems operate in Bulgaria, including:

- 0.48 kW autonomous lighting in the social homes for orphan children in Mezdra and Stara Zagora.
- 0.50 kW autonomous supply for the meteorological station on the Mourgash peak.
- 0.50 kW autonomous supply for the hut Mourgash.
- reserve supply for the meteorological station on the Moussala and Cherni Vrah peaks.

Altogether there are about 32 kW in total PV solar systems, 20 kW of which are grid-connected, operating in Bulgaria.

Figure 6 presents the installed PV capacities in different former socialist Central/East European countries. As can be seen Bulgaria occupies a middle place but, because it is in the most southwest position, it shows a serious backwardness in the amount of installed PV systems.

The market of solar thermal systems (collectors) in Bulgaria is estimated about 5,000 m^2/year which is considered a good rate. There are a number of firms that import such systems, as well as a small Bulgarian manufacture. The price of the Bulgarian thermal collectors is about 100 - 150 EUR/m^2 and 250 - 310 EUR/m^2 for complete mounted system. Thermal collectors are used mostly to equip private homes and some public buildings, for example the hostel for adults in Plovdiv, the hospital in Triavna, etc. Particularly important at this stage is the correct design, mounting and maintenance of the solar thermal systems in order to avoid discrediting the idea of applying these systems.

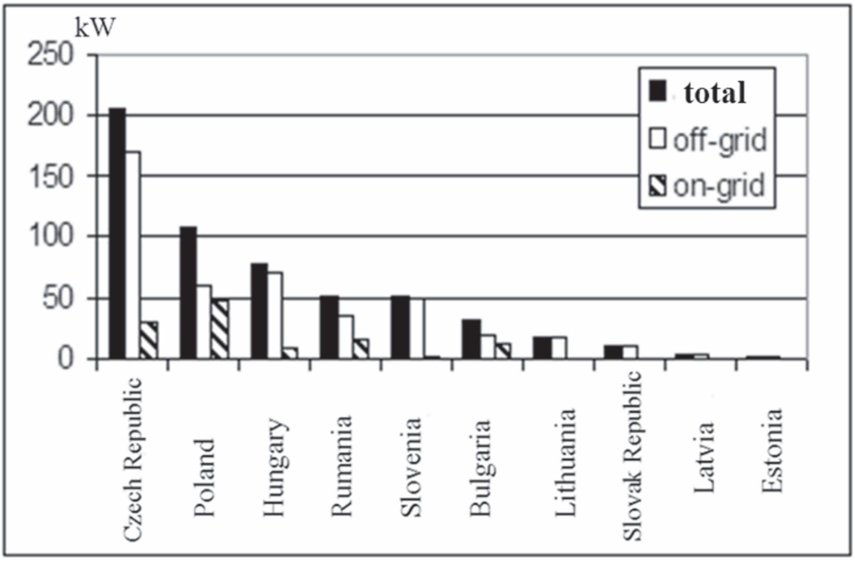

Figure 6. Installed PV systems in some Central/East European countries.

3. Fresh Water Resources in Bulgaria

Bulgarian fresh water resources in 2003 were 19,433 million cubic meters (a long-term average annual value for the period 1961-1998) or 2,484 cubic meters per person, which is higher than Denmark, Belgium, Czech Republic and Poland, but considerably less than the average level of Europe- 4,000 cubic meters per person. The fresh water extraction was 3,341 million cubic meters (excluding the Danube waters) and as a result the intensity of water use increased to 17.2 % in 2003.

Surface fresh waters are the main source in Bulgaria (average 91.8 % of fresh water derived for the period 1999-2003). Water derived from underground water sources showed stable tendency to decrease (467 millions cubic meters in 2003, which is 80% of total in 1999 and 32% in 1991).

The population with public water supply was 98.8% of total population in 2003 (100% of urban population and 96% of rural population). The water consumed by households is 95 litres – average per person for twenty-four-hour period in 2003 (99 litres per person in towns and 13 litres less in villages), which is 58% less than the member countries of EU (15) – 150 litres per person per day. The South-West region has the biggest water consumption - 123 litres, the North-East region -the smallest one- 79 litres per person as a result of the different price of water, respectively 0.26 EUR/m^3 and 0.59 EUR/m^3 (incl. VAT). The water for households in Sofia is cheapest (0.25 EUR/ m^3), where biggest consumption is registered - 147 litres per person per day.

The analysis of water consumption in economic sectors shows that 78% of used water in the period 1999 - 2003 was for cooling in the process of energy production and 70% of the cooling water returned into surface water sources after use.

The average annual water consumption for agricultural needs was 3% and for household purposes 7% of water used during the same period. The water used for irrigation was 173 million m^3, which was 76% more than 1999, but 14 times less than 1991. The used waters in 2003 (5,809 million cubic meters) were at the same level as 1999, but totalled 68% of the waters used in 1991.

The total volume of discharged waste waters during the period 1999 - 2002 is estimated between 746 and 955 million cubic meters, 64% of which is treated in industrial and other waste water treatment plants. There is an increase in the volume of the waste water discharged (1,194 million cubic meters), which is accompanied increased relative share of treated waters - 79.6 %.

The expenditure on protection of waters is 91 million EURs, which is 26 million EURs more than 1999. Its relative share in the total ecological expenditure also increases from 28.6% in 1999 to 31.2% in 2003.

As there is no need for desalination in Bulgaria no scientific or innovation activities in this field are being developed in this country. However the ever increasing fresh water shortage on a global scale and its rising prices may be a problem that Bulgarian society will have to face in the near future.

4. Ideas and Opportunities for Energy Efficiency and RES Utilisation in Bulgaria

Energy efficiency (EE) and the utilisation of RES is one of the government's priorities. It is unthinkable Bulgarian accession to the EU with an energy intensive economy and without increasing of the share of energy generation on RES.

In the 1970s and early 1980s, there was great national interest in energy policy and energy conservation. This was primarily due to the huge increase in the price of oil, caused by reductions in oil supplies as a result of the OPEC oil embargo in 1973 and the Iranian hostage crisis in 1979. The higher price for oil spurred private and governmental development towards renewable energy sources such as solar power, wind, geothermal, and biomass. In the late 1980s however, the national commitment to renewable energy waned as the price of oil plummeted. Neither the government, nor consumers, was willing to invest in more costly renewable energy sources and programs when non-renewable fossil fuels were so inexpensive.

In recent years, there has been a greater interest in the issue of energy, especially renewable energy. This interest is not the result of rapidly increasing energy prices - non-renewable energy, including oil, is abundant and relatively inexpensive. Renewed interest is the result of growing environmental concerns, like the burning of fossil fuels, which many believe contributes significantly to acid rain and global warming.

Public policy issues involving energy have tremendous economic implications. To ensure wise public policy, citizens and decision-makers must not only understand basic facts about energy sources, but must also know how to apply basic economic concepts in their analysis of energy issues.

EE and the utilisation of RES policy is a state policy. It is vitally important for this country and its purpose is:

- Help for the sustainable economic development of the country regarding the decreasing of energy intensity of the GDP by different EE measures and by putting high technologies for efficient power and RES usage into practice.

- Help for improvement and protection of the environment with popularization and construction of alternative ecological energy sources, which allow suitable treatment of different kinds of waste and lead to decrease in harmful emissions in the atmosphere.
- Help for improvement in the energy independence of the country and the creation of conditions for market oriented relations in the energy sector.

The main aspect in the country common energy policy is aimed at the securing of sustainable energy development, energy security in Bulgaria and a guaranteed secure supply of energy users at minimal costs. Also important is the rational and efficient utilisation of the fuels and energy in the whole cycle “generation - end usage”.

Bulgaria has the lowest GDP per capita and the highest specific usage of power per unit of GDP in comparison with the rest of the countries applying for EU membership. That indicator is an important element in the EE and on it depend the competitiveness of our goods and of Bulgarian economy as a whole.

The unenviable position of the EE has to be searched in the low culture of the Bulgarians with regards to the energy saving, determined mostly with the low life style of the most of the population. Surely we may say that a high general culture of the Bulgarians would mean also high culture with respect to the energy saving, because energy saving is directly linked to lower heating, electricity for hot and cold water bills.

Although considerable results for energy saving could be achieved at the primary applying of ordinary and cheap measures, they are also unaffordable for the mass Bulgarian. Energy saving measures as replacement of heating and illumination bodies, water blends or installation of measuring appliances for regulation or heat insulation is estimated to several average salaries. The society as a whole is not in condition for a year only to overcome the negatives of the past and the present which defines the extreme importance of the state, municipal, public and non-governmental structures for easing of the hard situation in the country. That could be achieved simultaneously with the world and European best practices for maximum environmental and energy protection and for introduction of the new and renewable energy sources.

5. Conclusions

The following basic conclusions were reached as a result of this work:

1. Bulgaria has good natural resources in the area of renewable energy sources, in particular in the area of solar energy utilisation.
2. In Bulgaria there is well educated and experienced scientific potential, enough scientific institutions and scientific knowledge as well as industrial capacity for the utilisation of certain kinds of renewable energies.
3. At the moment desalination, especially using solar energy for this purpose, as technology is not developed in Bulgaria. But such modern technology will be needed in the near future.
4. The utilisation of renewable energy resources now depends on the goodwill of the authorities to fill their proper place in a modern Bulgarian economy.

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SOLAR WATER DESALINATION IN THE ARAL SEA REGION

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Abstract. The efficacy of desalination device based on using direct osmosis method has been examined. The device with productivity of 1 m^3/hr consists of solar batteries with power of 500 W, water pretreatment unit on the base of fibroid sorbents, water disinfection device with specific power consumption of 0,1 Wh/m^3 and desalination device with power of 450 W. Due to the financial support of UNESCO in March, 2005 the pilot device with productivity of 1 m^3/hr was installed in Turtkul village of Aral Sea Region to remove salts from brackish water with a total concentration of about 17 g/l.

Keywords: direct osmosis; solar desalination; water hardness; oligodynamic method

1. Introduction

The question of population access to secure drinking water is critical in republics located in Aral Sea Region, and Uzbekistan is a showcase of this problem being a) the region's most populous country and b) having some of the worst quality of ground water (salt and mineral concentration, concentration of bacteria generally wildly exceeding maximum allowed levels). At least 35% of the population is currently drinking water that does not meet national quality standards, and 86% that is not up to international standards.

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Most of remote rural areas of Uzbekistan do not have access to electricity; therefore usage of solar energy for powering various water treatment devices[1] seems to be a very perspective trend.

There are many water desalination methods, such as distillation, electrodialysis, reverse osmosis, freeze desalination etc. Unfortunately these methods are not wide-spread in Uzbekistan due to the large amount of energy and/or the high cost required to realize and use them. One of the main weak points of using such methods in Uzbekistan is the need of high-qualified personnel to serve water purification systems that is unacceptable in small towns and villages.

The purpose of this work was to develop new low-energy consuming water desalination method using solar cells as an energy source and based on direct osmosis process.

2. Principle of the Method

To describe developed water desalination method based on direct osmosis process let us suppose that in section A (see Fig. 1) there is a liquid (the feed) containing solvent (water) and solubles (inorganic salts with concentration of dissociated ions C_a). Let us suppose that in section B there is a water solution of certain substance with initial concentration C_b. Let us call them as working fluid (WF) and working substance (WS) respectively. Let us also suppose that $C_a << C_b$. Then in order to equilibrate the difference in chemical potential, osmosis movement starts, i.e. water begins to diffuse through the membrane from section A to section B. In other words in section B WS water solution is diluted by clean water pulled out from section A. Then in section C clean water is expected to be pulled out of WS water solution using special separation process.

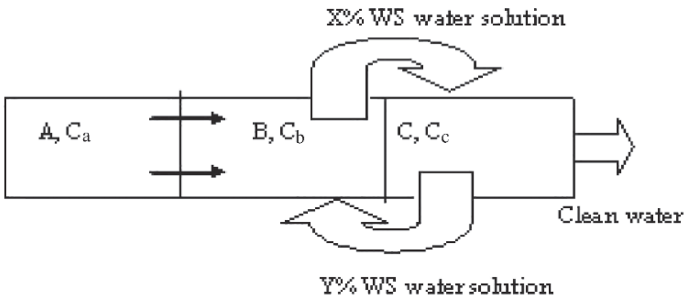

Figure 1. Principle of operation of direct osmosis desalination method (here Y>X).

The main problem of this water treatment method is in selection of WS (working substance).

The simplest and the most accessible methods of separation of water from working substance in section C are evaporation and freezing. Some materials that might be utilized as WS are given in Table 1

TABLE 1. Examples of materials can be used as a working substance

Type of working substance	Name	Specifications (t_{bp} - boiling point; t_f - fusing point)	How to use
Alcohol	Ethanol	t_{bp} = 78,39 °C	w.s. evaporation
	Glycerin	t_f = 20 °C	w.s. freezing
Ethers	Diethyl ether	t_{bp} = 35,6 °C	water freezing or w.s. evaporation
Amines	Ethylamine	t_{bp} = 16,6 °C	w.s. evaporation
	Trimethylamine	t_{bp} = 3,5 °C	w.s. evaporation
	Diethylamine	t_{bp} = 56,3 °C	w.s. evaporation
	Methylamine	t_{bp} = -6,5 °C (Methylamine gas is highly soluble in water)	w.s. evaporation
Ketones	Acetone	t_{bp} = 56,24 °C	w.s. evaporation

3. Materials and Equipment

In our experiments we used diethyl ether $(C_2H_5)_2O$ as the working substance and RE-1812-LP reverse osmotic membrane produced by SAEHAN Inc (South Korea) as the semi-permeable membrane for direct osmosis process. Solar batteries of 12 V with a total power of 500 W produced by Physical-Technical Institute (Tashkent, Uzbekistan) were used as an energy source (see Fig. 2). Ion-exchange fibroid sorbents developed in the Institute of Nuclear Physics of Academy of Sciences of Republic of Uzbekistan were used to remove salts of hardness and ions of iron. The chemical process of making fibroid cation-exchange sorbents[2] consists of treatment of polyacrylonitrile (PAN) cloth by a solutions of $NH_2NH_2 \cdot H_2O$ and NaOH. The specific surface of the fibroid sorbents is $(2 – 3) \cdot 10^4$ m^2/kg and exchange capacity is 3.5 - 4.0 meq/g. Water disinfection device based on oligodynamic method developed in the Institute of Nuclear Physics was used to kill bacteria to prevent destruction of semi-permeable membrane and prevent water contamination in emergency situations[3]. The device provides killing all types of pathogens in water and has very low specific power consumption of 0,1 Wh/m^3 (see Fig. 3).

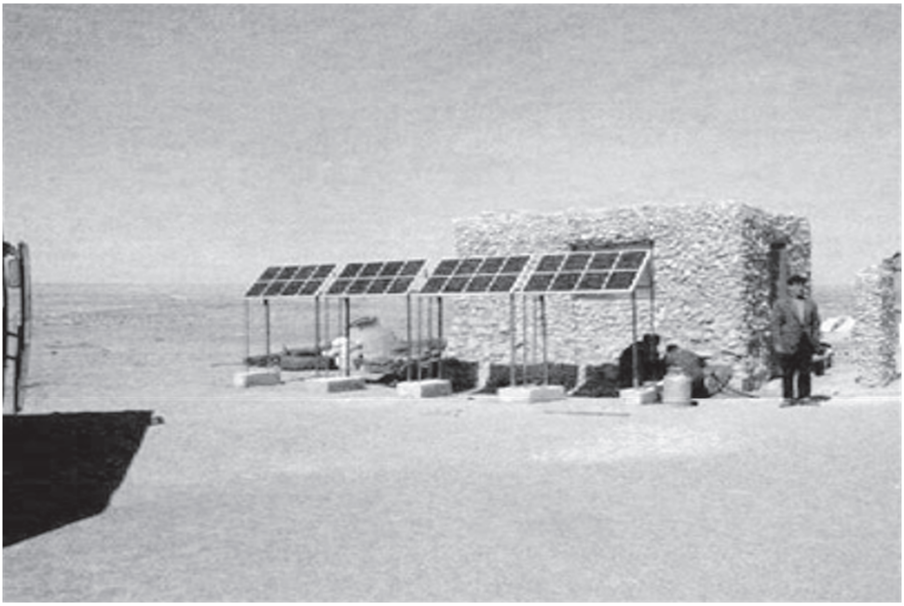

Figure 2. Solar batteries for experimental device installed in Aral Sea Region.

Figure 3. Water disinfecting device used for water pre-treatment.

The experimental water desalination device was constructed as shown in Fig. 4. Vessel with 80 liters of NaCl solution was allocated at height of 0.5 m to exert a hydrostatic feed pressure of 5 kPa on a semi-permeable membrane 2 lacking the capacity to diffuse anything other than water molecules. The flow rate was regulated by flow controller 10. On the other side of membrane 2 there was a working liquid: water solution of diethyl ether $(C_2H_5)_2O$ having boiling point of 35,6 ^oC and water solubility of 100 ml/l at 16 ^oC.

Then permeate (working liquid with clean water pulled out through the membrane 2) was divided into two parts by means of flow dividing valve 3. Then the most part of permeate came through the semi-permeable membrane by means of pump 4 with power of 75 W while the smaller part of permeate came in flashbox 6 having electrical heater with power of 100-400 W holding the temperature at 38-40 ^oC. As a result evaporating diethyl ether was pulled out from clean water.

Then clean water came in accumulator tank 8 whereas diethyl ether gas came in condenser 7, cooled by water 9. After that condensed diethyl ether was pulled out to the flow of working liquid by the ejector 5 reconcentrating the diethyl ether water solution for repeated use in section 2.

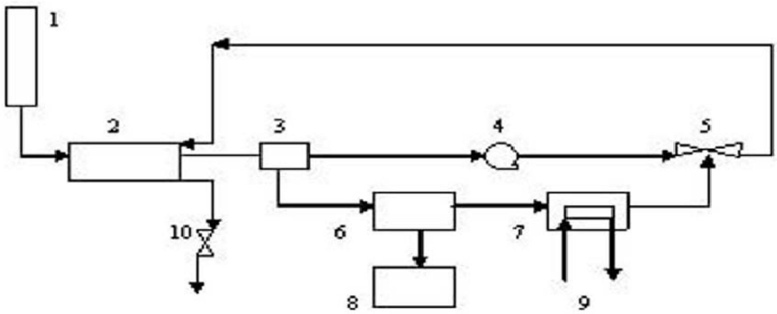

Figure 4. 1 - Vessel with NaCl water solution, 2- RO membrane, 3 - flow dividing valve, 4 pump, 5 - ejector, 6 - flashbox, 7- condenser, 8 - accumulator tank, 9 - cooling water, 10 - flow controller of feed water.

4. Results and Discussion

In our experiments we used diethyl ether $(C_2H_5)_2O$ as the working substance. Test results using the experimental laboratory device for feed water of different salinity are given in Table 2.

TABLE 2. Test results of the laboratory experimental device

Initial concentration of NaCl, g/l	P_f, MPa	Recovery (relation of permeate flowrate and feed flowrate)	Rotating flow rate of working substance, liters/h	Working liquid part by volume going for water separation	Clean water outbound, liters/h	Power of heater, W	Final concentration of NaCl, mg/l
1	-	0.1	60	0.05	25	100	<10
	1.96			0.1	53	250	
			300	0.01	25	100	
				0.02	52	250	
		0.5	60	0.05	25	100	
				0.1	53	250	
			300	0.05	25	100	
				0.1	52	250	
4	-	0.1	60	0.05	25	100	<10
	1.75			0.1	53	250	
			300	0.01	25	100	
				0.02	52	250	
		0.5	60	0.05	25	100	
				0.1	53	250	
			300	0.05	25	100	
				0.1	52	250	
20	-	0.1	60	0.05	31	130	<10
	0.04			0.1	-	250[1]	
			300	0.01	31	130	
				0.02	-	250[1]	
		0.5	60	0.05	31	130	
				0.1	-	250[1]	
			300	0.01	31	130	
				0.02	-	250[1]	

[1] The process stops soon because of reducing of water concentration in the working liquid.

Estimated value of osmotic pressure of our working liquid (100 ml/l $(C_2H_5)_2O$ water solution) is 2.35 MPa. Meanwhile for instance, 4 g/l NaCl water solution (with degree of dissociation of 0.44) has osmotic pressure of 0.39 MPa. Thus the difference in osmotic pressure was always large enough, i.e there was self-sustaining osmotic movement without necessity of usage energy-consuming pumps in contrast to reverse osmosis water treatment method. In our experimental device energy was consumed mainly at the stage of separation WS from the water (about 400 W) and for WS circulation in the constructed experimental model by the pump (about 75 W) to reach the output of 1 m^3 of clean water per hour.

Due to the financial support of UNESCO in March, 2005 the pilot device with productivity of 1 m^3/hr was installed in Turtkul village of Aral Sea Region (Fig. 5).

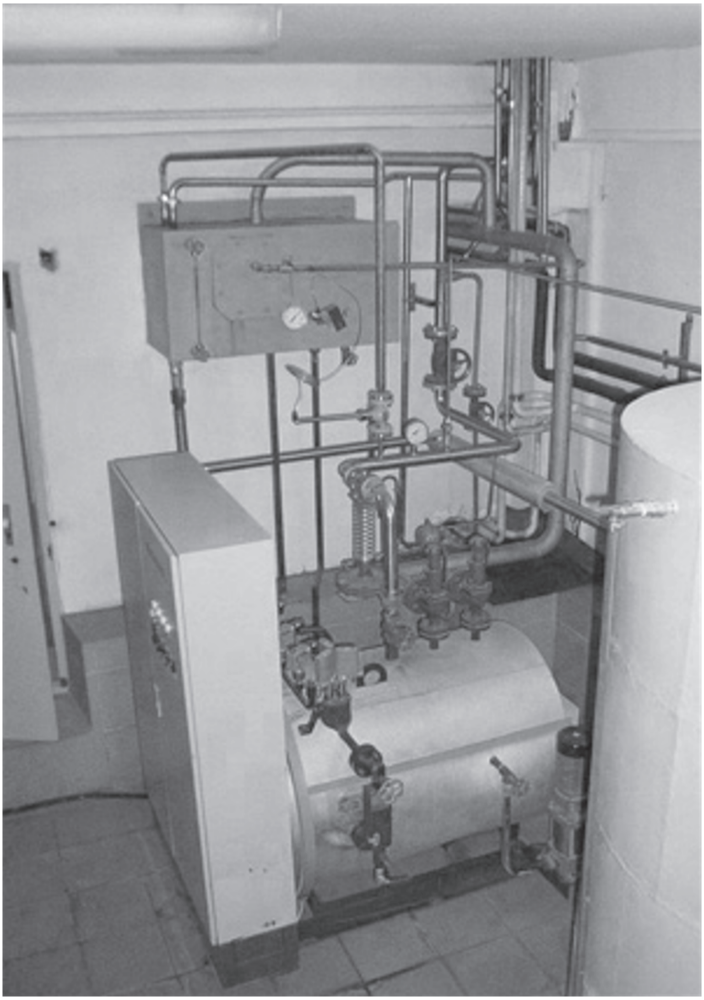

Figure 5. Pilot device installed in Turtkul village of Aral Sea Region.

Test results of the device are shown in Table 3. The device consists of solar batteries with power of 500 W, water pretreatment unit on the base of fibroid sorbents, water disinfection device with specific power consumption of 0,1 W-h/m^3 and desalination device with power of 450 W. Total concentration of salts in initial brackish water was about 17 g/l. It is significant that the energy consumption of the device can be decreased by changing of the electrical heater on a solar heater.

Our experiments have shown the following advantages of the proposed technique: a) the method does not require a high pressure pump to push water through the membrane; b) electric energy consumption of the method is very low (0.5 kWh/m^3 in comparison with 2-5 kWh/m^3 for reverse osmosis desalination) when solar energy or heat of ambient air are used to heat the water up to 36-40°C; c) surface area of the solar heat exchanger of the device is 3 – 30 times less than that of solar thermal desalination process because of lower solar energy consumption (80 MJ/m^3 in comparison with 2,500 MJ/m^3 for solar thermal desalination process without energy recovery and 250-500 MJ/m^3 with energy recovery); d) the method can be used for desalination of water with salt concentrations up to 40 g/l; e) since the disinfecting device is used in water pretreatment process the water keeps disinfecting properties for a long time (not less than 1 year) and water produced in hot time can be stored in water storage systems for cold seasons. Membrane scaling or fouling in the pilot device have been prevented by using ion exchange fibroid water filters to remove salts of hardness and iron ions and water disinfection device to kill bacteria.

TABLE 3. Purification of water sample taken from Aral Sea region

Items	Influent water, mg/l	Effluent water, mg/l
pH (at 25°C)	6.7	6.7
Ca	560	1.2
Mg	400	1.6
Cl	4590	0.7
NO_3	300	<0.02
SO_4	3825	0.8
Na	3300	2.3
K	1200	1.6

5. Conclusion

The test results obtained demonstrate the efficacy of the water desalination device based on direct osmosis method. The devices utilizing solar batteries as an energy source can be used for desalination of water in remote regions.

The energy consumption of the device can be decreased by changing of the electrical heater on a solar heater.

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STATUS AND PROSPECTS FOR SOLAR DESALINATION IN THE MENA REGION

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Abstract. Desalination has become one of the water supply sources in most of the countries in the Middle East and North Africa region. All MENA countries lie in the Sunbelt region and have the space needed for solar technologies. However, utilization of solar energy in desalination is still limited in the MENA region. The success of implementing solar technologies in desalination depends on the progress made in converting solar energy into electrical and thermal energy, as the process of desalination depends on these types of energies. Realizing that desalination is a major consumer of energy and starting to use solar technologies in desalination will increase the demand on these technologies, so making it possible to go for mass production of PV cells, collectors and solar thermal power plants. This would lead eventually to a reduction in cost of these technologies. On the other hand, energy consumption by desalination processes has been reduced significantly in recent years. This means that if solar technologies are used, less PV modules and area for collectors would be needed for each cubic meter of water produced.

Keywords: desalination; solar desalination; MENA; solar technologies; matching; promotion

1. Introduction

Desalination of brackish and seawater has become one of the viable solutions for water shortage in the Middle East and North Africa (MENA) region. Desalination processes are energy intensive. Some of the countries of the region are blessed with conventional sources of energy - oil and gas, and overcome their water problem by using large desalination plants

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powered by conventional energy. However, in remote areas, one option is to develop small to medium scale desalination units, powered by solar energy, which will treat brackish or seawater. In the non-oil producing countries, the small-scale units could use solar energy and use less of the expensive fossil fuels.

Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electrical grid is either not cost effective or not feasible, and where water scarcity is severe. The MENA region has outstanding solar resources which can be captured for use either by Photovoltaic (PV) devices or by direct absorption as thermal energy. The distribution of this resource is more evenly spread over the entire region than other Renewable Energy (RE) resources, which tend to be site specific. Huge areas are available for this resource to be utilized. Long-term development of this on a large scale will hinge on technical developments that will reduce the cost of electricity generated by PV or by solar thermal power plants.

Although solar desalination systems cannot compete with conventional systems in terms of the cost of water produced, they are applicable in certain areas and are likely to become more widely feasible solutions in the near future.

In various parts of the world, several solar desalination pilot plants have been installed and the majority have been successful in operation. Virtually all of them are custom designed for specific locations. Solar desalination is an important challenge and useful work has been done. Operational data and experience from these plants can be utilized to achieve higher reliability and cost minimization. However in order to come up with practical and viable plants, much remains to be done.

In this paper the status of desalination, desalination processes, solar technologies, matching solar technologies with desalination processes, and promoting solar desalination in the MENA regions are presented.

2. Desalination Processes

Desalination is a separation process that produces two streams, fresh water and saline solution (brine). Saline water is classified as brackish water when the salt concentration, mostly sodium chloride, is between 1,000 ppm and 10,000 ppm, hard brackish water when the salinity is 10,000 ppm to 35,000 ppm, and seawater when the salinity exceeds 35,000 ppm[1]. Two main commercial desalination technologies have gained acceptable recognition throughout the world, namely those based on thermal or on membrane processes. Membrane processes include: Reverse Osmosis (RO) and

Electrodialysis (ED). Whereas ED is more suitable for brackish water, RO can be used for both brackish and seawater. Thermal processes, due to their high-energy requirements, are normally used for seawater desalination.

Thermal processes, except freezing, mimic the natural process of producing rain, where saline water is heated, producing water vapor that is in turn condensed to form fresh water, thus producing fresh water by distillation. These processes include Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Vapor Compression (VC) Distillation. In all these processes, condensing steam is used to supply the latent heat needed to vaporize the water. Very pure water can be produced from these processes with TDS< 25 ppm and sometimes < 10 ppm. Such quality water is needed in many industrial processes such as power plants, refineries, chemical and petrochemical industries. It can also be blended with existing water sources to increase local potable water sources and enhance their quality. Thermal processes are not sensitive to the type of feed water with regard to salinity and contamination, because the product water is the condensed water vapor, leaving all the impurities in the liquid phase. This makes thermal processes more suitable to water with high salinity and microbiological content.

Thermal processes are robust, durable and, once in operation, require less maintenance. However, these processes, mainly MSF, require large amounts of energy for their operation. In fact, up to 30% of the operating cost may be attributed to providing energy for the operation of the plant. As a result, many thermal plants are constructed in conjunction with power plants to utilize exhausted steam from the latter. The associated costs of high-energy consumption can have particularly strong restraining effects on small and medium sized plants. However, thermal processes can utilize low grade, low cost sources of heat, as stack gases, cooling water streams or low pressure exhaust steam which would otherwise be lost and discarded to the environment. Heat from solar energy can also be used in such processes. In such cases, thermal processes that operate at low temperatures like the Low Temperature Multi Effect Distillation (LT-MED) and the Low Temperature Multi Effect Mechanical Vapor Compression (LT-MEMVC) can be used.

MSF and MED processes consist of a set of stages/effects at successively decreasing temperature and pressure. MSF process is based on the generation of vapor from seawater or brine due to a sudden pressure reduction when hot seawater enters an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at temperature around 100 ^{o}C. The maximum temperature is limited by the salt concentration to avoid scaling and this maximum limits the performance of the process. In MED, The steam generated in one effect is transferred to the next effect to heat the salt solution because the next effect is at lower temperature and pressure.

The performance of the process is proportional to the number of effects. MED plants normally uses an external steam supply at temperature about 70 °C. In TVC and MVC, after initial vapor is generated from the saline solution, this vapor is thermally or mechanically compressed to generate additional production.

The membrane desalination processes which do not involve phase change, are reverse osmosis (RO) and electrodialysis (ED). The first requires electricity or shaft power to drive a pump that increases the pressure of the saline solution to that required. This required pressure depends on the salt concentration of the resource of saline solution; it is normally around 70 bars for seawater desalination. ED requires electricity only. Both RO and ED are used for brackish water desalination, but only RO competes with distillation processes in seawater desalination.

The energy consumption in desalination processes is as follows: in thermal plants (MSF and MED) if not connected to power plants, 290 MJ/m^3 is required, and 160 MJ/m^3 when connected to power plants. The electrical consumption in thermal plants is 3.6 and 2.3 kWh/m^3 in MSF and MED, respectively. In RO plants and for seawater, electrical consumption is about 10 kWh/m^3 without energy recovery, 2-5 kWh/m^3 with energy recovery depending on the type of energy recovery system used. For small plants, the power consumption may exceed 15 kWh/m^3. In the case of brackish water desalination, the requirement is 1-3 kWh/m^3 for RO. For ED, the electrical consumption can vary from 0.5 – 10 kWh/m^3 depending on water salinity. For example, it would be, assuming product salinity of 500 ppm, 1.5 and 4 kWh/m^3 for feed water salinity of 1,500 and 3,500 ppm, respectively. For MVC, the requirement is 8.5 – 16 kWh/m^3 depending on plant size[1,2].

3. Status of Desalination

Desalination has become a viable solution to augment water supply in many MENA countries as well as other countries in the world. The growth of this business has been due to high demand on water encouraged by falling prices, which are for new projects in the order of US$ 0.5/m^3 with RO and less than US$ 1.0/m^3 for thermal processes. Both prices are now achievable in large plants.

The figure below, prepared using the data from Wangnick[2] Report No. 18, presents the growth of desalination in the MENA region and worldwide up to December 2003. About 52% of the desalination capacity worldwide is taking place in the MENA region. The GCC countries and Libya have the major share. Actually, Saudi Arabia is ranked first worldwide, followed by USA, then UAE. Most of the desalination in GCC countries and Libya is done by thermal processes (MSF and MED), mainly MSF. Thermal processes have been used due to the low cost of energy in these countries and the problems faced by membrane processes in dealing with the Arabian Gulf water. Membrane processes were not so successful due to fouling and scaling problems. However, latest developments in RO process are making end users reconsider their options; some plants are being set up in the Arabian Gulf.

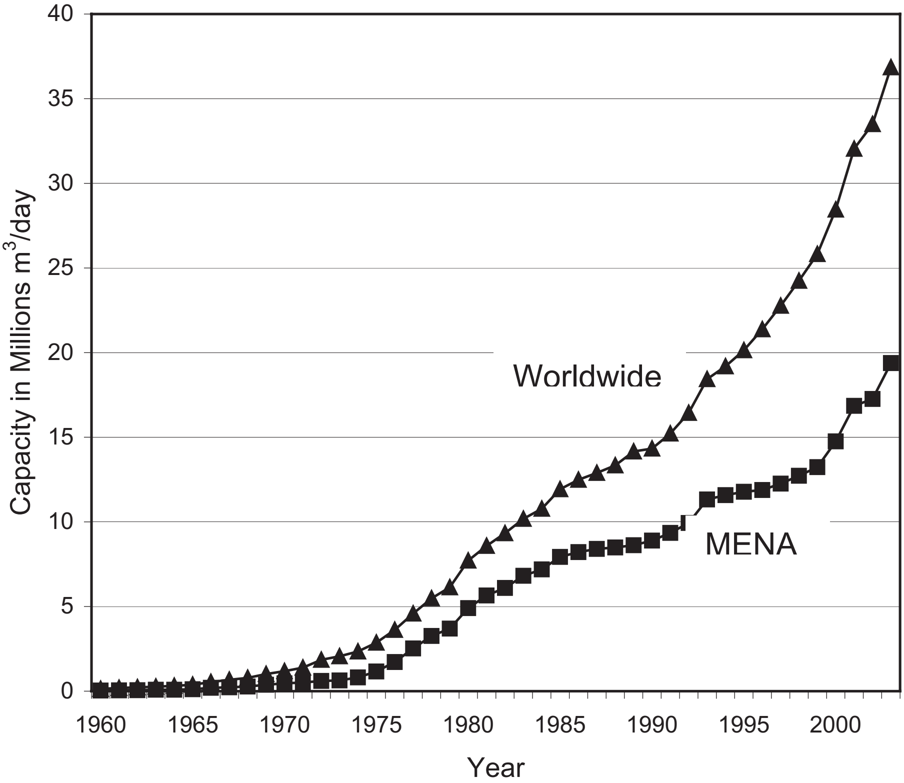

Figure 1. Desalination growth worldwide and in the MENA region[2].

The share of each process (desalinating brackish and sea water) in the GCC countries and Libya is: 73.5% MSF, 20.1% RO, 4% VC, 1.6% ED, 0.6% MED, 0.3% other. On the other hand, membrane processes are more widely used in other MENA countries for desalinating both brackish water and seawater; 60% RO, 14.2% ED, 11.2% MSF, 7.1% MED, 6.8% VC, 0.7% other. Worldwide, the MSF process is over 82% of the thermal processes production, while RO process is over 83% of membrane processes production[2].

4. Solar Energy Technologies

Desalination by means of solar energy is a suitable solution to provide fresh water to a number of regions. This solution becomes more competitive, especially for remote and rural areas where small quantities of water for human consumption are needed. Recently, more attention has been given to improving the efficiencies of the solar energy conversions, desalination technologies and their optimal coupling to make them economically viable for small and medium scale applications.

As discussed earlier, since the energy requirements in desalination processes play a major role, solar energy is considered for desalination. Solar energy can be converted into thermal or electrical energy. Thermal energy can be achieved in solar stills, collectors, or solar pond. Electrical energy can be produced from solar energy directly by photovoltaic conversion or via power plant heated by solar energy.

4.1. SOLAR STILLS

Solar stills have been in use for several decades. The solar still is a small production system, yielding on average $2-5\ \mathrm{L/day\ m^2}$. It can be used wherever fresh water demand is low and land is inexpensive. Many modifications to improve the performance of solar stills have been made. These include linking the desalination process with the solar energy collectors, incorporating a number of effects to recover the latent heat of condensation, improving the configurations and flow patterns to increase the heat transfer rates, and using less expensive materials of construction to reduce the cost. Nevertheless these systems are not economically viable for large-scale applications.

4.2. SOLAR COLLECTORS

Solar collectors are usually classified according to the temperature level reached by the thermal fluid in the collectors as follows[3,4].

- **Low temperature collectors** provide low-grade heat, only a few degrees above ambient air temperature and use unglazed flat plate collectors. This low-grade heat is not useful as a heat source to conventional thermal desalination processes.

- **Medium temperature collectors** provide heat of more than 43 ^{0}C and include glazed flat plate collectors as well as vacuum tube collectors using air or liquid as the heat transfer medium. They can be used to provide heat for thermal desalination processes by indirect heating with a heat exchanger.
- **High temperature collectors** such as parabolic troughs or dishes or central receiver systems. They typically concentrate the incoming solar radiation onto a focal point, from which a receiver collects the energy using a heat transfer fluid. The high temperature thermal energy can be used as thermal energy source in thermal desalination processes or can be used to generate electricity using a steam turbine. As the position of the sun varies over the course of the day and the year, sun tracking is required to ensure that the collector is always kept in the focus of the reflector for improving the efficiency. For large-scale desalination applications, these systems need large collector areas.

4.3. SOLAR POND

Solar ponds combine solar energy collection with long-term storage. The Salt concentration gradient in the pond helps in storing energy. Whereas the top temperature is close to ambient, a temperature of 90 ^{0}C can be reached at the bottom of the pond where salt concentration is highest. The temperature difference between the top and bottom layer of the pond is large enough to run a desalination unit, or to drive the vapor generator of an organic Rankine-cycle engine. Solar ponds have a rather large storage capacity which allows seasonal as well as diurnal thermal energy storage. The annual collection efficiency for useful heat for desalination is approx. 10 to 15% with sizes suitable for villages and small towns. The large storage capacity of solar ponds can be useful for continuous operation of desalination plants.

It has been reported that compared with other solar desalination technologies, solar ponds provide the most convenient and least expensive option for heat storage for daily and seasonal cycles. This is very important, both for operational and economic aspects, if steady and constant water production is required. Heat storage allows solar ponds to power desalination during cloudy days and night-time. Another advantage of desalination by solar ponds is that they can utilize what is often considered as waste product, namely reject brine, as a basis to build the solar pond. This is an important advantage for inland desalination[4,8].

If high temperature collectors or solar ponds are used for electricity generation, a desalination unit can be attached to utilize the reject heat from the electricity production process.

4.4. PHOTOVOLTAICS

Solar photovoltaic (PV) systems directly convert the sunlight into electricity by solar cells. Solar cells are made from semiconductor materials such as silicon, other semi-conductors may be used. A number of solar cells are usually interconnected and encapsulated together to form a PV module. Any number of PV modules can be combined to form an array, which will supply the power required by the load. In addition to the PV module, power conditioning equipment (e.g. charge controller, inverters) and energy storage equipment (e.g. batteries) may be required to supply energy to a desalination plant. Charge controllers are used to protect the battery from overcharging. Inverters are used to convert the direct current from the photovoltaic modules system to alternating current to the loads. PV is a matured technology with life expectancy of 20 to 30 years[3,4].

The main types of PV systems are the following[3,4]

- **Stand-alone systems** (not connected to the utility grid) – They provide either dc power or ac power by the use of an inverter.
- **Grid-connected systems** – These consist of PV arrays that are connected to the electricity grid via an inverter. In small and medium-sized systems the grid is used as a back-up source of energy, (any excess power from the PV system is fed into the grid). In the case of large centralized plants, the entire output is fed directly into the grid.
- **Hybrid systems** – These are autonomous systems consisting of PV arrays in combination with other energy sources, for example in combination with a diesel generator or another renewable energy source (e.g. wind).

5. Matching Desalination Processes with Solar Technologies

The selection of the appropriate solar desalination technology depends on a number of factors. These include, plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type of solar technology available. Among the several possible combinations of desalination and solar energy technologies, some seem to be more promising in terms of economic and technological feasibility than others. In addition to that, some combinations are better suited for large size plants, whereas others are better suited for small-scale application. Before any process selection can start, a number of basic parameters should be investigated. The first is the evaluation of the overall water resources. If brackish water is available then the salinity is normally lower than 10,000 ppm, and the energy requirement would be low. In inland sites, brackish water is normally available. On a coastal site seawater may be the only option[5].

Desalination Processes require thermal and/or electrical energy, which can be provided by solar technologies as mentioned above. If thermal energy can be extracted it can be directly used to drive a distillation process such as MSF, MED, TVC or other solar distillation processes. MED plants are more flexible to operate at partial load, less sensible to scaling, cheaper and more suitable for limited capacity than MSF plants. Also MED has greater potential than MSF for designs with high performance ratio. However, all distillation processes are energy intensive.

If electricity can be obtained, it is best suited to provide power for desalination processes, such as RO, ED, and MVC technologies. With regard to the process selection for seawater, RO has the lowest energy consumption. Nevertheless it requires skilled workers; mistakes in operation conditions may ruin the membranes, and the availability of chemical and membrane supplies. If these requirements are not a problem at the plant location, RO process has been the choice in most instances. Fluctuations of the available energy would ruin the RO system. Therefore, intermediate energy storage would be required, but it would reduce the available energy and increase the costs. In remote areas, ED is most suitable for brackish water desalination because it is more robust and its operation and maintenance are simpler than RO systems. In addition, ED process is able to adapt to changes of available energy input. On the other hand, although MVC consumes more energy than RO, it presents less problems due to the fluctuations of the energy resource than RO. MVC systems are more suitable for remote areas since they are more robust; they need fewer skilled workers and less chemicals than RO systems. In addition, they need no membrane replacement and offer a better quality product than RO[6].

The most promising and applicable combinations of solar technologies in desalination are shown in Table 1. Such systems should be characterized by robustness, simplicity of operation, low maintenance, compact size, easy transportation to site, simple pre-treatment and intake system to ensure proper operation and endurance of a plant in the often difficult conditions of the remote areas[3].

Existing experience has shown no significant technical problems concerning their combination. The most popular combination of technologies is the use of PV with reverse osmosis (see Figs. 2 and 3).

TABLE 1. Matching solar technology with desalination processes[3]

Form of energy	Feed water	Desalination technology
Thermal	Seawater	MED/MSF/TVC
Electrical	Seawater	RO/MVC
	Brackish	ED/RO

MED= Multi-effect distillation, MSF= Multi-stage flashing, TVC=Thermal Vapor Compression, RO=Reverse Osmosis, MVC= Mechanical Vapor Compression, ED= Electrodialysis

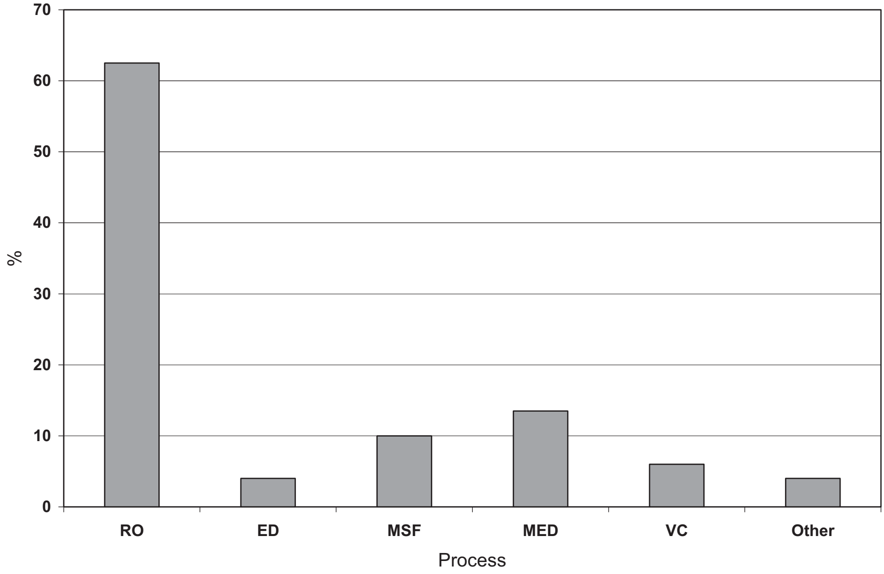

Figure 2. Desalination processes used in conjunction with renewable energy[5].

In distillation processes, large sizes are more attractive due to the relatively high heat loses from small units. Figures 2 and 3 present the desalination processes and the used renewable energy sources. Of the renewable energies mostly solar has been used. The hybrid power supply systems are normally wind and solar, maybe complemented with diesel generator[5].

TABLE 2. Solar distillation plants[3,5,6]

Plant location	Desalination process	m³/d	Solar collectors	Unit water cost
Abu Dhabi, UAE	ME, 18 effects	120	Evacuated tube	8 USD/m^3
Kuwait	MSF RO	25 20	Solar electricity generation system	
Kuwait	MSF auto-regulated	100	Parabolic trough	
Arabian Gulf	ME	6000	Parabolic trough	
Area of Hzag, Tunisia	Distillation	0.1-0.35	Solar collector	
Safat, Kuwait	MSF	10	Solar collector	
Near Dead Sea	MED	3000	Solar pond	
Al-Ain, UAE	ME, 55 stages; MSF, 75 stages	500	Parabolic trough	
PSA, Almeria, Spain	ME, heat pump	72	Parabolic trough	~ 3.5 €/m^3

Many small systems of direct solar desalination (e.g. solar stills) and several pilot plants of indirect solar desalination have been designed and implemented. Table 2 shows indirect solar desalination pilots implemented in the MENA region. Many plants are implemented elsewhere, mainly in Europe. The pilot plant in Spain is included in the table as its water cost is reported.

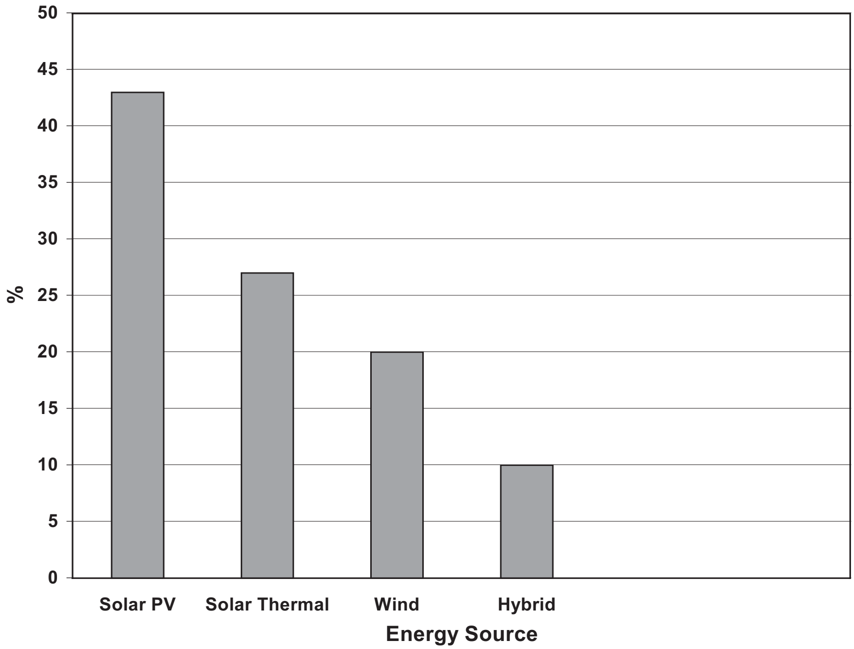

Figure 3. Energy sources for desalination[5].

Solar-pond powered desalination has been recommended as one of the most cost-effective systems. Furthermore, the shaft power from thermal solar energy may drive RO or MVC. Table 3 shows RO-PV plants in the MENA region and one plant in Italy, as its water cost is included.

TABLE 3. Reverse osmosis plants driven by photovoltaic cells in the MENA region[3,5,6]

Plant location	Water type (salinity)	Plant capacity (m^3/day)	Photovoltaic system	Unit water cost
Jeddah, Saudi Arabia	SW (42800 ppm)	3.2	8 kWp	
Red Sea, Egypt	BW (4400 ppm)	50	19.84 kWp (pump), 0.64 kWp (control equipment)	
Doha, Qatar	SW	5.7	11.2 kWp	
Hassi-Khebi, Algeria,	BW (3200 ppm)	22.8	2.59 kWp	
Lampedusa, Italy	SW	120	100 kWp PV	~6.5 €/m^3

SW = seawater, BW = brackish water.

6. Limitations for Using Solar Desalination Processes in the MENA Region

The demand for desalination comes mostly from countries that are rich in oil and gas, so does not make the consideration of solar energy attractive. On the other hand, the high cost of solar technologies does not make it a feasible alternative for the non-oil producing countries. Lack of funds for research and development also makes new developments/improvements to reduce the cost a barrier.

On the technical side, desalination systems have traditionally been designed to operate at a constant power input. Unpredictable and un-steady power input, force the desalination plant to operate in non-optimal conditions and may cause operational problems. Each desalination system has specific problems when it is connected to a variable power system. For instance, the reverse osmosis (RO) has to cope with the sensitivity of the membranes regarding fouling, scaling, as well as unpredictable phenomena due to start–stop cycles and partial load operation during periods of oscillating power supply. On the other hand the vapor compression system has considerable thermal inertia and requires considerable energy to get to the nominal working point.

Thus, for autonomous systems a small energy storage system, usually batteries, should be added to offer stable power to the desalination unit. Clearly this only applies to small electrically driven systems. Thermal storage can be added for thermal systems in the form of hot oil or hot water but is expensive[4]. Another limitation is the need for large surface area for solar still, PV modules, and collectors, thus high land requirements and investment costs of solar energy facilities, in spite of their low operation costs.

7. Promotion of Solar Desalination in the MENA Region

The use of solar energy in desalination introduces environmentally friendly technologies that produce minimum waste products, revitalizes rural communities by creating local industries and businesses, improves the quality of life for inhabitants living in rural areas, reduces mass migration of population from rural to urban areas, reduces the nation's bill for imported primary energy recourses, and might contribute to solutions of problems in the agriculture sector.

The following factors provide justifications and can be a catalyst for promoting solar desalination[7].

- Plant location. Many arid regions in the MENA countries are coastal areas and solar energy is available.
- Seasonal changes. Often freshwater demand increases due to tourism, at times when solar energy availability is high.
- Energy availability. Conventional energy supply is not always possible in remote areas: difficulties in fossil fuel supply or no grid available. In such cases, the use of solar energy permits sustainable socioeconomic development by using local resources.
- Self-sufficiency. Solar energy allows energetic diversification and avoids external dependence on energy supply for the non-oil producing countries.
- Technology. The development and commercialization of desalination systems driven by solar energy make technology exportation and cooperation possible among MENA countries and Europe.
- Environmental impact. Seawater desalination processes are strongly energy consuming. Therefore, the environmental effects of the

fossil fuels consumed are important. Currently, total worldwide capacity of desalinated water is about $40x10^6$ m^3/day.

- Economics and Health. In remote areas, fresh water requirements make the transport of fresh water at high costs and in proper hygienic conditions necessary.
- Operation and maintenance. The operation and maintenance of solar energy systems are normally easier than conventional energy ones. Therefore, they are suitable for remote areas.
- Promising commercial perspectives. The cost reduction of solar energy systems has been significant during the last decades. Therefore, future reductions as well as the rise in fossil fuel prices could make the competitiveness of seawater desalination driven by solar energy possible. Actually, using solar technologies in desalination will increase the demand on these technologies, making it possible to go for mass production, this would eventually lead to reduced costs.

Steps to be taken to promote the utilization of solar energy in desalination.

- Promote ways to enhance understanding of the role of solar energy could play in supplying electricity and water in the region, particularly for rural and remote areas. Stress the role it plays in preserving the environment and in contributing towards fewer unemployment.
- Urge non-governmental organizations in the MENA region and in Europe to enter into partnership, exchange knowledge and experience, and establish innovative programmers for the promotion of solar energy in desalination.
- Favor the access, transfer and sharing of knowledge on solar energy applications in desalination using state of the art communications technology.
- Promote and harmonize co-operation in training and research, as well as in the transfer of research disclosures to industry at the regional, inter-regional and international level.
- Demonstrate how the wide use of solar energy in desalination can be cost effective, it reduces the reliance on imported energy (for some countries of the region), saves foreign exchange, and it will be able to stretch the energy supply base without heavy investment.
- Identify and define selected strategic projects of regional importance which will trigger the use of solar energy in

desalination, thus opening competitive and sustainable markets for solar energy and desalination technologies, equipment and goods. For example, solar ponds in the vicinity of the Dead Sea.

- Favor the utilization of solar energy even for the oil-rich countries as this would extend the life time of the oil reserve which can be used for high quality industry rather than burning it.

There should be encouragement from countries that are now oil-rich by subsidizing desalination powered by solar energy. Actually for remote areas, the cost to extend the electrical grid or to transport oil fuel, may justify the use of solar energy to power desalination plants and supply electricity.

8. Conclusions

The MENA region, mainly the GCC countries, is relying heavily on desalination to augment their water supply. Desalination is needed in regions that normally have high solar irradiation, like the MENA region. The current solar technologies, photovoltaic and solar thermal systems, can be utilized and matched to the existing desalination processes. The fact that desalination processes require continuous operation, makes the use of batteries and thermal storage necessary as a solution to this problem, but increases the cost.

As desalination is energy intensive, it could become a mean of promoting solar energy technologies. This could play a major role in promoting development and expansion in the industry of solar energy technologies.

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THE POTENTIAL OF RENEWABLE ENERGIES IN SICILY FOR WATER DESALINATION APPLICATIONS

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Abstract. Energy and water have always been a central element of the insular condition due to their territorial, environmental and economic implications. The interdependence water–energy is increasingly evident on islands, and sometimes it even leads to a single management system for both. It is a determining factor in present development models. This paper describes the main issues of present and future water and energy policies in Sicily. A new Energy Master Plan will soon be adopted by the Regional Government which will increase the use of Renewable Energies (RE) encoure private investors. A special Bureau for Water Management plans to increase the capacity and efficiency of desalination plants already operating in Sicily as there are many areas with old distribution networks and scarce water resources. RE and desalination should be investments for the future and for private enterprises. Economic support is available both for RE electricity generation and for energy saving projects in general. An economic analysis of some possible applications of RE for desalination is presented. In the cases simulated we show how economic obstacles could be overcome.

Keywords: water; renewable energy; desalination; Sicily; photovoltaic; solar thermal; wind

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1. Introduction

Sicily's resources (sun, wind, water, biomass) are not sufficiently exploited. About 99% of the domestic energy demand is supplied by imported fossil sources. In spite of the huge water storage system in the region hundreds of thousands of people do not have a constant supply of drinking water. Funds and regulations to improve the efficiency of distribution and supply of water are available.

The new Energy Master Plan of Regione Sicilia has an action plan for the diffusion of Renewable Energy Systems (RES). It aims to supply about 6% of primary energy demand and about 12% of electricity production through RE by 2010.

Most of RE will come from wind energy. Wind farms with a power of about 1000 MW are being developed. The target for photovoltaic electricity is 20 MW. An ambitious target of 250.000 m^2 is also envisaged for solar thermal. The use of biomasses from agricultural and forestal activities (160 MW) is also planned.

The total (public + private) investment for implementation of energy facilities is about 1500 M€. Funding from UE, from National and Regional Governments amounting to 800 M€ is expected to be used during 2007-2010 for water and energy infrastructures.

2. Water Resources and Desalination in Sicily

Many problems in water supply in Sicily are due to the incomplete and unreliable connections between storage (dams) and production facilities (wells, reservoirs, springs). Local distribution networks are weak in many cities. The southern part of the island, where production is rarest, has a chronic debt of water. Desalination could be a solution for some of these areas. The biggest desalination plants were installed in Gela and Porto Empedocle from 1974 onwards. Today six other plants are operating in Sicily: one in Trapani and the others on the five islands of Lampedusa, Linosa, Pantelleria, Ustica and Lipari.

About 44,3 Mm^3 of desalinated water are produced by these plants. Unfortunately, only 31,3 Mm^3 are delivered to users,, due either to the weakness of the network or to the unreliability of the plants. This is about 5% of the regional demand.

The causes of this inefficiency differ from case to case. The system is heterogeneous from the point of view of technology, management, and local context.

A survey on the desalination system in Sicily was carried out by Cipollina et al. (2005a). Tables 1 and 2 summarize main technical data and performances of all the desalination plants in Sicily.

TABLE 1. Desalination plants in Sicily: typologies and capacities

Plant	Technology	Capacity (nominal)		Capacity (nominal)	Operation days	Capacity (actual)
		m^3/d	l/s	m^3/y	d	m^3/y
Gela	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	13.200	153	4.818.000	330	4.356.000
	MSF	14.400	167	5.256.000	330	4.752.000
	RO	16.848	195	6.149.520	330	5.559.840
Trapani	TVC-MED	8.700	100	3.175.500	330	2.871.000
	TVC-MED	8.700	100	3.175.500	330	2.871.000
	TVC-MED	8.700	100	3.175.500	330	2.871.000
	TVC-MED	8.700	100	3.175.500	330	2.871.000
Porto Empedocle	MVC	1.600	18	584.000	310	496.000
	MVC	1.600	18	584.000	310	496.000
	MVC	1.600	18	584.000	310	496.000
Lampedusa	MVC	450	5,2	164.250	300	135.000
	MVC	450	5,2	164.250	300	135.000
	MVC	50	0,6	18.250	300	15.000
Linosa	MVC	250	2,9	91.250	310	77.500
	MVC	250	2,9	91.250	310	77.500
Pantelleria “Maggiuluvedi”	EDR	450	5,2	164.250	300	135.000
	EDR	450	5,2	164.250	300	135.000
	RO	200	2,3	73.000	300	60.000
Pantelleria “Sataria”	MVC	1.600	18,5	58.400	310	496.000
	MVC	1.600	18,5	58.400	310	496.000
Lipari	MVC	1.600	18,5	58.400	310	496.000
	MVC	1.600	18,5	58.400	310	496.000
	MVC	1.600	18,5	58.400	310	496.000
Ustica	MVC	500	5,8	182.500	310	155.000
	MVC	500	5,8	182.500	310	155.000
Total		135.198	1.561,6	46.719.270		44.267.840

Authors have also studied ways to improve the efficiency of these plants. Some hypothesis are based on the integration of solar thermal systems in the MSF plant in Gela (Cipollina et al., 2005b). Other solutions are possible using solar energy (thermal or photovoltaic) in desalination. The Water Emergency Special Bureau (on the behalf of the Regional Government), also presented a programme for repowering and building desalination plants in 2004 (see Table 3). This plan encouraged the implementation of a stronger desalination platform.

TABLE 2. Desalination plants in Sicily: energy consumption

Site	Technology	Electricity consumption (actual)	Electricity consumption (literature)	Fuel consumption (literature)	Power
		kWh/m^3	kWh/m^3	Kg_{vapour}/Kg_{desal}	kW
Gela	MSF	1 – 1,2	2- 4	0,08 – 0,13	-
	MSF				
	MSF				
	MSF				
	MSF				
	RO	8 - 9	4-8	-	-
Trapani	TVC-MED	2,9	1-3	0,07 – 0,11	-
	TVC-MED				
	TVC-MED				
	TVC-MED				
Porto Empedocle	MVC	11 - 12	8 - 17	-	3100
	MVC				
	MVC				
Lampedusa	MVC	-	8 - 17	-	800
	MVC				
	MVC				
Linosa	MVC	-	8 - 17	-	800
	MVC				
Pantelleria "Maggiuluvedi"	EDR	-		-	320
	EDR				
	RO	-	4-8	-	
Pantelleria "Sataria"	MVC	-	8 - 17	-	1800
	MVC				
Lipari	MVC	-	8 - 17	-	4 engines x 1500 kVA
	MVC				
	MVC				
Ustica	MVC	-	8 - 17	-	3 engines x 608 kVA
	MVC				

TABLE 3. Action Plan for Desalination in the period 2006-2008

<table>
<tr><th rowspan="2">Plant</th><th colspan="3">Kind of action</th><th colspan="2">Works Schedule</th></tr>
<tr><th>New construction</th><th>Substitution</th><th>None</th><th>Start</th><th>End</th></tr>
<tr><td>Gela</td><td></td><td></td><td>X</td><td>2006</td><td>2008</td></tr>
<tr><td>Trapani</td><td></td><td>X</td><td></td><td>2006</td><td>2007</td></tr>
<tr><td>Porto Empedocle</td><td></td><td></td><td>X</td><td>2006</td><td>2007</td></tr>
<tr><td>Lampedusa</td><td></td><td>X</td><td></td><td>2006</td><td>2007</td></tr>
<tr><td>Linosa</td><td></td><td>X</td><td></td><td>2006</td><td>2007</td></tr>
<tr><td>Pantelleria “Maggiuluvedi”</td><td></td><td rowspan="2">X</td><td></td><td>2006</td><td>2007</td></tr>
<tr><td>Pantelleria “Sataria”</td><td></td><td></td><td>2006</td><td>2007</td></tr>
<tr><td>Lipari</td><td></td><td>X</td><td></td><td>2006</td><td>2007</td></tr>
<tr><td>Ustica</td><td></td><td></td><td>X</td><td>2006</td><td>2007</td></tr>
<tr><td>Salina</td><td>X</td><td></td><td></td><td>2006</td><td>2007</td></tr>
</table>

3. Energy Resources in Sicily and the State of the Energy Master Plan

Primary energy saving through the exploitation of renewable sources is necessary to achieve the Kyoto Protocol targets. Italy must reduce their greenhouse gas emissions by a further 6.5% below the 1990 levels by 2012.

This task needs policies toward more sustainable energy systems. Actions on a national scale must be coupled with actions on a regional scale. The Department of Energy and Environmental Research of the University of Palermo carried out a study on the Energy Master Plan (REMP) for the Regional Government. This paper presents assessed potential saving of primary energy and the reduction of greenhouse emissions, which should be achieved through energy planning. The REMP is still under discussion and examination by the Regional Government.

The REMP proposes a set of interventions dealing with:

- increasing RE use for electricity generation and for other ends;
- improving the existing power plants;
- reducing energy consumption in industrial, residential, agricultural and transport sectors through Demand Side Management (DSM) and a wider use of CHP systems.

Sicily has great potential for solar and wind power exploitation due to its favorable climatic conditions. Use of renewable sources gives opportunities to the environment and also to economic and social follow-ups.

TABLE 4. Action Plan for RES in 2006-2008

Time-steps	PV [MW]	Wind [MW]	Biomass [MW]	Solar [m^2]
<2006	10,00	123	-	70.000
2006-2008	4,00	400	80 MWt	260.000
2008-2010	4,00	500	160 MWt	500.000
2010-2012	5,00	200	60 MWe	-
Total Installed	23,00	1223	60 MWe; 240 MWt	830.000
Total Energy Saving [TJ/y]	126	7.044	4.361	2.287
Total Public Investment	115	85	125	75

Following Italian and EU energy policy the REMP has three main goals:

- Goal 1: CO_2eq emissions from Sicilian energy uses should be reduced by 8.30 x10^9 kg.
- Goal 2: Electricity through RE will reach 10-15% of the gross domestic electricity consumption by 2010;
- Goal 3: The primary energy saving accomplished through RE will reach 10-12% of the gross domestic consumption by 2010.

Table 4 shows target power of each RE to be implemented.

4. Potential and Opportunities of RES Exploitation for Desalination

Desalination with renewable energies could provide solutions in coastal areas with available wind and/or solar energy. These kinds of systems are the best way of providing water to areas isolated from the grid or to small islands (weak grid). A number of successful RES desalination applications already existing, prove that the coupling of the two technologies has reached technical maturity and can provide fresh water at a reasonable cost. But this is not sufficient for their wide application. A renewable energy driven desalination system also provides an essential product to local communities so social integration is important (Assimacopoulos, 2001).

The suitability of RES for desalination plants is summarized in Tables 5 and 6.

TABLE 5. RES and desalination plants: suitability

Kind of RET	Suitability for powering small-scale desalination plants
PV	Suited to plants requiring electrical energy, good match for small-scale
Solar thermal energy	Suited to plants requiring thermal energy, typically a good match for large-scale
Wind energy	Suited to plants requiring electrical energy, good match for small-scale
Geothermal	Suited to plants requiring thermal energy, typically a good match for large-scale. Resource Is very limited
Tidal	Possible well suited but technology isn’t mature enough yet
Wave	Possible well suited but technology isn’t mature enough yet
Hydropower	Possible well suited but technology isn’t mature enough yet

TABLE 6. RES and desalination plants: system size

Feed water available	Product water	RE resource available	System size			Suitable Desalination combination
			Small (1-50 m^3/d)	Medium (50-250 m^3/d)	Large (>250 m^3/d)	
Brackish Water	Distillate	Solar	X			Solar distillation
	Potable	Solar	X			PV - RO
	Potable	Solar	X			PV - ED
	Potable	Wind	X	X		Wind – RO
	Potable	Wind	X	X		Wind - ED
Sea Water	Distillate	Solar	X			Solar distillation
	Distillate	Solar		X	X	Solar thermal - MED
	Distillate	Solar			X	Solar thermal - MSF
	Potable	Solar	X			PV - RO
	Potable	Solar	X			PV - ED
	Potable	Wind	X	X		Wind – RO
	Potable	Wind	X	X		Wind - ED
	Potable	Wind		X	X	Wind – VC
	Potable	Geothermal		X	X	Geothermal - MED
	Potable	Geothermal			X	Geothermal - MSF

Today Reverse Osmosis (RO) is the most successful and suitable system in practical applications. It has been the lowest energy consumption per water output achieving smaller generation capacity that, if coupled with RE, will limit the specific investment cost. Evaporative Distillation (ED) is a valid alternative for low TDS brackish water. But RO gives the best results for high salt content brackish or for sea water. Salt content has no role in the choice of distillation method as it depends on the feed temperature, the availability of surface area for the solar energy field and the supply of electrical power. Distillation processes usually require evacuated or concentrating collectors to meet the high feed temperatures. On the contrary RO uses photovoltaic or wind for power production in small capacity plants but may be coupled to concentrating collectors or central receivers for electricity production and to drive large RO plants. (Chaibi, 2000), (Belessiotis, 2001).

Renewable energy sources are characterized by intermittent and variable intensity but desalination processes are designed for continuous steady state operation. This seems the main problem concerning the interfacing between the two technologies. Many systems with additional energy storage have been designed in order to couple the generation-demand asymmetry. Grid connected electricity driven systems can manage the energy exchange between the plant and the provider. "Virtual" energy storage into the grid gives important advantages and also by-passes many technical difficulties. Economic variables become more important when supporting regulation occurs. In many countries "green electricity" generation and delivery are in fact supported in different ways.

A short survey of suitable combinations of RET-desalination process is presented in this paper. The main focus is on economics, the favorable Italian regulations on RET support and "green electricity" trading is also investigated.

4.1. DESALINATION AND PV

PV powered RO or ED are promising technologies for desalination in small scale plants. It is well known that PV is one of the most expensive technologies in electricity generation and this is the main barrier to its diffusion. Since technical investigation is necessary to increase system reliability in coupling with RO plants, it is worth focusing on the economic opportunities related to the incentives available in many European countries. PV electricity production is supported by the Italian Government. Towards this end a law, the "Conto energia" decree, was passed in July 2005. The original target was to install 100 MW of PV systems, 60 MW were to be reached by small plants (1-50 kW) and the rest (40 MW) by larger installations (from 50 kW to 1 MW peak power). This first target was reached at once at the end of 2005. A new call for a further 200 MW was issued in January 2006.

The "Conto Energia" decree ensures two type of grants. The first one gives the right to receive a bonus per each kWh produced by PV. This applies both to energy used by the owner and to energy delivered to the grid. The second type of grant (net-metering) reduces costs for systems with peak power below 20 kW. Over 20 kW peak power the surplus electricity can be sold to the grid at established prices (see Table 7).

TABLE 7. Incentives of "Conto energia"

Peak Power	Grant	Other advantages
[kW]	[c€/kWh]	[-]
1-20	44,50	Net-metering: energy delivered to the grid is used as reduction in the user electrical bill
20-50	46,00	Energy not used can be sold to the grid at: 9,50 c€/kWh up to 500 MWh/year 8,00 c€/kWh between 500 and 1000 MWh/year 7,00 c€/kWh between 1000 and 2000 MWh/year
50-1000	49,00*	Energy not used can be sold to the grid at: 9,50 c€/kWh up to 500 MWh/year 8,00 c€/kWh between 500 and 1000 MWh/year 7,00 c€/kWh between 1000 and 2000 MWh/year

*the maximum grant (upper limit) the producer can obtain; the grant is proposed by the producer applying to the call for the incentive.

The Italian Law 133/99 also states that electricity generated by small systems is not subject to taxation, owners of systems over 20 kW are considered "electricity producers" just like any other Energy Utility.

The southern regions with highest solar irradiation (like Sicily) are favoured by this system. Moreover, the higher is the plant size (>50kW) the higher are the available financial benefits.

A case study was simulated for a PV installation in Trapani, Sicily. PV panels were assumed to be mounted on a fixed frame facing south and tilted at the same angle as the latitude (38°N). The average irradiation on the panels was 1963,7 kWh per m^2 per year. The expected electrical output of the PV is about 183,6 kWh/m^2/year.

Assuming that 8 m^2 of panel correspond to 1 kW of peak power, the total energy produced by the system per kWp is calculated at 1.468,8 kWh/kW/year.

Five different sizes of PV systems were considered: 10, 30, 100, 250 and 500 kWp.

TABLE 8. Economic assessment of desalination with PV with "Conto energia" grant (A = benefit from "Conto energia" grant; B = benefit from energy self-consumption; C = total benefit; D = profitability rate of the investment; E = total benefit over 20 years)

Installed power	Electricity production	A	B	C=A+B	SPT	D	E
[kW]	[MWh/y]	[k€/y]	[k€/y]	[k€/y]	[y]	[%]	[k€]
10	14,69	7,428	1,65	9,08	6,6	15,13	121,60
30	44,06	14,512	4,96	19,47	9,2	10,82	209,38
100	146,.88	51,527	16,53	68,05	8,8	11,34	761,02
250	367,20	128,816	41,31	170,13	8,8	11,34	1.902,55
500	734,40	257,.633	82,62	340,26	8,8	11,.34	3.805,10

Table 8 shows the benefits available according to the "Conto energia" rules (column A). The Italian electricity rate for industrial users varies from 9 to 14 c€/kWh according to the yearly consumption. Let's consider a average price of 9,9 c€/kWh. If the electricity produced is self consumed, the additional benefit is the difference between the price of purchase and sale (see column B). So the total benefit is the sum of the "Conto energia"grant plus this saving (column C=A+B).

Table 8 reports the Simple Payback Time (SPT) of the investment. SPT is the net investment divided by the average annual cash flow, and is expressed in years. SPT is easy to calculate, easy to understand and gives clear information on financial risk. But it doesn't measure profitability, doesn't account for the value of money during the time and ignores financial performance after the break-even period. The simple payback times were calculated taking into account a PV system costing 6.000,00 € per kWp. Table 8 also shows the profitability rate of the investment (the total cost of the system divided by the annual benefit), and the total benefit over 20 years (i.e the calculated annual benefit multiplied by the no. of years between the incentive period and the payback time).

Results show that reasonably short SPTs are achievable by Conto Energia for each size of plant. Financial performance is in general good.

The Conto Energia benefits cannot be combined with other incentives available today for RE such as the Green Certificates (GC) or White Certificates (for energy saving measures). The Green Certificate is a financial benefit available for "green electricity" producers. GC has a trade value because Electric Utilities has a compulsory target of 2% of green electricity (generated or purchased).

The smallest tradable stock of Green Certificates is related to 50 MWh of electricity generated. GCs are valid for a RE plant for 8 years. They are issued by the Italian grid manager (GRTN). GRTN certifies renewable power plants that are owned by private producers wishing to receive green certificates. It also manages and supervises GC trading within the Italian energy market.

GC price is defined by the market, every year the electricity produced by RE varies according to public directives. The price fixed by GRTN in 2005 was 108,92 €/MWh.

Table 9 shows economic performances of PV systems coupled to a desalination plant of 100 m^3/d and energy consumption of 3 kWh/m^3.

TABLE 9a. Economic assessment of PV with Green certificate incentive during the first 8 years (A = benefit from Green Certificates; B = benefit from energy sale; C = benefit from energy self-consumption; D = total benefit)

			During the incentive (0 < t < 8 years)				
Installed power	Electricity production	Electricity cons./ prod.	Number of GC	A	B	C	D=A+B+C
[kW]	[MWh/y]	[-]	[-]	[k€/y]	[k€/y]	[k€/y]	[€/y]
10	14,69	745,51	nothing	0	0	1,45	1,45
30	44,06	2,49	nothing	0	0	4,36	4,36
100	146,.88	0,75	2	10,89	9,50	4,64	25,03
250	367,20	0,30	7	38,12	33,25	1,70	73,07

TABLE 9b. Economic assessment of PV with Green certificate incentive after the 8th year (A = benefit from energy auto consumption; B = benefit from energy sale; C = total benefit)

			After the incentive (t > 8 years)			
Installed power	Electricity production	Electricity cons./ prod.	A	B	C=A+B	SPT
[kW]	[MWh/y]	[-]	[k€/y]	[k€/y]	[€/y]	[y]
10	14,69	745,51	1,45	0	1,45	41
30	44,06	2,49	4,36	0	4,36	41
100	146,.88	0,75	10,.84	3,551	14,39	36
250	367,20	0,30	10,84	24,482	35,32	34

It is clear that this kind of incentive is unsuitable for PV installation. SPTs are very long and there is a dramatic difference compared to the benefits available with the Conto Energia mechanism.

4.2. DESALINATION AND WIND

The idea of wind power as an energy source for desalination is not new. However the most challenging problem with the implementation of RE-powered desalination plants is the matching of intermittent RE power output with the steady energy demand for the desalination process. Although the wind is relatively predictable it is seldom constant and there will be periods when there will be none at all. The large high frequency component in wind turbulence means that electrical output from a wind turbine will fluctuate quite vigorously in minutes and seconds. A wind turbine meeting a load quite satisfactorily one moment may well fail to meet the load, only minutes or seconds later. Such problems raise the need for either a method of energy storage or a backup supply system. However desalination systems driven by wind power are the most frequent renewable energy desalination plants, but practical experience of such schemes is relatively scarse (Farrel et al., 2003).

To operate a wind-powered desalination plant, the system must be insensitive to repeated start-up and shut down cycles caused by sometimes rapidly changing wind conditions. Typical MVC plants are robust enough to withstand these situations (Farrel et al., 2003).

Fluctuations in the supply in wind energy ruin a process like RO. A lot of research have been focused on this issue.

Main technical problems include the operation of the reverse osmosis (RO) pumps in variable-speed mode where electrical power is proportional to wind speed, the off-grid operation wherein the wind turbine shaft power is used to directly drive the pumps, the operational benefits of adding energy storage through batteries, fuel cells, flywheels and other energy storage technologies and the effects of non-conventional utilization of the RO membranes .

Hybrid systems based on wind power offer multiple possibilities and great versatility. Modularity is one of their most favourable properties.

Obviously grid connected plants overcome these problems and make electricity exchange possible through the grid.

It is worth noting that treated water could be a means of energy storage for wind systems. The ambitious plans for wind energy installation in Sicily foresee the problem of electric grid management. The priority given to RE electricity by the grid rules can be a instability factor. Research is being carried out in order to support grid-managers and planners in this difficult task. A good working relationship between energy and water facilities is necessary to meet this end. Wind-water systems can be used to generate electricity during peak demand periods and produce water during off-peak periods.

An economic analysis of a desalination plant with a capacity of 1000 m^3/day is presented. A consumption of about 5 kWh/m^3 and an annual electricity demand of 1.825 GWh were assumed. Electricity is in part generated by a wind turbine with a nominal power of 1 MW. The power plant is grid-connected and used for the "storage" of surplus electricity.

The "green electricity" generated gives the opportunity to achieve stocks of Green Certificates (GC).

All the electricity produced by wind turbine sells at 0.07 €/kWh plus the GC value (when available). Electricity can be purchased from the provider at 0.086 €/kWh (i.e. average cost for industrial customers using up to 2 GWh/year).

Thus, there is a potential earning of 0.093 €/kWh during the first eight years and quick investment payback. The investment cost is about 1 M€ per MW installed.

Electricity production by wind turbines depends on the wind available on site. There is generally a minimum threshold of about 1500 hours of equivalent peak-power production.

Table 10 shows the economic performances of a 1 MW wind turbine on four different sites with equivalent hours ranging from 1000 to 2500 h.

It can be seen that the simple payback times are very short even in the worst scenario (1000 h). This confirms the high economic maturity of wind turbine technology.

TABLE 10a. Economic evaluation of Wind Turbine systems with Green Certificate incentive during the first 8 years (A = benefit from Green Certificates; B = benefit from energy sale; C = benefit from energy auto consumption; D = total benefit)

		During the incentive (0 < t < 8 years)				
Installed power	Electricity production	Number of GC	A	B	C	D=A+B+C
[kW]	[MWh/y]	[-]	[k€/y]	[k€/y]	[k€/y]	[k€/y]
1000	2.500	25	272,30	47,25	156,95	476,50
1000	2.000	20	217,84	12,25	156,.95	387,04
1000	1.500	15	163,38	0,00	129,00	292,38
1000	1.000	10	108,92	0,00	86,00	194,92

TABLE 10b. Economic evaluation of Wind Turbine systems with Green Certificate incentive after 8 years (A = benefit from energy self-consumption; B = benefit from energy sale; C = total benefit)

		After the incentive (t > 8 years)			
Installed power	Electricity production	A	B	C=A+B	SPT
[kW]	[MWh/y]	[k€/y]	[k€/y]	[€/y]	[y]
1000	14,69	156,95	47.25	204,20	2,10
1000	44,06	156,95	12.25	168,20	2,58
1000	146,.88	129,00	0,00	129,00	3,42
1000	367,20	86,00	0,00	86,00	5,13

4.3. DESALINATION AND SOLAR THERMAL

There are many solar plants used for water desalination, their technical and economic effectiveness depend mainly on the typology of solar collector.

Technical maturity of solar flat-plate collectors (FPC) varies widely, depending on design, manufacture and material used. Initial capital cost is not prohibitively high and ranges from 80 to about 250€/m^2 depending on the material used and the country of origin. Flat- plate collectors have low exit temperatures and are combined efficiently with solar stills or may be combined with small capacity MED but efficiencies are rather low. Providing hot water and desalted water may be an economical solution. Both solar collectors and solar distillation plants need large installation areas.

Evacuated tube collectors (ETC) are more suitable for conventional distillation plants, MED, MEB or TVC. The technology is mature and well tested. ETC are more expensive than flat-plate collectors ranging from 300-500€/m^2. Initial capital cost is high but operation costs are relatively low. They are generally more suitable for larger capacities than low temperature fiat plate collectors. Solar ponds are a possible source of heat for thermal desalination processes. Solar pond technology is also mature and widely tested. Solar troughs have been used mostly for electricity production as they are the simplest type of large area solar collectors that provide heat storage simultaneously (Belessiotis et al., 1996).

High temperature solar collectors, suitable mainly for MSF, MED, TVC and MVC distillation plants of larger capacities, are very expensive and unsuitable for use in small communities and/ or small capacities for desalinated water.

The combination of a solar desalination system utilizing the heat reject or the brine from MED or MSF as feed water to the solar plant could mitigate the environmental impact and dramatically increase the efficiency and cost effectiveness of the solar plant (Cipollina et al., 2005a).

The economic viability of Solar Thermal Technology for desalination was assessed assuming that all the heat produced by the solar collector could be utilised in the desalination process without any thermoelectric conversion.

The incentive suitable to this plant is related to the White Certificates (WC) mechanism. According to Italian regulations, WCs are linked to “eligible” energy saving. Also in this case, Energy Utilities must reach compulsory annual targets of energy saving in two ways, either by Demand Side Management measures or by purchasing White Certificates. The cost of these certificates is currently 100€/TOE.

In the case of a solar system with 100 m^2 of evacuated tube collectors and a gas-boiler back-up, the eligible yearly energy saving is about 10,4 TOE. Assuming an investment cost of 400€/ m^2, an O&M cost of 100€/year, natural gas at a cost of 0,3 €/Nm^3 and a lifetime of 15 years, the SPT of this investment is 10 years. This is considered a good value for the ETC plants.

5. Conclusions

This paper proposes a partial approach to the problem of RE-desalination applications It focuses on the financial and economic opportunities regarding the installation of PV or wind generation systems used to support a desalination (or any other type of) plant with a grid connected scheme. It is clear that the results have a general validity. In a similar way, solar thermal application with a reliable use of the heat generated, can benefit in Italy of supporting policies. On the other hand, it is well known that, for RE desalination applications, the economic variable plays a crucial role in the assessment of their convenience.

PV applications are economically effective thanks to the “Conto Energia”. High irradiation areas like Sicily could obtain pay back times which are shorter than 10 years. Green Certificates are unsuitable for PV but give Wind Energy good economic performances (i.e. SPT shorter than 3,5 years in moderately windy areas).

Solar thermal application when supported by the White Certificate mechanism can reach payback time of about 10 years.

Many examples of successful applications of RE desalination process are reported, demonstrating again that where and when design reliability is reached, the cost of RE systems is affordable.

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THE PSA EXPERIENCE ON SOLAR DESALINATION: TECHNOLOGY DEVELOPMENT AND RESEARCH ACTIVITIES

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Abstract. Seawater desalination is one of the most promising fields for the application of solar thermal energy due to the usual coincidence, in many places in the world, of water scarcity, seawater availability and good levels of solar radiation. During the 90s the Plataforma Solar de Almería (PSA) carried out a research project that successfully demonstrated the technical feasibility of solar seawater desalination using parabolic-trough solar collectors coupled with a conventional multi-effect distillation unit. In spite of significant achievements in the process energy efficiency, by the development and implementation of a double-effect absorption heat pump, the technology could not compete in cost reduction with conventional thermal distillation or reverse osmosis processes. In 2002, the R&D European Project AQUASOL was initiated at the PSA in order to improve the existing solar thermal desalination technology. This paper describes all these experiences along with a detailed description of the AQUASOL desalination system, currently under evaluation at the PSA.

Keywords: Solar energy; multi-effect distillation; absorption heat pump

1. Introduction

Continuous growth of world population, improved living standards in developing countries and contamination of the existing water resources are considered, according to the United Nations (UN World Water Development Report, 2003), the main causes of the world crisis that will

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take place during the first half of this century as a consequence of the growing fresh water shortage in many areas of the planet. The consumer savings required, promotion of water treatment and reuse may help alleviate this problem. However, there are many places (arid or remote areas) where the above measures are not enough in themselves, and external contributions are necessary, for example, water transfers from an excedentary river basin or the construction of desalination plants for both brackish and sea water. The latter may be one of the best alternatives, since more than 70% of the world population lives within a 70 km strip of seas or oceans (El-Dessouky and Ettouney, 2002).

However, we cannot let the solution of a water shortage problem aggravate a current problem like growing environmental pollution due to the use of so-called fossil fuels that have the additional drawback of being finite. Desalination processes are intensive energy consumers, so the feasibility of this option necessarily goes through the energy optimization of the technological processes employed, as well as the effective incorporation of renewable energies. Among these, solar thermal energy is one of the most promising options, as water shortage problems and high availability of the solar resource usually coincide geographically and seasonally. For high desalinated water production volumes, the best option is indirect solar desalination systems (García-Rodríguez, 2002), which consist of hooking up a conventional distillation plant to a solar collector field which provides the thermal energy required for the desalination process.

Distillation methods used in indirect solar desalination plants are multi-stage flash (MSF) and multi-effect distillation (MED). Conventional MSF plants, due to factors such as cost and apparently high efficiency, pushed out MED systems in the sixties, and only small-sized MED plants were built. However, in the last decade, interest in multi-effect distillation has been significantly renewed and the MED process is currently competing technically and economically with the MSF technology (Al-Shammiri and Safar, 1999; Alawadhi, 2002). Recent construction in Abu Dhabi of a MED plant with a 240.000 m^3/day capacity shows a breakthrough in large-scale MED plants (Vermey, 2003).

During the past years, several indirect solar desalination pilot plants have been designed and implemented (Delyannis, 1987; El-Nashar, 1985; Milow and Zarza, 1996; European Commission, 1998) using parabolic-trough concentrator, flat-plate and evacuated-tube solar collectors (El-Nashar, 2001; Madani, 1990). During the nineties, a unique experiment in solar seawater desalination at the Plataforma Solar de Almería (PSA) coupled a parabolic-trough solar field with a conventional MED distillation unit, optimizing the overall heat consumption of the system by the incorporation of a double effect absorption (LiBr-H_2O) heat pump (Zarza and Blanco, 1996). Based on this previous background and experience, in 2001, a project called "Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology" (DGXII-FPV AQUASOL Project, 2002-2006) was approved by the European Commission, and activities were initiated at PSA in 2002.

This paper reviews all the above mentioned experiences, emphasizing the description of the AQUASOL desalination system, which is currently under evaluation at the PSA facilities.

2. The PSA Solar Desalination Experience

CIEMAT (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, Spain) and DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt, Germany) decided in 1987 to develop an advanced solar thermal desalination system, thus initiating the so-called Solar Thermal Desalination (STD) Project carried out at the PSA until 1994. Two project phases were scheduled and executed during this period aiming to achieve specific project objectives.

Phase I was launched in 1988 and its evaluation finished in 1990. During this period a solar desalination system was implemented at the PSA, which was composed of: i) a 14-effect multi-effect distillation unit; ii) a solar thermal parabolic-trough collector field; and iii) a thermocline thermal energy storage tank. These subsystems were interconnected as shown in Figure 1. The system operated with synthetic oil that was heated as it circulated through the solar collectors. The solar energy was thus converted into thermal energy in the form of sensible heat of the oil, and was then stored in the thermal storage tank. Hot oil from the storage system provided the MED plant with the required thermal energy.

TABLE 1. Technical specifications of the PSA MED plant

Nominal distillate production	3 m^3/h
Heat source energy consumption	200 kW
Performance ratio	9.4 - 10.4
Output salinity	5 ppm (TDS)
Seawater flow:	
At 10ºC:	8 m^3/h
At 25ºC:	20 m^3/h
Feedwater flow:	8 m^3/h
Vacuum system	Hydroejectors (seawater at 3 bar)

During this phase a cogeneration scheme (power+water) was also tested. High-pressure steam was produced to drive a small power plant, and a fraction of this steam was used to feed the desalination plant, where it was sent to thermocompressors and mixed with the steam produced in the fourteenth effect. This mixture was then ejected into the evaporator of the first cell to restart the desalination process, decreasing the MED plant overall energy consumption.

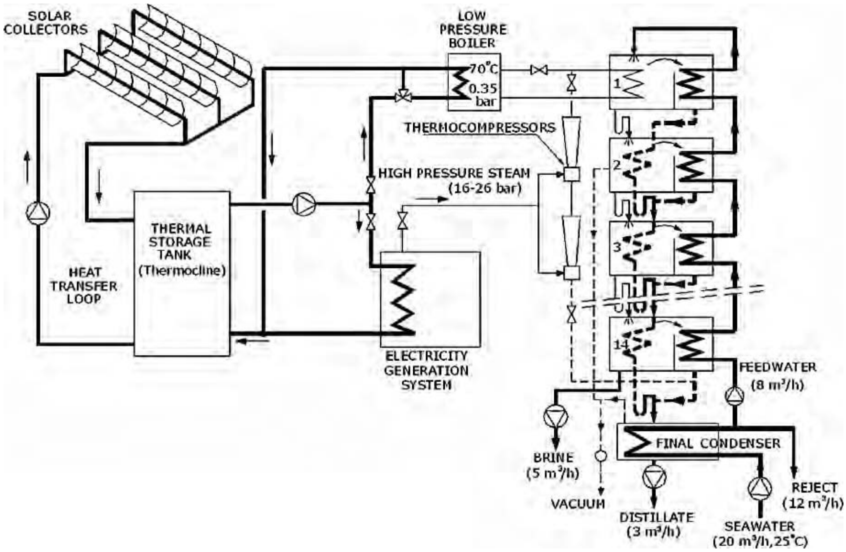

Figure 1. Schematic diagram of the solar MED system installed at PSA at Phase I of STD Project.

The solar desalination system showed high reliability in both configurations, low thermal inertia and specific electricity consumption in the range from 3.3 to 5 kW_eh/m^3 of distillate. The Performance Ratio (e.g. number of kg of distillate produced by 2326 kJ heat input) was within the range of 9.4 to 10.4 when operating with low-pressure steam, and increased up to the range of 12 to 14 when high-pressure steam was used to feed the plant.

From the results obtained during Phase I, it was possible to identify potential relevant improvements that could be implemented in the MED solar system to increase its efficiency and competitiveness. This analysis concluded that the plant electrical demand could be reduced by replacing the initial hydroejector-based vacuum system with a steam ejector system. On the other hand, the plant thermal demand could be reduced by 50% by incorporating a double-effect absorption heat pump coupled to the MED unit. Since these improvements would considerably reduce the specific cost of distillate produced by the optimized solar MED desalination system, it was decided to implement them during Phase II of the STD Project.

A schematic diagram of the improved desalination system in which an absorption heat pump was coupled to the MED plant is shown in Figure 2. The heat pump delivered 200 kW of thermal energy at 65°C to the MED plant. The desalination process in the plant evaporator body used only 90 of the 200 kW, while the remaining 110 kW were recovered by the heat pump evaporator at 35°C and pumped to usable temperature of 65°C. For this, the heat pump needed 90 kW of thermal power at 180°C. The energy consumption of the desalination system was thus reduced from 200 kW to 90 kW. The improvements implemented in the desalination system (i.e. absorption heat pump and steam-ejector based vacuum system) reduced the thermal energy consumption of the desalination system by 55%, from 67 to 30 kWh/m³ and electricity consumption by 12% from 3.3 to 2.9 kW$_e$h/m³.

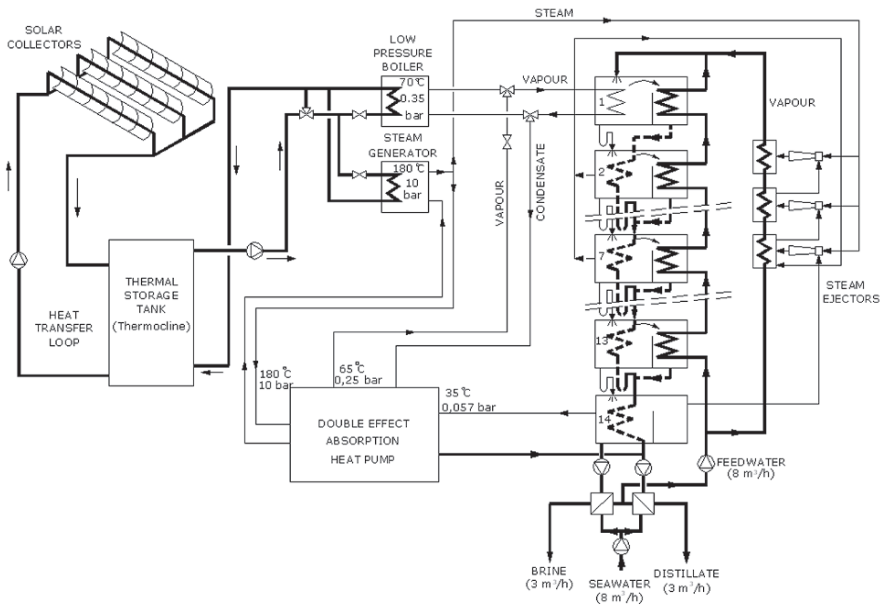

Figure 2. Improved solar MED system (STD Project - Phase II).

3. Solar Thermal System Improvement: The AQUASOL Project

Research activities in solar desalination at the PSA were boosted in 2002 by starting up a new combined (research & demonstration) project called Enhanced Zero Discharge Seawater Desalination using Hybrid Solar

Technology (AQUASOL, FP5-EVK1-CT2001-00102) partially supported by the European Commission under the Energy, Environment and Sustainable Development Programme. The main objective of this project is the development of seawater desalination technology based on multi-effect distillation that is energy efficient, low-cost and has zero discharge. In August 2004, the AQUASOL Project research phase was successfully concluded and all the subsystems were designed and implemented for their evaluation during the demonstration phase. The seawater system designed is made up of:

- A multi-effect distillation plant with 14 cells.
- A stationary CPC (Compound Parabolic Concentrator) solar collector field.
- A thermal storage system based on water.
- A double effect (LiBr-H_2O) absorption heat pump.
- A smoke-tube gas boiler.
- An advanced solar dryer for final treatment of the brine.

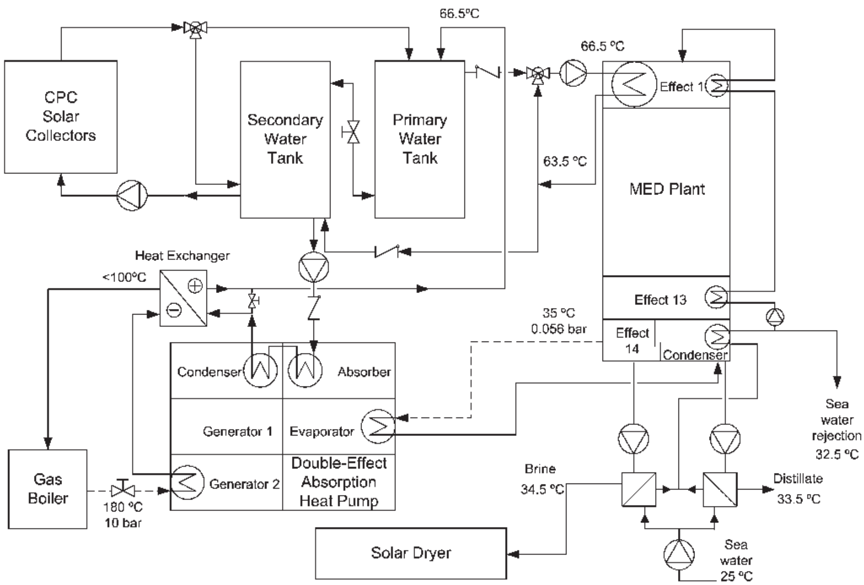

Figure 3. Final configuration proposed for AQUASOL seawater desalination system.

These subsystems are interconnected as shown in Figure 3. Unlike the STD Project, this new system operates with water as the heat transfer fluid, which circulates through the solar collectors in an open circuit with the storage tanks. In absence of solar radiation, the gas boiler feeds the absorption heat pump, which is also fed with low temperature steam from the last MED plant effect, in order to heat the water coming from first effect from 63.3ºC up to 66.5ºC.

3.1. THE DISTILLATION UNIT

The PSA SOL-14 desalination plant is a forward-feed multi-effect distillation unit manufactured and delivered by ENTROPIE in 1987 (See Figure 4). It has 14 cells, or effects, in a vertical arrangement, in which seawater is preheated on its way towards the first cell of the plant, which is at the top of the desalination tower.

Figure 4. Front view of the PSA MED Plant.

The original first cell that worked with low-pressure saturated steam (70ºC, 0.31 bar), has been replaced in the AQUASOL Project by a new one, working with the hot water coming directly from the thermal storage tank (See Table 2). A new horizontal tube bundle, front and rear water boxes and a new spraying tray with technical characteristics constrained to the dimensions of the first cell, have also been installed in the SOL-14 plant.

TABLE 2. Estimated performance of the new PSA MED plant first effect

	Desalination driven by solar collectors	**Desalination driven by absorption heat pump**
Power	200 kW	150 kW
Inlet /Outlet hot water temperature	75.0 / 71.0 ºC	66.5 / 63.5 ºC
Brine temperature (on first cell)	68ºC	62.0 ºC
Hot water flow rate	12.0 kg/s	12.0 kg/s
Pressure drop	0.4 bar g	0.4 bar g

3.2. THE SOLAR FIELD

The solar field is made up of 252 stationary solar collectors (CPC Ao Sol 1.12x) with a total surface area of approximately 500 m^2 arranged in four rows of 63 collectors (See Figure 5). Due to the specially designed hydraulic layout (reverse feeding mode), total flow rate (14.97 m^3/h) is equally distributed into the four rows (3.74 m^3/h) without further regulation.

Figure 5. 500 m^2 stationary CPC AQUASOL solar collector field.

The collectors are organized in groups of nine, all connected in parallel in each row, which in turn are connected in parallel to each other, feeding into the thermal storage system. Each group of nine collectors is organized in the following way: i) the collectors are oriented east-west to maximize energy collection; ii) each group is subdivided into three subgroups of three collectors; iii) into each subgroup, the collectors are connected in parallel; iv) each subgroup is connected to the next in series.

A transparent honeycomb-type insulation material inside the solar collector was considered during the research phase. However, at the operating temperatures that are expected in the system (below 80ºC) there is no net advantage in this. Furthermore, stagnation temperatures reached without the honeycomb are much safer in case of pump failure. The use of a new higher concentrating CPC collector prototype (1.5x) was considered, but was finally rejected because it would have meant a reduction in the number of hours operating with solar energy, and there was no need for higher temperatures than could be reached with the 1.12x CPC collector.

3.3. THERMAL STORAGE SYSTEM

The thermal storage system is made up of two interconnected 10 m^3-capacity water tanks (See Figure 6). The total volume finally chosen is based on the response time required by the gas boiler and the absorption heat pump to reach nominal operating conditions. The use of two tanks enables the solar contribution to be increased over the year as well as obtaining certain temperature stratification necessary to avoid the heat pump water inlet temperature exceeding the permissible range (60ºC – 70ºC).

Figure 6. Front view of the PSA desalination building with the two thermal storage tanks.

3.4. GAS BOILER

A propane gas-fired backup system is necessary to guarantee the particular operating conditions (the DEAHP requires steam at 180ºC) and permit 24-hour MED-plant operation (to reduce the impact of capital costs) in absence of solar radiation. During the design phase of the AQUASOL Project, it was decided to install a C-class smoke tube boiler so that the DEAHP could work at variable loads (from 30% to 100%). The gas to be burnt was stored in a 2,450-liter tank installed next to the distillation plant building. This tank volume provided an estimated autonomy of 143 hours at full load. Return condensate flow must be cooled in order to avoid flashing, and a heat exchanger was installed for this reason, transferring the energy to the stream that connects the absorption heat pump with the thermal storage tank.

3.5. DOUBLE-EFFECT ABSORPTION HEAT PUMP

The double effect absorption heat pump installed at PSA (see Figure 7) uses a water/lithium bromide solution as working fluid with the two solution circuits connected in parallel, which means that solution mass fraction that enters into each of the desorbers is identical. Parallel flow configuration offers thermodynamic and heat transfer benefits over series flow but requires more control complexity (Herold et al., 1996).

Three different system operating modes of the AQUASOL plant are possible depending on where the desalination unit energy supply comes from:

- Solar-only mode: energy to the first distillation effect comes exclusively from thermal energy from the solar collector field.
- Fossil-only mode: the double-effect heat pump supplies all of the heat required by the distillation plant
- Hybrid mode: the energy comes from both the heat pump and the solar field. It is planned to test two different operating philosophies. In the first, the heat pump works continuously 24 hours a day with a 30% minimum contribution, while second, pump starts up or shuts down, depending on the availability of the solar resource.

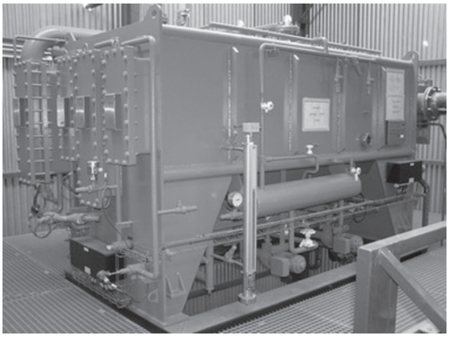

Figure 7. The new double-effect absorption heat pump installed at the PSA.

TABLE 3. Thermal design of the new DEAHP to be installed in AQUASOL Project

		DEAHP load (%)			
		100	**75**	**50**	**30**
Low pressure steam	**Power (kW)**	100	75	50	30
	Pressure inlet (bar)	0.051	0.051	0.051	0.051
	Temp. inlet (ºC)	35	35	35	35
	Flow rate (kg/s)	0.041	0.031	0.021	0.012
Cooling water	**Power (kW)**	186	136	90	60
	Temp. inlet (ºC)	64	64	64	64
	Temp. outlet (ºC)	67.7	66.7	65.8	65.2
	Flow rate (kg/s)	12	12	12	12
High pressure steam	**Power (kW)**	82	62.5	42	26
	Pressure inlet (bar)	10	10	10	10
	Temp. inlet (ºC)	180	180	180	180
	Flow rate (kg/s)	0.041	0.031	0.021	0.013
COP		1.22	1.20	1.18	1.15

Table 3 shows the thermal design of the DEAHP working at different load values. As can be seen, the coefficient of performance (COP), defined as the ratio between the power recovered at low temperature and the power delivered to the heat pump, drops as the steam load decreases.

An advanced control system regulates the three-way regulating valve in the recirculation loop of the MED plant first cell. Temperatures inside the thermal storage tanks must be carefully monitored to determine the appropriate recirculation flow and avoid temperatures above 70ºC inside the MED first effect and also the DEAHP operating load (when available solar radiation becomes insufficient to feed the MED plant by itself).

3.6. ADVANCED SOLAR DRYER

The purpose of the advanced solar dryer is to increase the concentration in the brine until it has reached the saturation point of calcium carbonate (16ºBe, Baumé scale). After the experimental evaluation of a series of small prototypes, a final solar dryer design was proposed for evaluation during the AQUASOL Project demonstration phase. This dryer consists of three parallel 4-m-x-17-m interconnected evaporation channels with brine stream circulating inside them. The evaporation channels have a plastic cover, a preheating section at the inlet, and a solar chimney located at the outlet to promote air stream inside the channels (See Figure 8).

Figure 8. Lateral view of the three advanced solar dryer modules.

A fourth open-air channel will be erected at the same time for realistic comparison of the new prototype's performance. A north-south orientation was finally chosen due to the predominant winds at the installation site. Simulation models foresee a 2.5 increase in efficiency compared to traditional open-air salt evaporation ponds.

4. Conclusions

In the current global framework, with growing oil market price instability and the environmental requirements derived from compliance with the Kyoto Protocol, sustainability of desalination must inevitably be through the improved efficiency of the technological processes involved as well as the use of renewable energies, such as solar energy. It is expected that the specific technological developments proposed in the AQUASOL project (new CPC collector designs, absorption pump, hybridization with natural gas and salt recovery) will be able to reduce the current high costs of the multi-effect distillation with solar energy. The expected result would be improved MED technology with market potential and suitable to be implanted in the Mediterranean area of our country.

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A REVIEW OF DESALINATION BY SOLAR STILL

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Abstract. This communicating article reviews desalination by solar still, and the recent studies on the solar still systems. The review includes basic principle of solar distillation, and also the quality of distilled water. A classification of the solar still systems was made in order to explain the types of solar still systems. General mathematical modeling methodology of solar stills and some mathematical modeling studies are given. The efficiency and performance of the solar still system are also given and discussed.

Keywords: Review, solar stills, performance.

1. Introduction

Distillation is one of many processes available for obtaining fresh water from salty, brackish or contaminated water; sunlight is one of several forms of heat energy that can be used to power that process. Sunlight has the advantage of zero fuel cost but it requires more space (for its collection) and generally more costly equipment to get high temperatures.

To dispel a common belief, it is not necessary to boil water to distill it. Simply elevating its temperature, at values lower than its boiling point, will adequately increase the evaporation rate. In fact, although vigorous boiling hastens the distillation process it can also force unwanted residue into the distillate, defeating purification. Furthermore, to boil water with sunlight requires more costly apparatus than is needed to distill it a little more slowly without boiling.

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Many levels of purification can be achieved with this process, depending upon the intended application. Sterilized water for medical uses requires a different process than that used to make drinking water. Purification of water heavy in dissolved salts differs from purification of water that has been dirtied by other chemicals or suspended solids.

The present dollar cost of solar-distilled drinking water is several times that of water provided by most municipal utilities, but it costs less energy-wise. On the other hand, solar-distilled water is much less expensive than bottled water purchased in the store.

For people concerned about the quality of their municipally supplied drinking water and unhappy with other methods of additional purification available to them, solar distillation of tap water or brackish groundwater can be a pleasant, energy-efficient option. Solar distillation of potable water from saline (salty) water has been practiced for many years in tropical and sub-tropical regions where fresh water is scarce. Critical seasonal water shortages happen with increasing frequency in some parts of the world.

Solar still is a distillation system which can be small or large. It is designed either to serve the needs of a single family, producing from ½ to 3 gallons of drinking water a day on the average, or to produce much greater amounts for an entire neighborhood or village. In some parts of the world the scarcity of fresh water is partially overcome by covering shallow salt water basins with glass in greenhouse-like structures. These solar energy-distilling plants are relatively inexpensive, low technology systems, especially useful where the need for small plants exists.

The aim of this study is to present the basic principles of distillation by solar still, types of solar still systems, and the recent developments in solar still systems.

2. Distillation by Solar Still

Solar still is a device to desalinate impure water like brackish or saline water. It is a simple device to get potable/fresh distilled water from impure water, using solar energy as fuel, for its various applications in domestic, and industrial sectors. The basic concept of using solar energy to obtain drinkable fresh water from salty, brackish or contaminated water is really quite simple. Water left in an open container in an open area will evaporate into the air. The purpose of a solar still is to capture this evaporated (or distilled) water by condensing it onto a cool surface.

2.1. PRINCIPLES OF A SOLAR STILL

Increasing water temperature and the area of water in contact with the air can accelerate the rate of evaporation. A wide, shallow black painted pan makes an ideal vessel for the water. It should probably be baked in the sun for a while before it is used in order to free the paint of any volatile toxicants, which might otherwise evaporate and condense along with the drinking water. The pan is painted black (or some other dark color) to maximize the amount of solar energy absorbed. It should also be wide and shallow to increase the surface area, assuming the availability of a substance with good solar absorbing properties and durability in heated salt water.

To capture and condense the evaporated water, we need some kind of surface close to the heated salt water, which is several degrees cooler than the water. The evaporating pan is usually covered by a sheet of clear glass or translucent plastic (to allow sunlight to reach the water) which is tilted to a slight angle to let the fresh water that condenses on its underside trickle down to a collecting trough. The glass cerates a cavity and also holds the heat inside. Figure 1 combines all these components in a simple solar still design.

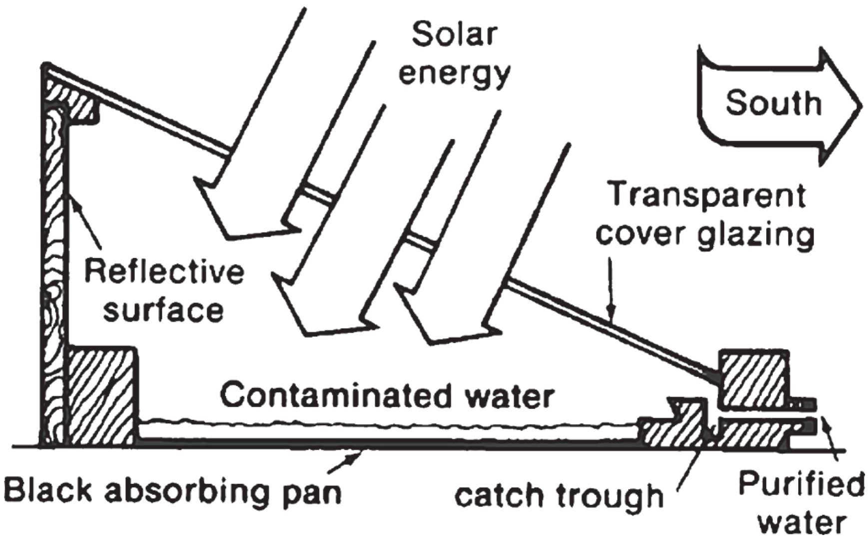

Figure 1. A simple solar still design.

2.2. WATER QUALITY

In principle, the water from a solar still should be quite pure. The slow distillation process allows only pure water to evaporate from the pan and collect on the cover, leaving all particulate contaminants behind.

Since a clean glass cover plate and storage vessel should produce no contaminants, the catch basin, or trough, remains as the potential source of direct contamination (if the design allows for catchments of rain, air pollutants in the rain could also be a form of contamination.).

The catch trough should be made of material unlikely to degrade water flowing through it, even at the moderately elevated temperatures, which might be encountered. PVC (polyvinyl chloride) plastic plumbing pipe is commonly available at relatively low cost. Since vinyl chloride has been identified as a potentially harmful carcinogen, one should be very careful about using this material in a drinking water system. Fortunately, some PVC formulations have been designed for use in potable water systems; however, other formulations are not so-designed and could pose a problem.

Secondary potential sources of contamination include materials present in the air inside the distiller, and in the lining or coating of the evaporating pan, which might somehow find their way into the water condensing on the underside of the cover glass.

It is possible that a chemical in the feed water (or in the still itself) which evaporates along with the water could condense on the underside of the cover and be carried into the catch basin. There are several ways to minimize contamination from the materials in the still itself. Preconditioning of the distiller by "baking" it under the sun for several days may be sufficient to drive off most volatiles. Non-volatile materials left behind in the concentrate may be discarded. Avoiding the use of materials containing known toxicants is another way to ensure condensate water purity.

With care in design and operation, the solar still should, therefore, be capable of producing good drinking water free of cancer-causing pollutants and other harmful substances, water that is colorless, odorless and, unfortunately, tasteless. When the minerals common to drinking water are removed, taste goes, too. One flavor recommendation is to add small amounts of minerals or salts to the distilled water, since the minerals found in water may be healthful.

Hanson et al. (2004) studied distilled water quality on a single-basin solar still. They reported the performance of a single-basin solar still for the removal of a selected group of inorganic bacteriological and organic contaminants in laboratory environment and actual field environment.

2.3. TYPES OF SOLAR STILL

Solar distillation systems are classified into two groups in terms of energy supply: passive and active solar stills. The passive solar still systems are conventional solar still systems which use solar energy as the only source of thermal energy. However, in the active solar stills, extra thermal energy is given to the passive solar still for faster evaporation. This extra thermal energy may be obtained from a solar collector (Badran and Al-Tahaineh, 2005, Badran et al., 2005, Voropoulos et al., 2001), or any available waste thermal energy from any industrial plant, such as a power plant.

In terms of structure of the conventional solar still (see Fig. 1), different types of the basin-type solar still systems can be found in literature. Examples of those are single-slope double-basin solar still (Al-Karaghouli and Alnaser, 2004), single-slop triple-basin solar still (El-Sebaii, 2005), pyramid-shaped solar still (Fath et al. 2003b), conventional solar still with sponge cubes in basin (Abu-Hijlej and Rababah, 2003), double-slope single-basin solar still (Al-Hayek and Badran, 2004).

There are some other interesting solar still designs; for instance, vertical solar still (Boukar and Harmin, 2005) which has a vertical single-wick (holding the feed water) and vertical condensing surface. Another similar design has multiple vertical-wicks and a single vertical condensing surface with flat-plate reflector (Tanaka and Nakatake, 2005). Aybar et al. (2005) studied the inclined solar distillation system in which water flows down on the inclined absorber plate (bare plate or covered with black wick) and evaporated water condenses on the inclined glass cover. Bouchekima et al. (2001) designed a capillary film solar still system. El-Bahi and Inan (1999) designed a basin-type solar still which is coupled with a condenser to increase the condensation rate. In a study by Hongfei (Hongfei, 2001, Hongfei and Xinshi, 2002), a solar still system with a regenerator is designed.

2.4. MODELING OF SOLAR STILL

Any type of solar still system can be modeled using energy balance and mass balance equations for the system. Since the main energy source is solar intensity which depends on the time of day, the basic energy and mass balance equations must be time dependent. These transient basic energy and mass balance equations, and the basic thermal resistance network for a basin-type solar still can be found in the book of Duffie and Beckman (1991).

In the modeling of the solar still, the most important parameters are convection heat transfer coefficients to estimate heat transfer from the glass, heat losses from the bottom and sides of the cavity, evaporation rate (or evaporation coefficient), and condensation rate (or condensation coefficient).

In literature there are many modeling-simulation studies of solar stills. For example, Bouchekima et al. (2003) present modeling and simulation of the capillary film solar still. Fath et al. (2003a, 2003b) present mathematical modeling of the multi-basin solar still with a passive condenser section, and thermal analysis of pyramid-shaped multi-slope and single-slope solar configurations. Abu-Hijleh and Mousa (1997) give the mathematical modeling of a basin-solar still with cooling effects of the glass cover. Janarthhanan et al. (2005) derive an analytical expression for the modeling of a floating tilted wick solar still system. In his numerical study, El-Sebaii (2005) presents the governing equations for modeling with heat transfer coefficient correlations to investigate the thermal performance of a triple-basin solar still. Tripathi and Tiwari (2004) consider the solar radiation that comes not only to the glass cover but also to each of side walls of still, and they calculate the total energy gain by the water, and they use this total energy in the energy balance equation. Aybar (2006) gives mathematical modeling of a falling-water inclined solar distillation system in his study. Voropoulos et al. (2000) discuss the transport phenomena (i.e. heat transfer between glass cover and water, and the rate of evaporation) in the conventional basin-type solar still.

2.5. PERFORMANCE OF SOLAR STILL

As in all thermal systems, we can talk about efficiency and performance of solar stills. The thermal instantaneous efficiency of a solar still is defined (Tiwari, 2002) as

$$\eta_i = \frac{\dot{q}_{ew}}{I(t)} = \frac{h_{ew}\left(T_w - T_g\right)}{I(t)} \tag{1}$$

which is the ratio of the evaporative heat transfer rate ($\dot{q}_{ev}$) from water surface to glass cover in W/m^2 to the instantaneous solar radiation intensity (*I(t)*) in W/m^2. In the Eq.1, h_{ew} is evaporative heat transfer coefficient, T_w and T_g are the average water temperature, and the average glass temperature, respectively.

The performance of a solar still system can be defined as the ratio of desired output to the required input. Here the desired output is the amount of distilled water, and the required input is of course the solar energy collected. Now we can define this concept as the production rate performance (PRP) of absorber plate, as

$$PRP = \frac{\text{Total Distilled Water within Time Interval}}{\text{Total Solar Energy absorbed within Time Interval}} \tag{2}$$

The instantaneous condensation rate is $\dot{m}_i$ (kg/s) per square meter of absorber plate. Then, the production rate performance within Δt is written as

$$PRP = \frac{\sum \dot{m}_i \cdot \Delta t}{\sum I \cdot \Delta t} \text{(kg of distilled water per m}^2\text{/ kJ solar energy per m}^2\text{)} \tag{3}$$

where Δt is the time interval over which the solar radiation intensity (*I(t)* in W/m^2) and the condensation rate ($\dot{m}_i$ (kg/s)) are measured.

Of course, the performance of the system (or efficiency of the system) depends on meteorological parameters, namely wind velocity, solar radiation, sky temperature, ambient temperature. Besides the meteorological parameters, it also depends on the water parameters, such as salt concentration, algae formation on water, and mineral layers on basin liner.

3. Conclusion

Solar still is the simplest device to get potable/fresh distilled water from impure water using solar energy as fuel. The basin type single-solar still can be classified as a conventional solar still system. There are many different designs of solar still system in the open literature. Researchers have modified the conventional solar still system to get a better performance, such as multi-basin, multi-slop solar still systems, and coupled with solar collector to increase the water temperature. Especially, solar stills look like the best choice to obtain fresh drinkable water in remote areas usage.

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SOLAR THERMAL DESALINATION USING THE MULTIPLE EFFECT HUMIDIFICATION (MEH)-METHOD

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Abstract. Solar driven desalination systems based on evaporation of sea water and subsequent condensation of the generated steam have been investigated worldwide for many years[1]. Starting from simple but sophisticated solar stills working very reliably and self sufficient on small scale drinking water production in the range up to 0.5 m³ per day, improved concepts have been realized mainly at a research level up to now. The main tasks in term of efficiency of such concepts were the reduction of specific energy consumption and by that requested solar aperture area per cubic meter of water produced daily. One of the concepts is the Multiple Effect Humidification (MEH) method. The enclosure comprising heat and mass transfer is separated from the solar collectors for heat supply of the process. Evaporation and condensation surfaces are oriented to enable continuous temperature stratification along the heat and mass transfer process, resulting in small temperature gap to keep the process running. Most of the energy afforded in the evaporator is regained in the condenser keeping the energy demand on a very low level of less than 120 kWh/m³. Such systems have been available as an industrial product since November 2005. A demonstration system was installed and commissioned in Jeddah/Kingdom of Saudi-Arabia.

Keywords: Multiple Effect Humidification–Dehumidification, Solar Desalination, Energy Recovery, Efficient, Autonomous, Decentralized, Maintenance free

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1. Introduction

The demand on reliable and autonomously operating desalination systems is increasing continuously. These systems are meant for a basic drinking water and fresh water supply for decentralized houses without grid connection in cities supplied from urban water supply fed by desalination or natural water sources. At present such customers are typically supplied by trucks or use water of desperate quality. To improve the situation of such settlements and to enable settlements in arid areas, a large number of small scale desalination systems are needed.

At the same time, present water desalination methods are an energy-intensive and highly engineered matter. For serving remote areas and small scale water demand, most of the current thermal desalination technologies are not suitable to be downscaled. Thus, thermal systems are not used in regions with low infrastructure and for the decentralized supply of remote areas because of their permanent need for qualified maintenance and electricity supply. Reverse Osmosis (RO) systems are available in small scale installations worldwide, but sometimes fail due to insufficient or unqualified maintenance.

For such locations the use of small-scale, decentralised solar desalination systems, as presented in this paper, having low maintenance demand, is desirable and makes economic sense. "Small" systems means those with product water rates of 0.5 m^3 up to 100 m^3 per day.

During the last ten years, the process of Multiple Effect Humidification-Dehumidification was further developed from the basic idea established at the University of Munich at the physics department for applied thermodynamics [6, 7, 8] up to the present state. Many years of theoretical works, laboratory research and applied field tests formed the basis for the commercial desalination system presented. The present step is a considerable one towards effective and market price conform series production of small scale desalination systems for remote areas.

Other research and development institutions realized promising technical modifications applying the fundamental idea of the MEH-method. This is based on continuous increase of temperature level along the heat and mass exchange surfaces. Main tasks are adapted enthalpy-flows of humid air and fluid exchanging energy in each level of condenser and evaporator. Some solutions apply high technical efforts to reach the aim of volume flow adaptation[14], others apply finite number of stages to approximate to the continuous solution[15]. The present configuration applies a simple but optimum designed geometrical arrangement of the heat and mass transfer surfaces to fulfill the task of adapted flows of enthalpy in each level of the system.

The principal long term reliability and energy effectiveness of the method was demonstrated in several research and demonstration projects [5,10,13], most of them in cooperation with the Bavarian Center for applied energy research in Munich.

The company TiNOX®, well known in the market since 1994 for its highly selective absorber material for solar thermal collectors, is starting new business activities within production and operation know-how of processes applying mid temperature solar thermal energy. The first appliance is solar thermal desalination. During the last three years, the series production of cost effective desalination units and systems was followed up in close cooperation with the sister company MAGE Watermanagement GmbH in Haimburg/Austria. Here the production know-how using stainless steel and plastic materials was applied to come to a cost effective production process.

2. Optimized MEH-Process Based on Long Term Experience From R & D

2.1. THEORETICAL DESCRIPTION OF THE OPTIMIZED MEH-DESALINATION METHOD

In order to run the most energy efficient evaporation and condensation process, fundamental thermodynamic principles have to be taken into account. Most important factor is the enthalpy-temperature characteristic of vapor saturated humid air at ambient pressure. This can be found to be

$$h_{humid\_air} = \underbrace{\left(c_{p,\,air} + x c_{p,\,vapor}\right)T}_{h_{sen}} + \underbrace{\left(x r_0\right)}_{h_{lat}} \tag{1}$$

Herein, if assuming saturated air at any state, the specific water content x is determined as the ratio of kg water vapor per kg of dry air. The resulting effective heat capacity $c_{p,hA}^{\mathrm{eff}}$ is derived as

$$c_{p,hA}^{\mathrm{eff}}(T) \equiv \frac{\mathrm{d}h_{hA}}{\mathrm{d}T} \equiv \equiv c_{p,air} + x(T)\cdot c_{p,vapor} + \frac{\mathrm{d}}{\mathrm{d}T}\left(x(T)\cdot r(T)\right) \tag{2}$$

As the water content of saturated humid air rises in first approximation exponentially with temperature, $c_{p,hA}^{\mathrm{eff}}$ is increasing in the same way.

On the other hand, during condensation and evaporation this heat is necessarily taken from or transferred to a volume flow of liquid water. As the enthalpy-temperature characteristic of the fluid is linear with temperature, the regarding function is depicted as

$$h_{seawater} = c_{p,\,seawater}\left(T - T_0 \right) \tag{3}$$

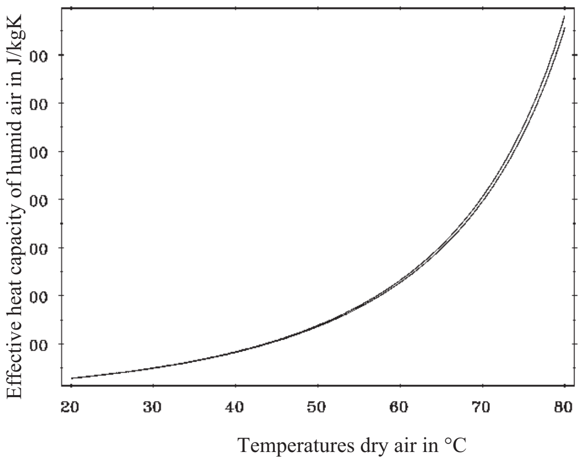

Figure 1. Effective heat capacity comprising latent and sensitive heat of a packet of saturated air at temperature T. Two lines arise due to reduced steam pressure over sea water

In case of separated chambers for evaporation and condensation, not allowing the flow of humid air to "tune" in terms of adapted enthalpy flows along the exchange areas in flow direction *z*, a temperature difference is enforced by the different enthalpy-temperature characteristics of humid air and fluid water.

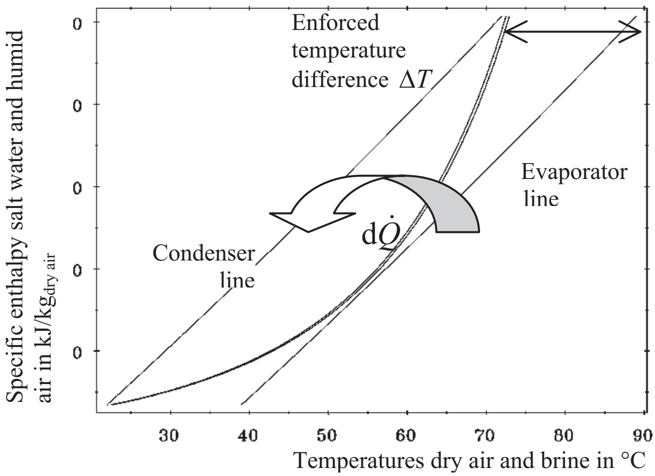

Figure 2. Heat and mass transfer in a system without adapted volume flows.

Without adaptation of volume flows of dry air and fluid, a significant global temperature difference causing high entropy production is enforced during heat and mass transfer. “Specific” herein is related to mass flow of dry air.

In order to minimize the overall entropy production over the length of the condenser and evaporator *dz*

$$ {}_{i}\dot{S} = \int_{z=0}^{z_0} \left(\frac{\mathrm{d}_i\dot{S}}{\mathrm{d}z} \right) \mathrm{d}z \approx \int_{z=0}^{z} \frac{\mathrm{d}\dot{Q}(z)}{\mathrm{d}z} \frac{\Delta T}{T^2(z)} \mathrm{d}z \tag{4} $$

the temperature gradient dT/dz of fluid and humid air has to be equalized on both sides of the heat flux process during evaporation and condensation. This can be achieved by a constant temperature difference dT in each height z. As the specific heat capacities change with temperature as pointed out above, this means that the volume flow of water and humid air exchanging enthalpy in each height element of the condenser/evaporator dz needs to be adapted in such a way, that the absolute heat capacities identified with the flow $\dot{m}_{air}(z)$

$$ C_{p,hA}^{\mathrm{eff}}(T, z) \equiv \frac{\mathrm{d}h_{hA}}{\mathrm{d}T} \cdot \dot{m}_{air}(z) \tag{5} $$

and of the water flow $\dot{m}_{water}(z)$ in condenser/evaporator are equal.

$$ C_{p,water}^{\mathrm{eff}}(T, z) \equiv \frac{\mathrm{d}h_{water}}{\mathrm{d}T} \cdot \dot{m}_{water}(z) \tag{6} $$

In the presented realization of the MEH-method, this happens by a specially defined geometrical design of evaporation and condensation surfaces, so that a part of the air flow can turn off to the other component.

In Figure 3 the flow of humid air is adapted to the heat capacity of the corresponding fluid. Thus the enforced temperature difference as depicted in figure 2 is not obtained. The finite temperature difference between condenser outlet and evaporator inlet is caused by the finite heat and mass transfer coefficients of the exchange processes involved.

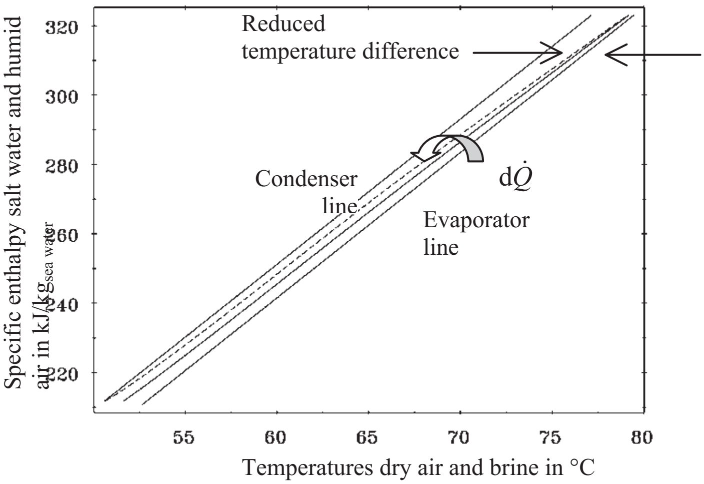

Figure 3. Adapting the volume flows of dry air and fluid in the correct way, the temperature difference is mainly determined by heat and mass flow resistances. "Specific" herein is related to mass flow of salt water.

2.2. PILOT INSTALLATIONS HAVE BEEN SUPPLYING LONG-TERM EXPERIENCE IN FIELD OPERATION

The improvements in design and operation strategy were tested in several research projects performed by the University of Munich and the Bavarian Center for Applied Energy Research from 1994 up to 2003.

A first project installation supplying fresh water from a beach well to a holiday resort started from 1994 and operated till 1999 on the west coast of Fuerteventura. The system was operated without using heat storage and was supplied by 4.2 m^2 tubular and 3.8 m^2 flat plate collector field, supplying about 0.2 m^3 of fresh water per day. The system was monitored regarding energy and water balances and the long term experience with materials is based on trial modifications at this plant.

Modified systems based on the experience from these days were installed in Sfax/Tunisia (Partners: TAS GmbH, Verein für solare Meerwasserentsalzung and Ecole Nationale d'Ingénieurs de Sfax), in Gran Canaria (CIEA/ITC und Fraunhofer ISE; Solar collectors by Fraunhofer ISE Freiburg Germany[11] (funded by the European commission) and in Muscat/Sultanate of Oman[10] (Thermosolar and Sultan Qaboos University of Muscat, funded by the Middle East Desalination Research Center, MEDRC).

3. Bringing Solar Desalination into the Market

3.1. USE OF STANDARDIZED COMPONENTS

Top task when considering series production is efficient design and standardization of components. Reasonably as many ordinary available parts as possible should be used for cost effective production. In the present case, incorporation of transport casing and device containment was an essential step towards cost reduction. A standard 20"-CSC-container ensuring low freight rates during international transportation is modified to carry the main components condenser and evaporator. An inside thermal isolation ensures optimum thermodynamic results. All parts needed for operation of the system such as pumps, valves, controllers are included in a small cabin implemented in the containment. Thus, the container is ready for operation as it comes out from production and may be quickly connected and put into operation at the respective locations.

3.2. CORROSION FREE MATERIALS ENSURE LONG LIFE TIME

Material selection is the main aspect of cost reduction potential previous to personal costs. Durability and functionality versus costs is the balance to be kept. Thus, all parts in contact with the brine are made from polypropylene or high-alloyed stainless steel. The complete casing is vapor tight and lined with welded stainless steel. Heat and mass exchange surfaces are made from specially temperature treated and heat conduction enhanced polypropylene.

Those performance enhanced condenser plates are aggregated applying a time optimized extrusion welding method to stacks of condensation units.

High effort was set on the long term durability of the installation. Based on improvements learned from the former experiences with the pilot installations, twenty years life time can be expected, ensuring reasonable water prices and low maintenance demand during operation.

3.3. DEMONSTRATION SYSTEM OPERATING IN JEDDAH/SAUDI ARABIA

Commercial desalination systems are presently set up in Arabian countries, the first operating demonstration system was set up in Jeddah /Saudi Arabia in November 2005. The system comprises a designed daily fresh water capacity of 5 m^3 and is supplied by a 140 m^2 solar thermal collector field and a 10 m^3 heat storage tank ensuring 24 hours per day water production at solar driven operation: First measuring results from this installation can be expected in Summer 2006.

Figure 4. Interior installation components manufactured by CNC-moulding cutter.

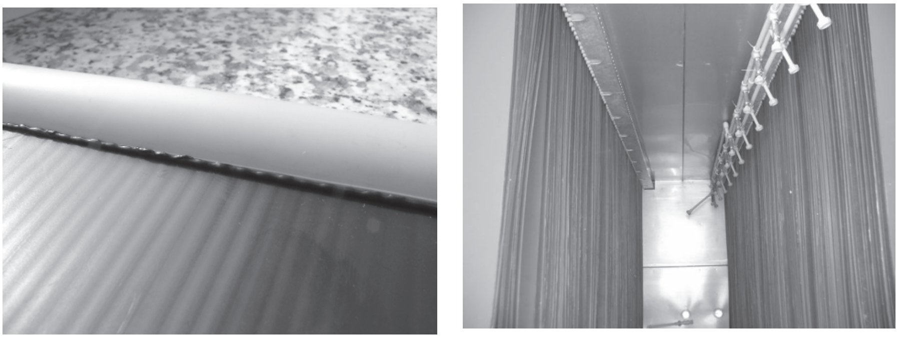

Figure 5. Newly developed plastic welding method ensures high performing condenser plates made from polypropylene material.

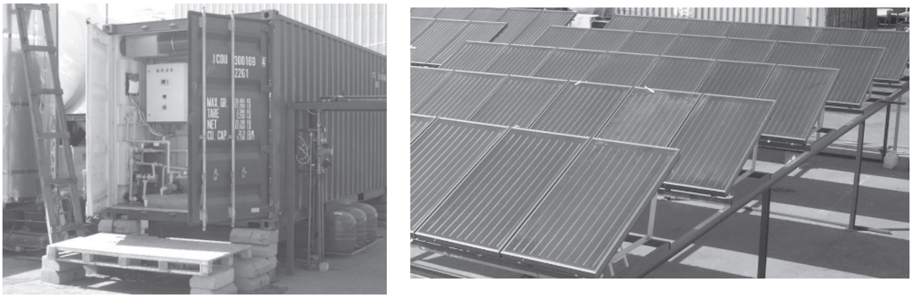

Figure 6. First commercial MEH-desalination unit produced by MAGE / TiNOX .

3.4. COST ANALYSIS OF SMALL SCALE DESALINATION PROCESSES

Decentralized fresh water supply is a matter of different responsibilities underlying different influences. These are mainly water extraction, treatment, storage and distribution. In the case of desalination, the balance between investment and operational costs is one of the main aspects for fundamental decisions regarding two possible strategies to minimize lifetime water costs: low investment or low operational costs.

For middle scale installations (water production capacities from 5000 up to more than 10000 m³ per day), the investment share on life time water costs is relatively low compared to small scale installations. At present it is reported to be in the range of between 0.2 and 0.5€ per m³ depending on the local conditions and the method applied[1]. The costs of water distribution and costs due to leakages in the distribution grid are rarely monitored. Such costs vary between 0.1 € and 0.8 € per m³ with respect to local conditions. Operational costs due to energy consumption, chemical additives dosing, maintenance and spare parts are in the range of 0.2 €/m³ to 0.7 €/m³. All of this sums up to life time water costs for mid-range installations of between 0.5 €/m³ and 2 €/m³. These are the costs for installations in middle size towns, for larger holiday resorts comprising several hotels and island installations.

For small scale installations in the range from 500 up to 5000 m³ per day, water costs in the range of between 0.7 and 3.1 € per m³ are reported. Very small installations of capacities from between 5 up to some 100 m³ per day are currently mainly served by small Reverse Osmosis (RO) installations. Due to local conditions, plants of this size are mainly operated by brackish water with salinities of between 2000 and 8000 ppm *TDS*. As reverse osmosis is highly sensitive to salt content with respect to membrane retain factor and pressures applied, the investment costs are extremely dependent on the raw water source. In the case of sea water, the investment cost share for the desalination system is between 0.5 and 1.4 €/m³. Operation and maintenance costs explode at installations of this size. Regarding sea water RO, maintenance companies report on maintenance and energy costs between 0.9 and 2.8 €/m³ including labor costs. Thus, the resulting water prices range from 1.4 €/m³ up to 4.2 €/m³. The main aspect and advantage of the presented decentralized installation is its low maintenance demand and no need of chemical pretreatment. Furthermore, the supply by low temperature heat as main energy source allows the application of waste heat from generators where available or allows the supply of relatively inexpensive solar heat, where sufficient and stable energy supply from the grid is not available. For electrical driven desalination systems such as RO units, an additional supply e.g. from photovoltaic cells (PV) or small diesel driven generator (CHP) has to be considered.

Assuming specific energy demand of decentralized RO to be 7 $kWh_{el.}/m^3$, the additional costs per m³ are in the range of 2.8 €/m³ for PV-RO and 1.4 €/m³ for RO using generator power.

Comparing those costs with the predicted water costs of solar MEH-Desalination allows characterizing the locations where the presented system has its cost advantages compared to electrical driven RO-units and where its application makes economic sense. Among these are decentralized resorts, weekend houses, military stations, remote villages and small marinas. Saving the thermal to mechanical conversion losses allows the Multi Effect Humidification (MEH) process to compete economically with the Reverse Osmosis (RO) process for such decentralized applications. This can be enforced by use of waste heat from small diesel or gas electrical generators (combined heat and power, CHP).

TABLE 1. Cost comparison for small scale desalination methods

Costs in €/m³ operation/total	**Heat source**	**Electricity source**	**1 m² per day**	**5 m³ per day**	**10 m³ per day**
MEH waste heat	CHP	CHP	4.56/6.20 €	2.86/3.94 €	2.40/3.34 €
MEH solar thermal	Solar coll.	Grid	7.22/8.87 €	5.17/6.25 €	4.77/5.71 €
MEH autonomous	Solar coll.	Photovoltaic	8.8 / 10.2 €	5.94/6.78 €	5.13/5.73 €
RO grid connected	-	Grid	-	0.90 to 2.80 € /1.40 to 4.20 €	
RO – Genset	-	Generator	-	1.00 to 2.70 € / 2.80 to 5.60 €	
RO – PV	-	Photovoltaic	-	0.70 to 2.6 € / 4.20 to 7.- €	

The final conclusion of table 1 is that reverse osmosis has light cost advantages also at small scale applications over 5 m³ per day in installations where standard electrical grid connection is available and electricity prices are at or below 0.15 €/kWh. In all other cases, the use of thermal desalination units as the MEH system should be considered when looking at the costs and easiness of operation.

Nomenclature

c_p	Specific Heat Capacity
h	Specific Enthalpy
m	Mass
Q	Heat
r_0	Evaporation enthalpy
S	Entropy
T	Temperature
x	Water load of humid air in kg/kg
z	Height in 3-Dimensional coordinates

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BEYOND PILOT PROJECTS: THE FEASIBILITY OF IMMEDIATE TECHNOLOGY TRANSFER FROM TRIED AND TESTED MARITIME AND OFFSHORE REVERSE OSMOSIS SYSTEMS TO STATIONARY SOLAR AND WIND POWERED DESALINATION SOLUTIONS

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Abstract. Recent years have seen a large number of newly developed pilot projects for solar desalination based upon a variety of technological approaches. This paper explores the possibility of moving into direct installation and practical application of small to medium sized off-grid hybrid (solar, wind) powered Reverse Osmosis desalination systems using commercially available energy optimized equipment from the maritime, yachting and off-shore sectors. The focus is on exploring the feasibility of implementing this technology for remote applications in rural settings of developing countries. Various systems including an actual application are presented, as well as energy options and operational problems described, keeping appropriate technology requirements in mind. Some economic considerations are included.

Keywords: renewable energy, desalination, Reverse Osmosis, technology transfer, water supply, appropriate technology, rural development

1. Introduction

During the last 100 years many different technologies for solar desalination and water treatment have been devised, mostly resulting in small scale pilot projects or single household drinking water solutions based upon various

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solar distillation and humidification/dehumidification concepts. More recently, a number of newly developed renewable energy based Reverse Osmosis pilot projects and also market ready solutions have been developed and installed. A number of feasibility studies were carried out and various new energy recovery options developed and tested. Examples for newly developed market ready technologies are the Photovoltaic based Australian Solco Desalination System, which is successfully operating with brackish water in the Maldives, and the German Wind Powered Desalination Systems developed by ENERCON, which has been successfully running as a prototype for several years. However, it is surprising to see that there have been a large number of pilot projects during the last ten years that have never resulted in wide spread application of solar or wind powered RO technology, despite the clear and desperate need for functional and reliable off-grid water demineralization solutions in many rural locations around the world.

As a consulting scientist, I am less interested in developing new technologies than in finding applicable existing solutions, and from the point of view of this author, there are numerous readily available and well-tested options which are ready for immediate application. In the maritime sector several companies have long offered reliable, lightweight and small scale energy optimized Reverse Osmosis solutions, especially for yachting applications. These systems have been built, tested and operated by the thousands, often under difficult circumstances, and there are three decades of experience with reliability, maintenance and life cycle assessment[1] (Horizon Company Information, 2004). In addition this technology is surprisingly economical, which is mainly the result of competition and standardized industrial mass production. There is no tangible technological reason, why maritime Reverse Osmosis equipment should not be installed in Photovoltaic or wind powered settings, for which I will later show an example.

In addition to mere technological feasibility, appropriate technology requirements must be kept in mind. As summarized for example by van der Valk (2005) appropriateness depends on[2]:

1. Accessibility for the people using the technology
2. Functionality of the technology
3. Quality of the technology
4. Sustainability
5. Manageability
6. Enabling environment

The above points, which are of interest to all involved aid and development agencies and authorities, will be addressed.

2. Accessibility and Functionality of the Technology

2.1. AVAILABILITY AND ACCESSIBILITY

All-in-one off-the-shelf marine Reverse Osmosis 'Watermakers' with capacities between several hundred and a few thousand liters per day, are offered by several manufacturers and distributors literally around the globe.

Some of the major manufacturers in Europe and the United States are:

- Schenker (Italy, www.Schenker.it)
- Spectra Watermakers (California, www.spectrawatermakers.com)
- Horizon (California, www.hrosystems.com)
- Stromme (Norway, www.stromme.com)

According to company information from Horizon, a global network of 200 licensed dealers exists for Horizon (seemingly also known under the brand name "Sea Recovery") Watermakers alone. A major distributor in Germany which provided me with significant information is the marine supply and outfitting company Ferropilot (www.ferropilot.de). The company kindly provided me with detailed technical literature and experience reports on various marine RO Systems. The systems are available on short notice and can be shipped to and installed in any location at short notice. In 2005 Ferropilot delivered 8 marine Reverse Osmosis water making kits for application within post-Tsunami aid projects in the Aceh province in Indonesia. The systems are readily available.

2.2. TECHNICAL ASPECTS AND PERFORMANCE

The following concrete technical example refers to the model "Schenker Modular Electron 60" and is translated / reprinted with the permission of internal Ferropilot company publications[3].

Watermaker Group Dimensions:

- Length: 67 cm, width: 30 cm, height: 30 cm; weight: 29 kg
- Pumping-Group Dimensions:
- Length: 34 cm, width: 9 cm, height: 35 cm, net weight: 12 kg

- Power supply: 12 VDC +/- 20 % (version 60M12); power consumption: 250 Watt average, including pumps and installed pre-filters, leading to a standardized energy requirement of ca. 4.2 kw/h per cubic meter product water. Different power supply options (120 or 230V AC) are available.

The production rate is in the range of 60 l/h +/- 20 % with salt water at 25° C and a salt content of 35,000 ppm. The average continuous quality of the product water is in the range of 300 ppm TDS. Typical limits are temperatures of 40° C and TDS above 50,000 ppm.

Some of the latest systems operate without anti-scalants and anti-foulants, using physical solutions instead, so the ongoing need for an ongoing and costly supply of chemical components will no longer be a major issue. Progress also was made regarding the membrane lifecycles. In continuous operation the membrane lifetimes range between 2 and 5 years, with suggested cleaning intervals of one to two years.

Systems like the one described here are shipped ready to install with all plumbing and repair kits included, and the capacity is already sufficient to supply a small village with drinking water, and Ferropilot assured that it would be possible to provide maintenance training for local technicians.

2.3. GOING SOLAR

To use the words of Peter de Vries, CEO of the renewable energy service company "Contained Energy" in Jakarta, the only difference between installing a marine Reverse Osmosis unit on a yacht to installing one that is hooked up to solar energy on land is that the latter is much easier to do. Contained Energy routinely offers Photovaltaic powered solar RO sets in Indonesia, entirely based upon standardized industrial products, namely Mitsubishi solar panels, high performance batteries, the required electronics and standard Horizon/Spectra Watermakers[4].

The main issue with Reverse Osmosis is that it needs a reliable and continuous power supply, and since solar and wind energy are notoriously variable the only viable solution to date is to include batteries in the electrical system. Numerous doubts have rightfully been raised related to the batteries in terms of environmental friendliness, sustainability and reliability, or in short: their general appropriateness. As a result during the last years several researchers and research groups invested significant effort in developing renewable energy based RO systems that operate without batteries. However, despite some very noteable technical achievements, so far no such technology has achieved market readiness (see for example Thompson, M. and Infield, D. 2002, for an overview of batteryless approaches[5]). Having said that, I shall proceed further and look for solutions that are available.

2.4. UNIDO APPROACH TO RURAL ELECTRIFICATION

It is noteworthy, that in the field of photovoltaic based rural electrification in developing countries, the rural energy programme of the United Nations Develoment Organisation considers battery based installations as appropriate technology. The reason is simply that there is no alternative to batteries if continuous power supply is to be assured throughout the night. At the same time, as environmentally problematic as they may be, lead batteries are widely available even in rural regions of developing countries and hence are not a scarce resource. Maintenance as well as replacement can be organized even in remote locations[*].

The following is an example of a UNIDO plan for the installation of hybrid (wind, PV) power systems for community center electrification in Sudan. The text is quoted and reprinted with the permission of UNIDO (Alexander Varghese, UNIDO initiative on rural energy for productive use, Vienna[6]).

"During day time, DC power generated by the solar PV array is stored in the battery bank through a hybrid controller, which maximizes charging current and prevents excessive discharge/overcharge. Wind turbine generator starts generating power when wind speed exceeds cut-in speed of the mini wind turbine (above 2.7 m/s). Output from the wind battery charger is also stored in the battery bank through hybrid controller. During windy periods excess energy generated by the wind battery charger is dissipated through a progressive heater (Dump Load). The wind turbine is self-regulated type with protection for overspeed. Energy stored in the battery is drawn by electrical loads through the inverter, which converts PV power into AC power. The inverter has built-in protection for short-circuit, reverse polarity, low battery voltage and overload. The battery bank is designed to feed the loads up to two days, during non-sun/wind days.

SOLAR PV - WIND HYBRID POWER SPECIFICATIONS of 5 –10 kW:

- PV array power = 2100 to 3600 watts
- Micro wind turbine/generator = 3.5 to 6.5 kW

[*] Based upon own observations and personal communication with Sunil Ghorawat, CEO of Fontuswater, Delhi, who re-emphasized this point during a concrete project discussion

- System voltage = 48
- Battery bank capacity, (*not indicated*) – industry itandard
- Solar PV module, model: (not indicated) – industry standard
- No. of solar PV modules: (not indicated) - Industry standard
- Inverter rating (VA): 5000
- Output AC wave form: Sine-wave
- Output AC voltage (V_{nom}), +/-10%: 230 V/AC
- Output AC frequency, Hertz, +/-0.5 %: 50 Hz.

(…)

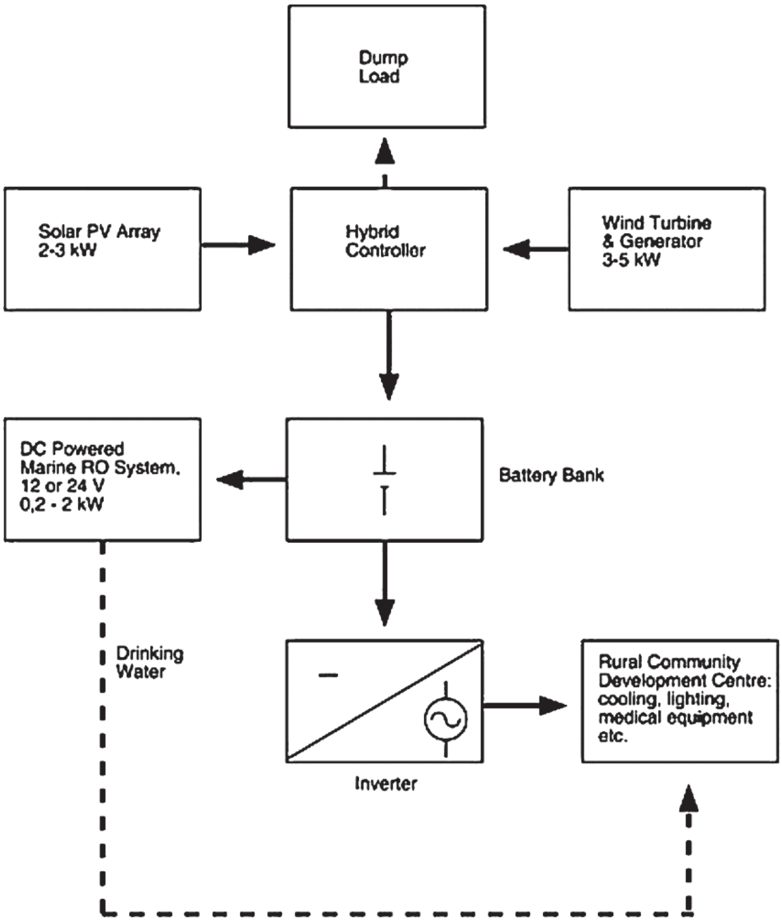

Figure 1. Combined Community Centre Electrification and Water Desalination with Renewable Energy.

Single crystalline solar cells (are used), which is the industry standard. Solar cells (are) to be laminated between high transmission, impact-resistant glass using ultra violet resistant polymer to provide (…) protection (from environmental influences), reliability and ruggedness. Anodized aluminium frame to facilitate mounting and installation."

Again, we talk about a standard layout entirely utilizing established technology. An optimized marine Reverse Osmosis desalinator could easily be added to this system, which also requires regular attention of a technically trained person (not necessarily a fully trained technician).

2.5. SUSTAINABILITY, MANAGEABILITY AND THE ENABLING ENVIRONMENT

While quality aspects are not a major issue for this discussion, since all the manufacturers of marine RO systems adhere to modern total quality management standards, the issues of this heading are all of major concern and need to be addressed through research. It is my assessment that technology is not the problem, while capacity building and acceptance of this technology are. In 2005 I talked privately to a Tunisian expert on renewable energy. I asked to what degree rural communities in Tunisia would accept modern water treatment technology based upon renewable energy. His answer was plain: They don't. I do not know if the situation is that extreme, but experience and research into past projects show that socio-economic and psychological factors are the main issues regarding the long term success of a project. The systems are available and – certainly in the context of increasing fossil fuel prices and looming oil scarcity – economical, but long term strategies for their continued operation need to be developed.

The approach of the Australian company Solco is to offer a total water solution – a solar powered RO system including bottle-filling and cleaning station all installed in one container. In addition the entire operation, maintenance and water distribution is carried out by members of the local community[7] (presentation by Ali Kanzari on the ADU-RES workshop in Hammamet, 2005). The immediate competitor is bottled water that has to be transported by truck or boat, and not large scale urban water supply, making the Reverse Osmosis water quite competitive.

Environmental sustainability is a highly important factor, and the only issue that may be of concern in this context may be the use of lead or other heavy metal accumulators. But when it comes to an immediate life-and-death issue like the much needed drinking water supply, this may be a small price well worth paying, in comparison to the alternatives.

The main issue is to identify the stakeholders, identify existing capacities, convince local communities of the importance and reliability of this technology and establish the required maintenance networks. Here education plays at least as big a role as technology. The outlined approach can definitely be applied instantly, wherever funding is available and proper oversight guaranteed.

2.5.1. *Economic- and Cost issues*

Standard modular off-the-shelve systems are available at low prices and can easily be outfitted with solar or wind powered electricity supply. While the initial capital costs are clear, the ongoing operation and maintenance depends on many factors, including cost and availability of qualified local labor, spare parts, pumping and storing requirements and drastically differing water quality requiring very different pre-treatment (filtering, sterilizing, anti scaling) efforts.

An example of a fully packaged small scale system is the PV-RO system offered by the Indonesian company "Contained Energy"[8]. It consists of:

- Spectra Watermaker "Cape Horn"
- Remote control panel
- 4 x 120 WP Mitsubishi PV Panels
- Solar Tracker
- Controls & Gel Batteries for 20 x 7 operation

The system produces 1000 l drinking water per day and comes with a one year warranty on the overall system and a 20 year warranty on the solar panels. The total price as of summer 2006 is US$ 9990 or € 7845 respectively or € 7.8 investment per litre daily production capacity. If a lifetime of 10 years and annual operation costs of 10% of the initial capital costs are assumed, the average water price for ten years of operation would be in the range of ca. € 4.30/m^3 or ca. € 2.15 for twenty years lifetime. Currently in Germany the combined freshwater and wastewater costs are in the range between ca. € 4 and € 10, so the solar RO system of Contained Energy can be considered competitive. If the costs for bottled water are taken into account, solar powered RO systems are vastly superior from the economic point of view.

Another highly innovative approach is the "Spectra Aquifer", a miniature stand-alone desalination factory in-a-box. The entire self contained kit was specifically designed for use under rugged expedition conditions. It is ready to use and includes feed-water pump, pre-filters, pressurizer, energy recovery system, built in batteries, and it comes fully assembled in an easily transported container[9]. The Australian Marine supplier Outback Marine offers the Aquifer 150 with a daily production capacity of 524 litres for AU$ 10404,69 or ca. € 6121, an initial investment per litre daily production of ca. € 11.61. Also available is the Aquifer 350 with a daily capacity of 1368 litres. It is listed with AU$ 13988.73 or ca. Euro 8230, and initial investment of ca. € 6 per litre daily production capacity[10].

These systems already are affordable and easy to use, and they can be considered cost-effective applications within various settings for both ongoing water supply as well as emergency assistance.

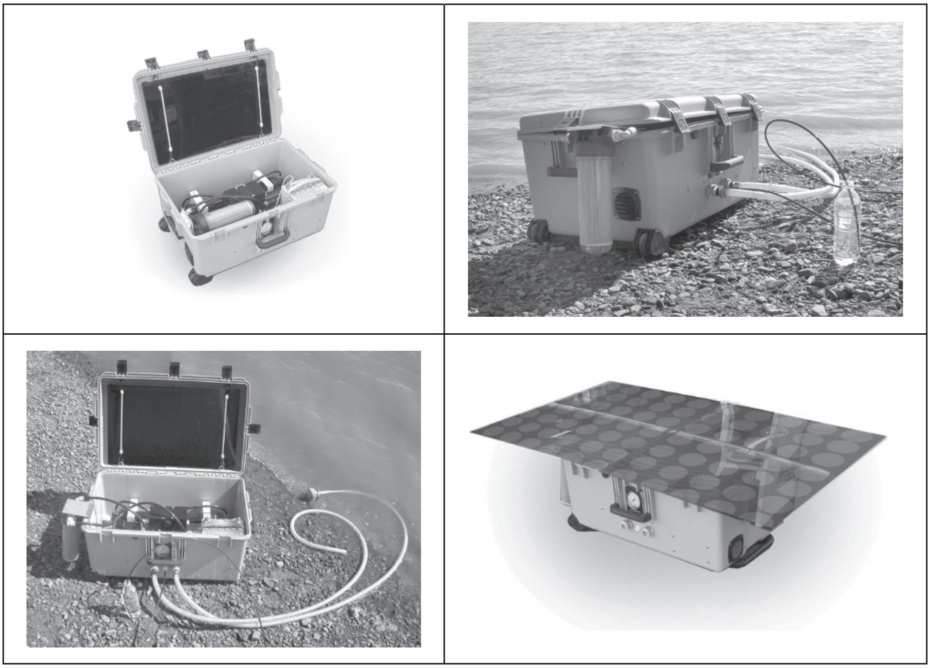

Figure 2. some pictures of the Portable Spectra Aquifer 150 solar Desalination system (pictures published with permission of Spectra Watermakers).

2.5.2. *Is Community Water management a Solution?*

The history of water aid projects is a history of failure, and the latest fashion in this field bears the promising title "Community Water Management". As Schouten and Moriarty (2003, p. 18 f) point out, Community Water Management arises out of need and often as a response to failure of structures within national government or international organisations[11]. They stress that communities, especially small rural communities in developing countries, cannot solve the problems by themselves. Any community based approach to water management and water supply needs to be embedded in a larger, possibly hierarchical, enabling environment on regional and national levels to guarantee ongoing training, support, maintenance and information exchange about procedures and experiences among communities and community water managers and technicians.

Claude Bile-Bile of MINMEE[#] (2001) described a number of problematic factors and possible solutions related to community water management in Cameroon – this does not specifically refer to desalination technologies, but the general aspects remain valid. The main issue is again that appropriate technology is available, but there are major problems related to the continued monitoring and maintenance, which include[12]:

- Discontinued state services
- Insufficient abilities of managing committees compared to the size and complexity of the systems they manage
- Lack of sanctions of recalcitrant users for failing to contribute to operation and maintenance
- Frequent interventions by incompetent actors in the sector
- Highly diversified technology creating maintenance difficulties even in even the same region
- Absence of professionalism on the part of some state actors
- Absence of legal national policy guiding intervention in the sector

Several approaches to address these inhibiting factors have already been partly implemented in Cameroon, among them:

- Regional harmonization of manual pumps to facilitate maintenance
- Consolidation of a network of local technicians for repairs
- Water resources law in the process of being promulgated
- Old systems with sophisticated (complex) technology are being transformed and simplified to enable management by users

Other measures that are equally valid for the implementation of existing solar and wind energy solutions in combination with readily available energy optimized portable Reverse Osmosis desalination technology include:

- Training and incorporation of young, local entrepreneurs in the maintenance system

[#] Le Ministère des Mines, de l'Eau et de l'Energie, Cameroon

- Future involvement of municipalities (and regional governments) in supporting assisting management committees in tasks above their capacity and capability
- Creation of an adequate institutional framework for the sector

3. Conclusion

The technology for solar Reverse Osmosis desalination in rural areas of developing countries already exists and could be instantly applied. Every desalination technology, including for example the most simple, low capacity solar stills, needs a minimum amount of attention in the form of maintenance, repair and operation procedures to assure continued operation and product water safety. This will also be true for every future technology. The problems that need to be addressed are mainly social, financial and political and not of technological nature. To not seriously address and solve them is entirely unacceptable in the face of pressing needs in a world where five million children die annually from consuming unsafe drinking water. This situation is not only an ongoing humanitarian disaster of enormous proportions – it also is a serious security issue that needs to be tackled from all sides.

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SOLAR STILLS: 10 YEARS OF PRACTICAL EXPERIENCE IN COMMERCIALISING SOLAR STILLS WORLDWIDE

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Abstract. The purpose of this document is to explain the principle of a commercial Solar Still developed by Wilfried Rosendahl, Germany. It explains the practical and decentralized application of such as system and the experience over many years of operation.

Keywords: Solar Still, decentralized, renewable, affordable, drinking water, distilled water

1. Working Principle of Solar Still

The Rosendahl system is a single-step process, in which the power production, evaporation and condensation takes place in a single collector.

The collectors can distil nearly any kind of water - although the system was initially developed for sea or brackish water. The untreated water is most commonly extracted from an intermediate tank, or taken directly from a pipe. Untreated water can come from wells, rivers, lakes or the sea; basically almost any kind of raw water can be used.

A patented electronic monitoring system with the help of a radiation sensor regulates the quantity of the untreated water to the collector or a whole group of collectors, thus allowing that only the right quantity of untreated water is processed by the system with respect to the radiation of the sun.

Only the exact amount of untreated water then passes into a channel for untreated water in the collector "1” , and then drips over wicks onto a black absorber fleece “5”. This special fleece can handle UV rays for many years and is food genuine.

L. Rizzuti et al. (eds.), Solar Desalination for the 21st Century, 239–246.

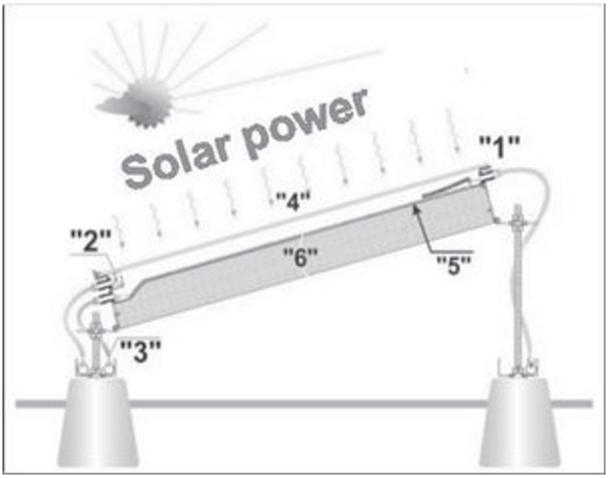

Figure 1. Detailed view of the Rosendahl collector and its working principle.

Figure 2. View how raw water enters fleece.

Figure 3. This picture shows how the water condenses underneath the glass and how it leaves the collector.

The heat insulation "6" prevents losses of energy by the collector bottom. Using only energy from the sun the moist fleece heats up to temperatures of 80-90 °C. Around 50 % of the untreated water evaporates and condenses under the cooler glass cover “4”. The glass cover is made of standard window glass and can be obtained from any standard glass dealer.

This condensed liquid is the drinking water and it flows into a condensation channel "2”, and flows out of the side of the collector. The remaining untreated water "3”, leaves the collector. It carries the dirt and salt from the fleece. However, the remaining untreated water is also purified on its way through the collector, by a combination of UV rays (sterilisation) and high operating temperature.

All metal components which come into contact with water are made of stainless steel, the precondition for the longevity of the product. All outside parts are galvanized. The assembly takes place usually on sturdy threaded rods. In connection with hinge holding the gutters are easily put into a horizontal position while the absorber fleece is positioned in a precisely defined angle. The lifespan and the safety of the collectors can now be expected to be over 20 years.

The intake of untreated water must be performed in such doses that around 50% evaporates and 50% remains as brine. Too much raw water results in unnecessary heat loss and therefore poor performance. Too little leads to salt crusting and drying-out, also poor performance. In order to get to grips with these problems a guided electronic control system was developed, which controls a solenoid valve.

If sea water is used as untreated water then the brine can be converted into sea salt. This enables sea salt production to be used as an additional source of income. Otherwise, the brine must be transferred back to the sea, which poses no environmental problems whatsoever. It is also possible to establish a seepage well.

Figure 4. This picture shows the inventor with a F8-250 Compact Unit that carries all the parts needed to purify water virtually anywhere (decentralised).

When obtaining sea water from a site on the coast it may be possible to use a well as source. This has the advantage of filtering the water to a certain extent. The processing of fresh water is mostly used in smaller, family-friendly plants, for producing mineral and germ free drinking water. The waste water from the collectors can be used here for watering plants or other uses.

The collector itself is mounted and embedded on a metal frame. Additionally it carries a solar collector to run any pumps and the electrical control unit (incl. a rechargeable battery). It has two tanks, one for the raw water and one for the drinking water and connected with pipes.

The only difference in the type of collectors is their size. The basic principle is the same in all of them. Over the years the collectors have become more and more efficient. Currently the 8th generation of collectors with a production per m^2 of collector surface of 6-8 litres per day is standard. The versions are reflected in the product name F8 (F stands for Flat Collector). 2 sizes are available:

F8-Mini: 1006 x 806mm, 0,8m^2 surface, production* ca. 5 litres per day
F8-250: 2520 x 1050mm, 2,5m^2 surface, production* ca. 15-20 litres per day

*depending on local climate

The collectors are scalable according to your budget needs or the required water production. You could easily add collectors to existing collectors or remove them individually. Even if one collector breaks, the others will continue the production. The collector itself is extremely robust and easy to repair, as the cover glass might break. Since there are almost no moving parts it is not very likely that a collector is not working properly or breaks down at all.

The largest true life application of this system is available with our partner in Puerto Rico called Solasia de Puerto Rico. Basically Solasia is offering a packaged solution with a raw water tank, Rosendahl Collector and a solar cell that provides all required electricity for pumps etc as well as the indoor installation (cable, pipes etc) for private households that do not have a reliable drinking water source. The system works in principle are shown in the following.

Figure 5. Solar stills integrated in household.

2. Household Size Installation

In household installations the input is the raw water from public sources where quality and reliability are not always perfect. The raw water is stored in tanks on the roof (gravity system) in this case (possible also in gardens, backyards, etc) and used for toilet or in the kitchen. The raw water is also fed into the collectors that produce drinking water. The drinking water is stored in a tank in the house (or anywhere else) and used with a separate tap in the kitchen as pure drinking water. The remaining raw water leaves to a rainwater tank as can be used to water the garden etc.

3. Group Size Installation

A group of 4 collectors was produced and set up in Egypt using a salt water well with salt production as a by product. Important lessons with mixed results in the quality of local material as well as social factors have been learned.

Another group of 4 collectors was placed in Cuba for scientific research and testing. Excellent results were obtained in the practical application as well as in the quality of the drinking water (distilled water).

RSD Collectors are freely scalable. Up to 100 collectors can be set up in a group still using only one set up of electronic controls.

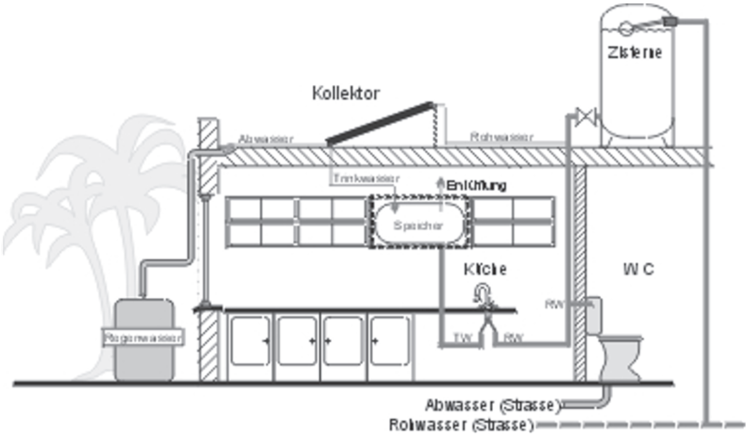

Figure 6. Complete package of licensed partner in Puerto Rico including raw water tank, solar cell, Rosendahl collector.

Figure 7. Group of 4 collectors in Egypt.

Figure 8. Group of 4 collectors installed in Cuba.

4. Local Production

Practically all of the components of the Rosendahl system can be purchased and produced locally.

The benefit of working with local partners is that they know best the local requirement, that they can install and run the system, are contact point for any queries and deal with the local community. They only use RSD collectors as a core and build the infrastructure around it themselves.

Figure 9. Training in Germany.

5. Training/Know How Transfer

In order to train and help local people to produce or install the RSD System Wilfried Rosendahl either goes into the countries or have guests coming to see the production live in our factory in Hanover/Germany. The picture shows the latest training of an engineer from Mali/Africa. An extensive video coverage that demonstrates the system, how it is set up, how it works in detail etc is already available on our internet site in the section for our partners. Some video are also available for public use (multimedia). Plenty of photos for our partners document each step of the collector production.

This DVD documentary video about all the installation and technical details is available and passed on to the trainees.

6. Water Quality

The drinking water or distillate produced from the RSD Rosendahl System has been tested and reviewed by the American "Water Quality Association" in 1999 and was awarded with its gold medal. The objective of WQA is to help consumers choose quality water treatment products. WQA developed its Gold Seal Certification Program—issuing the first Gold Seal in 1959. WQA only awards the Gold Seal to those systems, components, or additives that have met or exceeded industry standards for contaminant reduction, structural integrity, and material safety. It has also been tested and verified in China and other countries.

7. About DWC

DWC is a water consultant that is offering its clients independent advice on the most appropriate product and processes for a sustainable, decentralized and renewable water supply and waste water management. We believe that the shown product could be a possible solution for a specific problem whereas other challenges might require a different approach selecting and applying other products and services.

SOLAR DRIVEN DESALINATION SYSTEMS BASED ON MEMBRANE DISTILLATION

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Abstract. New membrane distillation modules and desalination systems were developed which are completely powered by solar energy for stand-alone operation. The membrane distillation modules with heat recovery function need about 100 kWh of thermal energy per m^3 of high quality distillate (conductivity as low as 20µS/cm measured). Four 'compact systems' with a capacity of about 100 litres/day and a larger 'two loop system' with a capacity of about 1000 litres per day were installed recently.

Keywords: desalination, solar desalination, membrane distillation, solar collectors, renewable energy driven desalination systems, drinking water.

1. Introduction

In many places world wide drinkable water is already scarce and it is commonly expected that the lack of drinking water will rise dramatically in the future. Today, sea and brackish water desalination plants are well developed in industrial scales to provide big cities with fresh water. Small villages or settlements in remote rural areas without infrastructure do not profit from these techniques. The technical complexity of the large plants is very high and can not easily be scaled down to very small systems and water demands. Furthermore, the lack of energy sources as well as a

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missing connection to the grid complicates the use of standard desalination techniques in these places. In arid and semi-arid regions the lack of drinkable water often corresponds with a high solar insulation. This favours the use of solar energy as the driving force for water treatment systems. Especially in remote rural areas with low infrastructure and no grid connection, stand alone operating systems for the desalination of brackish or sea water are suitable to provide small settlements with clean potable water.

Within the scope of two projects co-financed by the European Commission, the Fraunhofer ISE develops solar driven 'compact desalination systems' for capacity range between 100 and 500 l/day and 'larger systems' for the capacity range up to 20 m³/day. All systems are completely solar energy driven. The energy for the desalination process is supplied by solar thermal collectors, the energy for auxiliary equipment such as pumps and valves is supplied by PV. The development focuses on the very low technical complexity and a long maintenance-free operation time.

2. Membrane Distillation (MD)

The desalination technique used in the systems is the membrane distillation technique, see references. Apart from some experimental systems the MD-technique has not been used in conventional desalination plants up to now, but with regard to the implementation into solar driven stand-alone desalination systems it holds important advantages.

- The operating temperature of the MD process is in the range of 60 to 80 °C. At this temperature level solar collectors perform well.
- The membranes used in MD are resistant to fouling and scaling.
- Chemical pre-treatment of the feed water is not necessary.
- Intermittent operation of the module is possible without heat storage.
- The system efficiency and the high water quality produced are almost independent of the salinity of the feed water.

The principle of membrane distillation is briefly described in the following: Contrary to membranes for RO, which have a pore diameter in the range of 0.1 to 3.5 nm, membranes for membrane distillation have a pore diameter of about 0.2mm. The separation effect of these polymer membranes is based on their hydrophobic nature. This means that up to a certain limiting pressure, liquid water can not enter the pores. Molecular water in the form of steam can pass through the membrane. Figure 1 illustrates the operating principle of membrane distillation. On one side of the membrane there is salt water, for example at a temperature of 80°C. If there is a lower temperature on the other side of the membrane, created for example by cooling the condenser foil to 75°C, then there exists a partial pressure difference for water vapour across the membrane. This is the driving force that makes the vapour pass through the membrane. The water vapour condenses on the low-temperature side and distillate is formed.

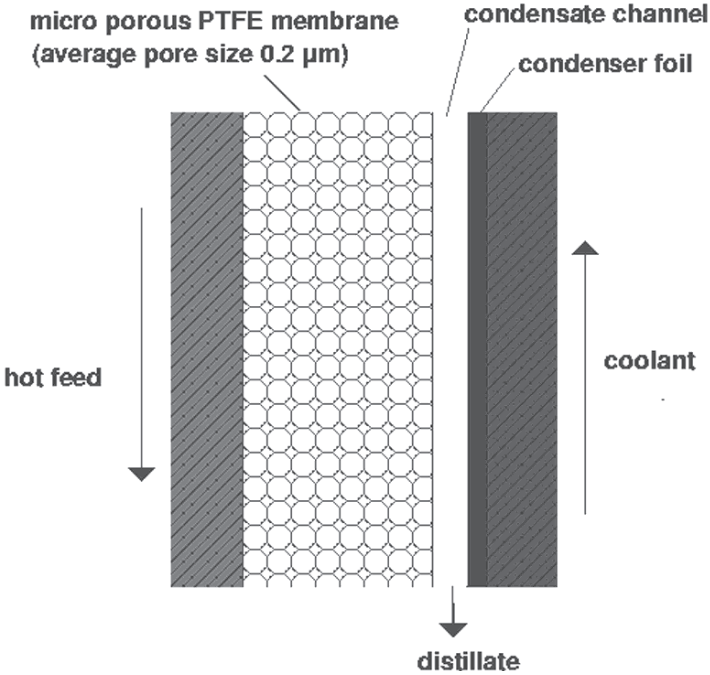

Figure 1. Principle of membrane distillation.

For the design of a solar-powered desalination system, the question of energy efficiency is very important, since the investment costs mainly depend on the area of solar collectors to be installed. Also, the power consumption of the auxiliary equipment (for example the pump) which will be supplied by PV has an important influence on the total system costs. Therefore, the system design has to focus on a very good heat recovery function to minimise the need for thermal energy. Heat recovery can be achieved by an external heat exchanger or by an internal heat recovery function, where the feed water is used directly as a coolant for the condenser channel.

The internal construction principle of the MD module with integrated heat recovery is shown in figure 2. Altogether, there are three different channels: the condenser channel, the evaporator channel, and the distillate channel. The condenser and the distillate channel are separated by an impermeable condensation foil, while the evaporator and the distillate channel are separated by a hydrophobic, water-vapour-permeable membrane. The hot water (e.g. 80°C inlet temperature) is directed along this membrane, passing the evaporator channel from its inlet to its outlet while cooling down (e.g. 30°C evaporator outlet temperature). The feed water (e.g. 25°C inlet temperature) passes the condenser channel in counter-flow from its inlet to its outlet while warming up (e.g. 75°C outlet temperature). The partial pressure difference caused by the temperature difference across both sides of the membrane is the driving force for the steam passing through the membrane. The heat of evaporation is transferred to the feed water by condensation along the condenser foil. Thus the heat of evaporation is (partly) recovered for the process.

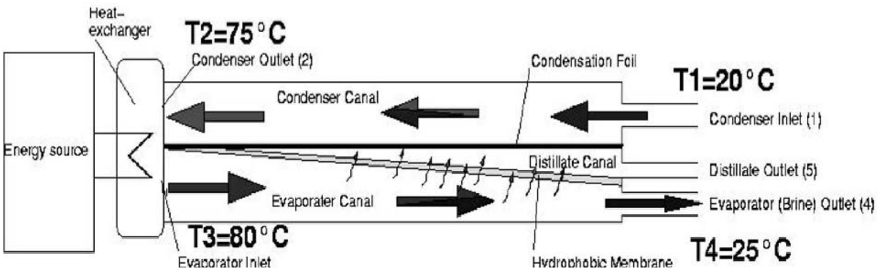

Figure 2. Schematic set-up of a membrane distillation module with internal heat recovery function.

Because the energy for evaporation is removed from the brine, the brine temperature decreases. The liquid distillate is gained from the distillate outlet at a temperature level between the feed inlet and the brine outlet. The heat input which is necessary for the required temperature gradient between the two channels (e.g. 5°C) is introduced into the system between the condenser outlet and the evaporator inlet. Thus the thermal energy consumption of the system is given by the volume flow rate and the temperature increase of the feed water between these two points. The heat recovery function is important to achieve a low specific thermal energy consumption of the module. The technical specifications of the MD module are:

- hydrophobic PTFE membrane, mean pore size 0.2mm
- height 450 - 650 mm, diameter 300 - 400 mm
- membrane area 7 to 10 m²

- feed temperature at evaporator inlet 60 - 85 °C
- specific thermal energy consumption 100 - 200 $kWh/m^3_{distillate}$
- distillate output 10-30 l/h
- all components are made of polymer materials (PP, PTFE, synthetic resin).

3. Compact System

A compact system with a distillate capacity of about 100 litres per day was developed and four compact systems were installed within the frame of the EU-projects. The first one was installed in Pozo Izquierdo (Gran Canaria) in December 2004, the next ones were installed in Alexandria (Egypt) in July 2005, in Irbid (Jordan) in August 2005, and one in Kelaa near Marrakech (Morocco) in September 2005. All systems are in permanent operation. A sketch of the system set up is given in Figure 3. Figure 4 shows a picture of the system installed in Gran Canaria.

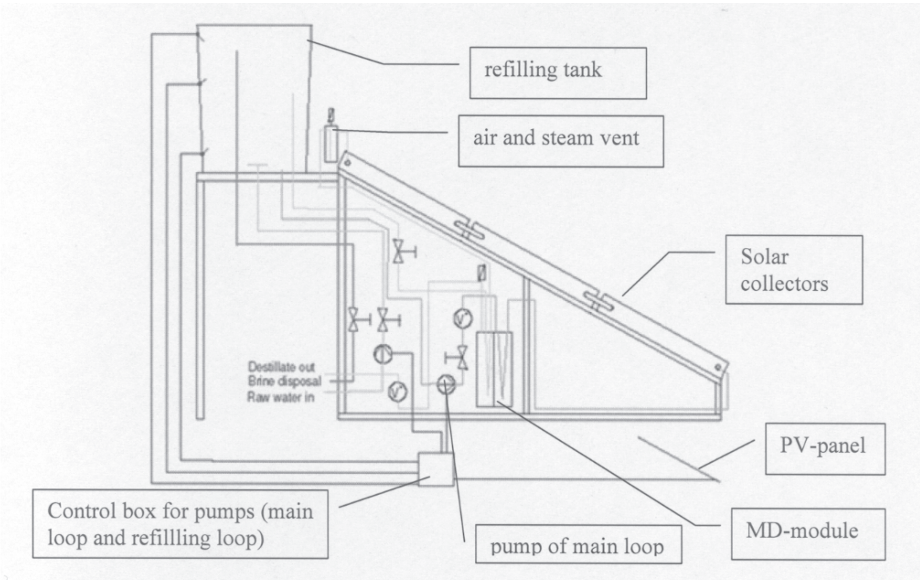

Figure 3. Schematic of the compact system.

The main components of the system are a 500 l feed storage, one MD-module, a 6 m² solar collector, a pump and a PV module. While the feed storage is mounted above the collectors, most of the hydraulic components are installed in a closed housing under the back side of the collectors. The salty feed water is pumped from the feed storage to the condenser inlet of the MD-module. It is pre-heated and leaves the condenser, enters the collector field, leaves the collector field, enters the evaporator of the MD-module, leaves the evaporator and flows back to the feed storage. The distillate is supplied to a fresh water tank. The salt concentration of the feed water increases while the content of water in the feed storage decreases due to the fact that distillate is produced from a part of the feed water. Therefore three float switches control the liquid level in the feed storage. If the bottom should be reached by the liquid level then the whole system is stopped to avoid the pump running dry. This case should not occur during standard operation conditions and the switch can therefore be considered as an emergency switch. If the centre float switch is reached by the decreasing water level, the refilling of the feed storage is started by opening a magnetic valve in the raw water supply line. The valve keeps open until the upper float level switch is reached by the rising water level. The magnetic valve is also powered from the PV panel. The temperature of the water in the feed storage rises during system operation since the temperature of the recycled concentrated feed leaving the evaporator is about 5 to 10K higher than the feed entering the condenser inlet. During the night, the feed storage is cooled down by the ambient.

Figure 4. Picture of the compact system installed in Gran Canaria in December 2004.

4. Solar Thermal Collector

The solar collectors used for the Gran Canaria system are produced by the project partner ESE from Belgium. The collector area is 3 x 2.4m² = 7.2m².

The absorber is selectively coated and the collector cover is made from anti-reflective double glass. The U-value of the collector is about 2.5 W/(m^2 K). The riser and header tubes are made from CuNi10Fe because the absorber has to withstand hot sea-water: The collectors are directly integrated into the salt water loop instead of using a seawater resistant heat exchanger. Thus the number of components in the system is kept small. It was an important development aim to achieve a low technical complexity, low costs and high system reliability. For the systems in Jordan, Egypt and Morocco single glassed collectors without anti-reflection coating produced by the project partner FENIS from Turkey were used. In these systems the collector area is 3 x 1.91m^2 = 5.73m^2.

5. Control System

The control strategy has to be as simple and robust as possible but at the same time as efficient as possible. The DC-driven pump is connected to a maximum power point converter (MPP) and supplied by a 80 W_{peak} PV-module. Thus the volume flow in the system is directly controlled by the irradiation on the PV-module. This simple control mechanism can be very effective if the characteristics of the pump and the PV-panel, the hydraulic characteristics of the system and the thermal performance of the collectors are chosen to fit together perfectly. For low solar irradiation the thermal energy gained from the collectors is low, so that a low volume flow is needed to achieve a reasonable operation temperature for the MD-process. During hours of operation with high solar irradiation (during noon time) a high volume flow is needed to keep the operation temperature at a certain maximum of 85 to 90°C. An electro-mechanical temperature switch is used to start the system pump when a certain temperature level is reached at the collector area outlet. That switch is necessary since the capacity effect of the thermal collectors is much higher than the one of the PV panel which responds immediately on the solar irradiation. The switch is important especially for the system start-up in the morning when the hydraulic loop is completely cold and needs time to reach the minimum operation temperature of 50°C.

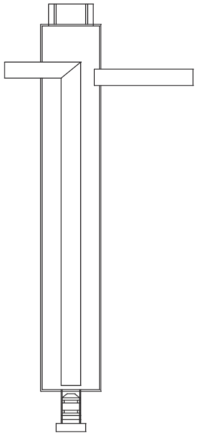

Figure 5. Sketch of the degasser (left) and photo during system stagnation. (2=inlet to degasser, 3=air and stem vent).

There are also design features to increase and assure the reliability of the system: A case of system stagnation could occur if there is a feed water failure or if the system pump fails. Then the temperature in the collector field rises in a first step up to 100°C and the water starts to boil in the collector. Steam is formed and partly replaces the liquid water in the absorber tubes. In a second step, super heated steam is formed in the upper part of the collector area. But the polymer materials used in the MD-module are only long term temperature resistant up to 100°C. Therefore it is important to avoid a steam flow from the collector outlet to the MD-module. For that case a special bottle construction as sketched in Figure 5 is used to separate steam from liquid water. The hot water from the collector outlet enters the degasser bottle via pipe 1. The entrance of the outlet tube 2 is at the bottom of the degasser bottle. On the top of the bottle there is a nut where an aspirator with an integrated float valve is mounted. In the case of stagnation, steam accumulates in the upper part of the bottle and is blown out via the aspirator. That situation is shown in the picture of Figure 5. On the bottom of the bottle there is still liquid water until the feed storage is completely emptied by steam. The bottle is refilled via the evaporator channel of the MD-module because of the hydrostatic pressure of the feed water column. If the system falls completely dry, then the temperature in the collector absorber may even rise up to 220°C. But the hot air leaves the bottle via the aspirator. Measurements during testing operation of that stagnation period have shown that the temperature at the collector outlet was about 120°C while the temperature at the evaporator inlet of the MD-module never exceeded 80°C. Thus, even in field applications where feed water cut-offs may actually be very likely, the system is protected against over-heating and does not get destroyed.

The degasser bottle has also an important function during standard system operation: Dissolved air becomes free when water is heated up. These air bubbles could partly block membrane pores and thus reduce the vapour transfer. In this case the degasser bottle functions as an air separator which avoids this effect.

All four compact systems are monitored in detail in order to evaluate their performance, to learn more about their operating behaviour and to improve the systems in further development work. Figure 6 shows measurements from August to October 2005 of the system installed in Alexandria, Egypt. About 50 to 75 litres of distillate are produced per day, depending on the irradiation. More evaluated measurements from the other systems will be presented at the conference.

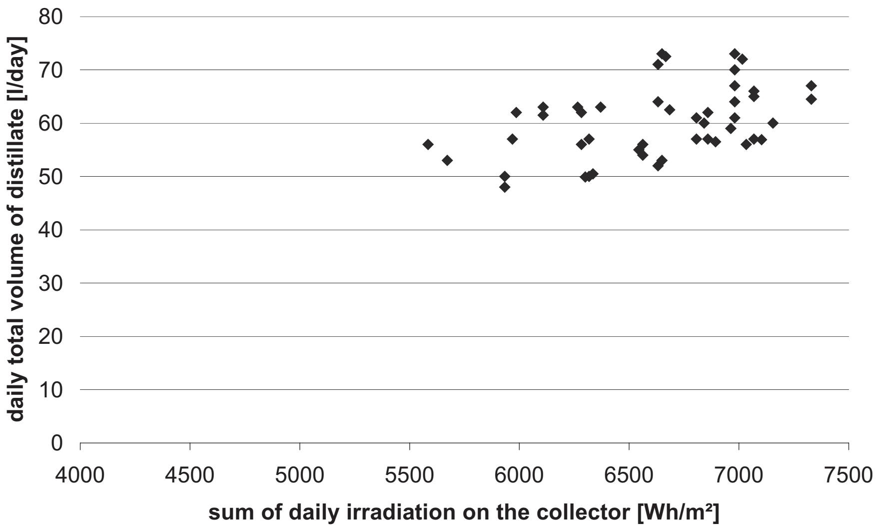

Figure 6. Daily volume of distillate produced by the compact system installed in Alexandria, Egypt (Data from August to October 2005).

6. Two-Loop System Installed in Aqaba (Jordan)

A first 'large' system was installed in December 2005 at the Marine Science Station in Aqaba (Jordan). The system is designed for a daily distillate capacity of about 1000 litres. Figure 7 shows a sketch of the system set up. There are four main differences compared to the compact systems:

- a thermal storage tank is used to allow an extended operation time of the MD-modules also for some hours after sun-set (which means more distillate production per MD-module). The storage tank has a volume of 3 m^3.

- it is a two loops system: the desalination loop is operated with sea water. It is separated by a heat exchanger from the loop of the collectors and the thermal storage tank which is operated with normal water as heat transfer fluid. The collectors do not need the sea-water resistant absorbers which are necessary for the compact systems. The collector area of the system in Aqaba is 80 m^2 of single glassed collectors (from FENIS).

- there are four MD-modules operated in parallel in the desalination loop. The MD-modules are exactly the same as in the compact systems.

- a control unit is used to control the operation of the system. At low irradiation times the desalination unit is operated with heat directly from the collector field. If enough radiation is available the surplus energy can be stored in the storage tank and after sun-set the desalination process can be continued with heat from the tank.

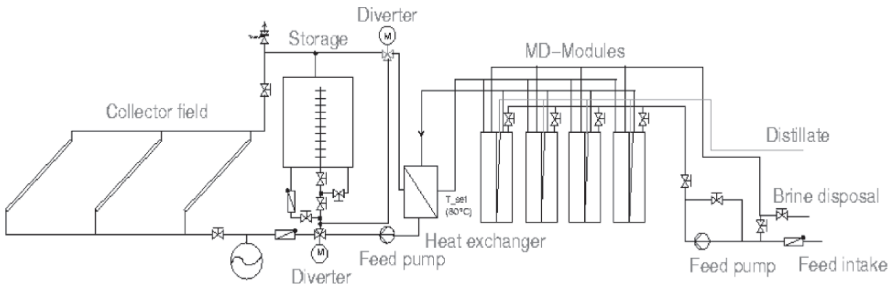

Figure 7. System set up of a two-loops system set up in Aqaba, Jordan.

This larger system is also completely operated by solar energy alone: the pumps and all control components are supplied by PV-modules. First measurement results and operation experiences will be reported in the conference. A second two-loop system will also be installed at the test site in Gran Canaria in March 2006.

7. Conclusions

There are five MD-based solar desalination systems in operation now in four different countries and in different climatic conditions. The technical results and the operating experiences are very promising. We are continuing the development work and we are most interested to carry out field application projects of these systems together with interested partners. Systems of this type which use our membrane distillation modules with internal heat recovery function may be designed for a capacity range up to about 20 m³ per day.

Aknowledgments

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POTENTIAL APPLICATION OF SOLAR HEAT COLLECTORS TO AN EASYMED® THERMAL DESALINATION UNIT

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Abstract. - EasyMED, a new MED process constructed with plates has shown good performances for desalination of salted water in laboratory. In order to prove the reliability of this process in real conditions, a three effects evaporator was operated in La Spezia (Italy). This unit is composed of three effects in series and five cells in parallel and is heated by hot water at about 75°C. 3 m^3/day of high quality distillate with conductivity lower than 20 μS/cm was obtained. The overall heat transfer coefficients between heating water and seawater falling film reached 1400 $W/m^2.°C$ whereas the coefficient between condensing vapour and evaporating seawater is about 4000 $W/m^2.°C$. The influence of the heating fluid temperature and the heating fluid flowrate is studied. The results were used to design a ten-effects industrial unit producing about 150 m^3/day. The potential application of solar heat collectors to supply thermal energy to this MED plate process is studied.

Keywords: MED; plate; evaporation; thermal desalination; solar heat collector

1. Introduction

Water shortage has become one of the major problems in many countries worldwide, with a continuous increase due to population growth and higher living standards. Amongst the ways to solve this problem, seawater desalination appears as a major contender for providing a sustainable source of fresh water in arid zones. This solution is also supported by the fact that more than 70% of the world population lives within a 70 km strip of seas or oceans[1].

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However, the main drawback of desalination processes, especially thermal ones, is their high energy consumption. One way to limit the energy cost of thermal processes is the use of waste heat rejected by power stations or any industries. A low-temperature multi-effect distillation (MED) process is very suitable to be combined with low temperature waste heat (60-75°C). Another attractive solution, especially for remote areas blessed with abundant solar radiation, is to use solar energy to produce steam or hot water to provide thermal energy [2,3,4]. Apart from energy cost implications, the use of solar energy to operate desalination units, limits the environmental pollution caused by the release of green house gases resulting from burning fossil fuels.

In this paper, an innovative MED patented process[5,6] is presented. This system, known as EasyMED, is composed of many identical elementary cells associated in series and in parallel to form an evaporator whose production may reach 150 m^3/day. This system will be more compact than classical tube evaporators, it will also be easier to transport and to assemble without skilled labour.

The first experimental results obtained with a three-effects pilot unit tested on the Mediterranean sea shore in La Spezia (Italy) are presented. They are used to propose a preliminary design of an industrial process: a ten-effects MED plant producing around 150m^3/day. The potential application of solar heat collectors to supply hot water to the EasyMED process is finally examined.

This work was supported by the European Union through the 5th PCRD EasyMED project EVK1-CT-2001-00095.

2. Description of the EasyMED Process

The EasyMED patented process[5] is composed of an association of simple "human-size" elementary cells. Each cell is composed of two thin metallic vertical plates separated by a 3 cm thick polypropylene frame. The latter divides the cell in two zones: one for evaporation and one for condensation (Figure 1). The seawater to be evaporated flows as a falling film along plates heated by condensing vapour coming from the previous effect (Figures 1 and 2). Moreover, grids are placed inside the frames to prevent plates crushing and to promote film turbulence. The vapour flows from one zone to the other through sloped holes inside the system, thus reducing thermal losses and complex piping between successive effects.

Compared to the classical MED, the EasyMED process has the following advantages:

- Less heat loss due to the absence of external piping between the effects.
- The elementary cells with common sizes are easily transportable and may be assembled on the operating site without skillful workforce.
- It is a very compact system, thus enlarging the potential use by reducing the weight of the system and the raw material consumption.
- No large shell to contain the heat transfer surface area is required. On the opposite, classical shell and tube evaporator requires large cylindrical shell that needs specific lifting appliance. In the same way, in the new system of Pressed Plate Falling Film developed by AlfaLaval[7], the plates and their support is located inside a large cylindrical cell used to recover vapour.

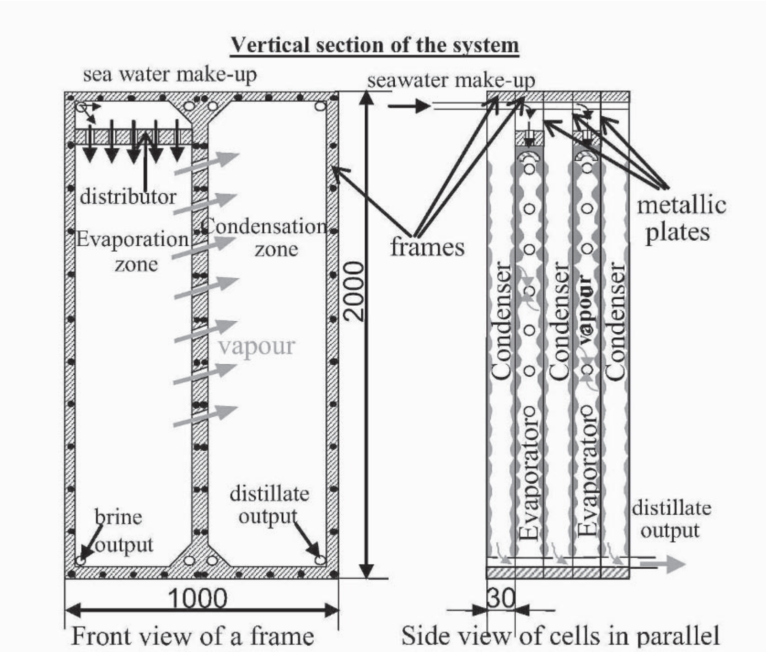

Figure 1. Front view and side view of elementary cells of EasyMED process (dimensions in mm).

3. Description of the Easy-MED 3 Effects Seaside Unit

The laboratory studies performed with a transparent wall single-effect unit[6], and with a three-effects unit[8] have confirmed the feasibility of the EasyMED process for closed-loop operation with synthetic salted water.

The design of the process and its operating conditions have also been optimized.

Then, a larger unit composed of **three effects in series and five cells in parallel** (Figures 2 and 3) was designed and installed in La Spezia (Italy) in order to validate this innovative process in real conditions.

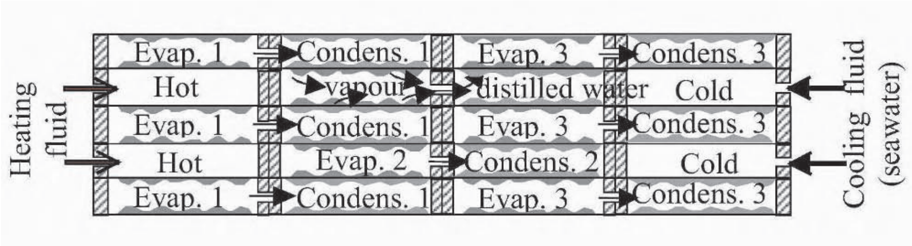

Figure 2. Top view of the association of elementary cells: 3 in series x 5 in parallel.

3.1. MAIN CHARACTERISTICS OF THE SEASIDE PILOT

The specification and the design features of the seaside pilot are described in a previous paper[9]. The main characteristics are recalled hereafter.

The core of the process is composed of:

- 8 double cells: polypropylene frames (as depicted by Figure 1)

- 8 stainless steel (316 L) plates (2 m x 1 m x 1 mm) located behind and in front of each frame.

- 4 single cells: polypropylene frames (2 m x 0.5 m x 3 cm). These cells are used as heating (or cooling) cells and are totally filled with heating (or cooling) water that flows upward along the metallic plates. To increase heat transfer, horizontal metallic baffles spaced by 10 cm are added to reduce the cross sectional area for the liquid flow and increase Reynolds' number[6].

- 16 grid systems placed inside the evaporation and condensation zones. They are composed of 3 grids. Two plane square mesh grids are placed against plates, their horizontal wires act as film turbulence promoters. Those grids from opposite sides of a cell are linked to a third folded grid, whose role is to prevent crushing of plates due to pressure differences between effects[6].

- 8 single thicker stainless steel plates (2 m x 1 m x 2 mm) are used as external faces of the pilot.

- The different pieces of the pilot are assembled with 240 threaded rods of nominal diameter 8 mm with adapted nuts and rings. Water and air tightness is ensured by O-ring EPDM seals placed in grooves machined in the frames.

3.2. OPERATION OF THE PILOT

- To ensure **heating** of the first evaporation cells, **hot water** (heated by three electrical resistances of 12 kW) at about 75°C is used. The circulation of heating water from one tank to the two heating cells is ensured by a centrifugal pump.

- The **cooling** of the last condenser is ensured by seawater. Then warm seawater leaving the cooling cells is partly used to feed the evaporation cells, the other part is rejected to sea.

- Brine and distilled water coming from the different effects flow by gravity in two waterboxes located below the pilot (figure 3). Then distillate or brine are extracted by two peristaltic pumps. These pumps are controlled by frequency drivers to maintain constant level of liquid in each waterbox.

A fraction of the brine is recycled and mixed with warm seawater to feed the evaporation cells in order to reduce the energy required to heat seawater up to its boiling point.

- **Vacuum** is produced by an hydroejector; the motive fluid is tap water circulating in a closed loop from a tank with a pump. Non-condensable gases are extracted from the inside of the pilot with pipes at the upper part of the condensation zones and from the distillate and brine waterboxes.

- The **pressure difference** between effects is obtained with **diaphgrams**. These diaphragms are 40 mm diameter stainless steel disks (1 mm thickness) drilled with calibrated holes whose diameters range between 0.5 and 10 mm. They are placed in the union fittings on the three circuits linked to the hydroejector (extraction of brine or distillate or non-condensable gas).

All the sensors (temperature, conductivity, pressure and flowrate) and control systems are linked to a PC acquisition system equipped with the Testpoint® software.

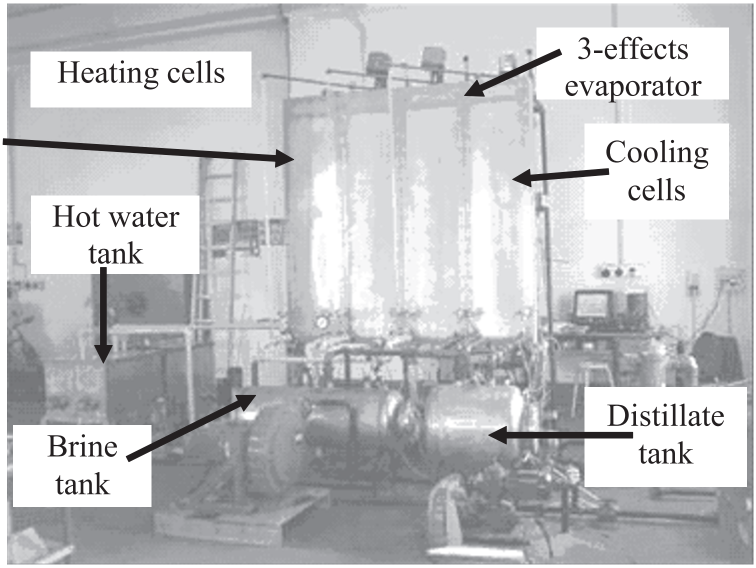

Figure 3. Photograph of the experimental three-effect seaside unit.

4. Experimental Results of the Sea Side Unit

4.1. EXPERIMENTAL CONDITIONS.

Following the previous laboratory units results[6, 8] and after preliminary tests on the seaside unit, the following operating conditions were chosen:

- falling film flowrate on each plate = 85 L/h
- heat carrier fluid temperature T_{hi} varying between 65 and 80 °C
- heat carrier fluid flowrate Q_h varying from 3 to 7 m^3/h
- logarithmic mean temperature difference between heating cells and evaporators of the first effect ≈ 10 °C
- logarithmic mean temperature difference between condensation cells and evaporation cells of the next effects between 4 and 6°C.

4.2. INFLUENCE OF THE HEATING FLUID TEMPERATURE

4.2.1. *Distillate production*

All the experiments have allowed the production of good quality distillate with conductivity lower than 20 µS/cm.

The calculated distillate flowrates are presented in figure 4 as a function of the heating fluid temperature for a heating fluid flowrate Q_h = 7 m^3/h. The distillate flowrates are calculated in neglecting thermal losses and suction of vapour with non-condensable gases by hydro-ejector. The measured distillate flowrates were not reliable since gear wheel flowmeters were disturbed by the presence of vapor bubbles in the boiling liquid and were inefficient at temperatures higher than 65°C. Therefore, the production might be slightly overestimated.

The production ranges between 100 and 130 L/h, that is about 3 m^3/day. It does not vary significantly with heating fluid temperature, which is quite surprising. In this system, any increase of heating fluid temperature leads to an increase of the brine (and distillate) temperature in each effect. As a consequence, pressures in the two waterboxes rise. Since the pressure difference between successive effects and the waterboxes are caused by diaphragms, pressure in each effect also rises. Therefore, the temperature difference between heating fluid and top brine temperature was quite constant (≈ 10°C) due to the increase of pressure inside effects. That leads to quite a constant power transferred between heating cells and evaporating cells of the first effect. That's why the distillate production is not significantly affected by the top brine temperature. This observation is important especially if the use of indirect solar energy is foreseen to supply thermal energy to the first effect. In the present configuration for three effects, the production is not affected by a 14% decrease of heating source temperature.

4.2.2. *Overall heat transfer coefficients*

The **heat transfer coefficient between heating cells and evaporator 1**, $\mathbf{K_{h\text{-}E1}}$, and the mean logarithmic temperature difference between heating cells and evaporation cells of effect 1, $\Delta Tml_{h\text{-}E1}$, are presented in figure 5 as functions of heating fluid inlet temperature for Q_h = 7 m^3/h.

$\Delta Tml_{h\text{-}E1}$ is calculated assuming that the film temperature is constant and equal to the top brine temperature T_{b1}.

The overall heat transfer coefficient $K_{h\text{-}E1}$ decreases with hot water temperature, this seems to be due to the slight increase of the temperature difference $\Delta Tml_{h\text{-}E1}$. The overall heat transfer coefficient ranges between 1000 and 1400 W/m^2.°C. These quite low values are mainly due to the important thermal convective resistance of hot water. The latter could be reduced by using low pressure steam instead of liquid water to increase the power density transferred to the first effect and consequently to the following effects.

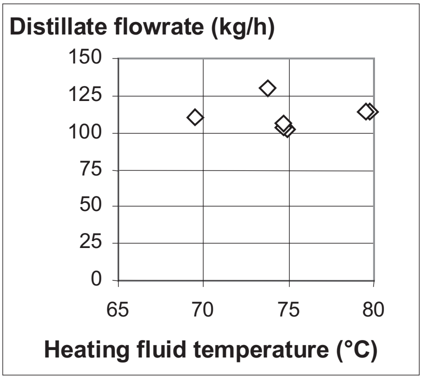

Figure 4. Variation of calculated distillate flowrate with heating fluid temperature for $Q_h = 7\ m^3/h$.

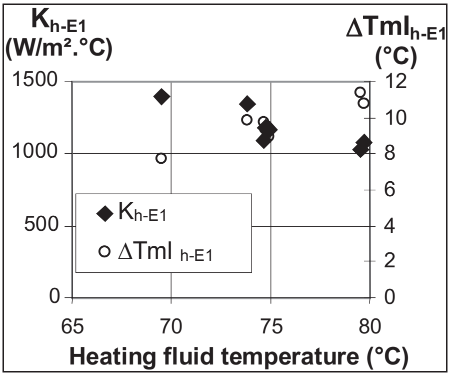

Figure 5. Heat transfer coefficient between heating cell and evaporator 1 and mean temperature difference as functions of heating fluid inlet temperature for Q_h=7 m^3/h.

The variation of the overall **heat transfer coefficient between condensation zone of effect 1 and evaporation zone of effect 2, $K_{C1\text{-}E2}$,** with heating fluid temperature is presented in Figure 6.

The vapour temperature in effect 1 is assumed to be $T_{b1} - \nu_1$ (where ν_1 is the boiling point elevation), whereas the film temperature in evaporators 2 is assumed to be constant and equal to T_{b2}.

Measured values of $K_{C1\text{-}E2}$ ranges between 2100 and 3700 W/m^2.°C for $\Delta Tml_{C1\text{-}E2}$ ranging between 2.5 and 4°C. These values are of the same order of magnitude as for horizontal tube evaporators[10] whose typical values are 3300 W/m^2.°C for 1 mm thick tubes made of copper-nickel or aluminium-brass alloys that have higher thermal conductivities than stainless steel. Comparison with new plate evaporators applied for desalination are more difficult since high heat transfer coefficients are announced but numerical values are not reported for confidentiality reasons[11].

Figure 6 shows that there is no clear dependence of $K_{C1\text{-}E2}$ on the heating water temperature. It seems that the heat power transferred between effects 1 and 2 remains constant since a decrease of $\Delta Tml_{C1\text{-}E2}$ is followed by an increase in $K_{C1\text{-}E2}$.

The same phenomenon is observed for the transfer between **effects 2 and 3**. The values of **$K_{C2\text{-}E3}$** range between 1400 and 2200 W/m^2.°C, these lower values are due to the fact that $\Delta Tml_{C2\text{-}E3}$ is higher (around 6°C).

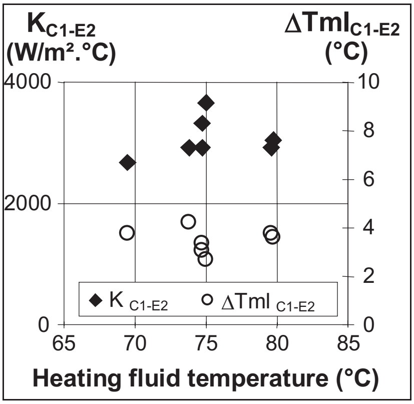

Figure 6. Heat transfer coefficient between condenser 1 and evaporator 2 as a function of effect 2 brine temperature for Q_h=7 m³/h.

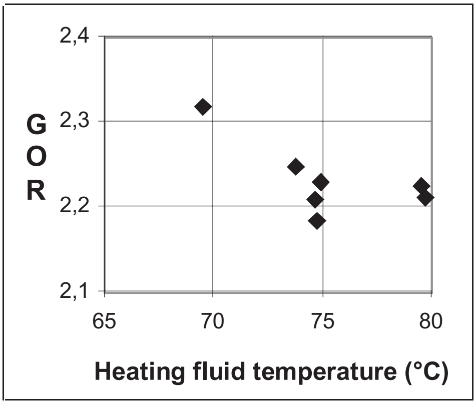

Figure 7. Gain Output Ratio as a function of heating fluid temperature for Q_h =7 m³/h.

4.2.3. *Gain Output Ratio*

This coefficient is the ratio of the energy used to vaporize the distillate in each of the three effects divided by the power released by hot water in heating cells.

The variation of GOR with heating fluid temperature is presented in Figure 7. A slight decrease of the GOR is observed. When heating fluid temperature is increased and consequently brine temperatures, it is necessary to supply more energy for the preheating of salted water. The values of GOR are around 2.3, that is largely lower than the theoretical value of 3 for an ideal three-effect unit. Indeed the fraction of supplied energy used to preheat salted water up to its boiling point is quite important, about 17% in each effect. The falling film flowrate must be high enough to ensure good wetting of the plates, therefore to avoid the preheating of large amount of cold seawater, it is necessary to recycle part of the brine, around 80%. This brine comes from the waterbox which temperature is near than boiling temperature in effect 3 and it is mixed with seawater leaving the cooling cells. Thus, the salted water inlet temperature is about 10°C lower than the boiling point. For classical MED, the brine coming from one effect is used to feed the following. In this case no energy is consumed for preheating and consequently higher GOR are obtained.

5. Preliminary Design of a Ten Effects Desalination Unit

The unit was designed considering the following assumptions:

a) The top Brine Temperature is limited to 70°C to reduce corrosion and scaling problems in order to enable the use of low grade materials like 316L stainless steel.

b) The seawater temperature (cooling water) is assumed to be 25°C

c) The temperature difference between successive effects = 4°C.

d) The core of the process should be mounted and transported using standard container (6 m long and 2.5m wide). 50 cells in parallel lead to a width of about 1.8 m, whereas 10 effects in series give a length of 5.5m.

The assumptions a) to d) lead to a design with 10 effects in series.

e) The power density[6] between heating cells and the first effect is about 15 kW/m^2 for $\Delta Tml_{h\text{-}E1}$ = 12°C. Since the plate exchange area between the heating cells and the first effect evaporation cells is 35 m^2, the required thermal power has to be 530 kW.

Under these conditions, the expected distillate flowrate is around 16 L/h/active plate that is 19 m^3/day for the first effect.

6/ According to the three effects unit results for which GOR is around 2.2 , a GOR of 7.6 is expected for the ten effects unit.

The previous assumptions lead to the calculated performances of Table 1.

TABLE 1. Summary of the predicted performances and geometric characteristics of the ten effect unit and 50 cells in parallel

Cooling seawater flowrate	m^3/day	1200
Heating water flowrate	m^3/day	1850
Inlet - Outlet heating water temperature	°C	85 - 79
Power supply	kW	530
GOR	/	7.6
Salted water Feed	m^3/day	1020
Distillate flowrate	m^3/day	150
Specific thermal energy consumption	kWh/ m^3	86
Specific electric consumption for pumps	kWh/ m^3	2,2
Length* Height* Width	m	5.5*2*1.8
Volume	m^3	20
Weight	Tons	9.1
Daily Water production /Unit volume	m^{3}of water per day /m^{3}of unit	7.5

The weight of the core of the ten-effect unit will be around 9 tons for a low volume of 20 m^3. Therefore, it is shown that the EasyMED process is really compact. Comparison of the ten effects unit with other industrial units shows that the specific production per unit volume is largely higher for the EasyMED process. In Mirfa (UAE), a spray film low temperature[10] plant with four units each composed of four effects produces 7500m^3/day. Each effect sizes 4.8m diameter, 12m length and then 3472 m^3 for the whole unit. It weighs about 240 tons. The ratio water production divided by the volume of the process is about 2m^3 of water/day/ m^3 of unit whereas this ratio is three times higher, around 7.5 for the EasyMED process.

A first economic evaluation of this process leads to a specific water cost of 1.4 €/m^3 if free waste thermal energy is available.

6. Potential use of Solar Collectors to Provide Thermal Energy

A rapid evaluation of the solar collector area required to provide 530 kW of thermal energy at 85°C was performed by using the results of El-NASHAR[4,12] obtained with a Multiple-Effect Stack (MES) distillation system coupled with high-efficiency evacuated tube collectors. The following equation[4] inferred from the 'SOLDES' program for a MES distiller whose capacity is about 500 m^3/day and for the average solar irradiation of Abu-Dhabi was used:

$$M = \left(-57{,}304.9 + 49.5475 \cdot A_c - 0.003355 \cdot A_c^2\right) + \left(-190{,}122.4 + 16{,}142.3 \cdot N - 331.81 \cdot N^2\right) + \left(99{,}400 - 1350 \cdot T_b - T_b^2\right)$$

Considering N = 10 effects, top brine temperature T_b = 70°C leads to a solar collector area A_c = 4500 m^2 to reach a daily production M = 150 m^3/day.

Considering that the solar radiation lasts 8 hours per day, a heat storage system has to store 2* 530 kW as hot water in order to allow the plant to run nighttime. In order to supply continuously 1850 m^3/hour of hot water at more than 85°C in the heating cells, it is necessary to heat water with solar collectors from 79°C to 98.5 °C if thermal losses lead to a 1.5 °C temperature drop during night. The heat storage will be performed by a heat accumulator thermally stratified system using 550 m^3 of water as the heat storage medium.

Further studies are required to develop a more precise design of the solar collection system and to analyze the economic feasibility of such a process and the necessity to associate it with a classical fuel-powered system for winter season.

7. Conclusion

First tests with the three-effects seaside EasyMED unit have demonstrated the feasibility of this innovative process. The heat transfer coefficient between heating cells and evaporation cells of the first effect reached 1400 W/m^2.°C. The heat transfer coefficient between condensation cells and evaporation cells reached 3700 W/m^2.°C. Thanks to brine recycling it was possible to reach a daily production of 3 m^3 and GOR of 2.3. Further experiments will enable us to optimize the operating conditions and increase performances. The preliminary design of a ten-effects industrial unit is proposed. The plant is expected to produce 150m^3/day with 50 cells in parallel. Such a unit could be combined with solar collector system of 4500 m^2 to provide thermal energy during summer time. Further studies will enable us to refine the preliminary design and to analyze the economic feasibility of this process using solar energy.

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MEMBRANE DESALINATION DRIVEN BY SOLAR ENERGY

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Abstract. In recent years, membrane technology has become increasingly significant and has been widely used in desalination. Some membrane processes, such as reverse osmosis and electrodialysis are used commercially while others such as membrane distillation are still in the research and development stages. This study reviewed the current status of a number of solar thermal and solar PV technologies that can be coupled with water membrane-based desalination processes. Solar systems have the potential to power membrane-based desalination plants but still cannot compete favorably with fossil fuel based energy desalination. Nevertheless, these systems remain a valid option for small scale units in remote areas.

Keywords: solar energy; reverse osmosis; electrodialysis; membrane distillation; PV; energy consumption.

1. Introduction

Desalination inherently consumes a lot of energy, the theoretical minimum for seawater being around 0.8 kWh/m^3. In practice, figures greater than 2.0 kWh/m^3 are typical. Cost calculations for commercial desalination processes, which includes multi-stage flash (MSF), multi-effect distillation (MED) and seawater reverse osmosis (SWRO) show that energy cost varies over a range of 30% to 50%. Recently, considerable attention has been given to the use of renewable energy as sources for desalination, especially in remote areas and islands, because of the high costs of fossil fuels,

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difficulties in obtaining it, attempts to conserve fossil fuels, interest in reducing air pollution, and the lack of electrical power in remote areas. But in spite of the aforementioned favorable characteristics, the renewable energy contribution to cover energy demand worldwide, though increasing, is still marginal. Apart from hydroelectric energy, the other principal resources (solar, wind, geothermal) cover together little more than 1% of worldwide energy production (Cesare 2001). Of the 23 million m^3 of fresh water produced daily, only 46 000 m^3, or 0.02 %, originates from plants with renewable energy systems.

Solar energy can be used for seawater desalination either by producing the thermal energy required to drive the phase-change processes or by producing the electricity required to drive the membrane processes. Solar desalination processes can be devised in two main types: direct and indirect collection systems. The “direct method” uses solar energy to produce distillate directly in the solar still, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection, the other for desalination). The direct solar energy method uses a variety of simple stills suitable for very small water demands; indirect methods use thermal or electrical energy and can be classified as: distillation methods using solar collectors or membrane methods using solar collectors and/or photovoltaics for power generation. The low environmental impact as well as the easy operation and maintenance are also incitements for this technology (Garzia-Rodriguez, 2002a). The feasible solar energy - desalination technology combinations are depicted in the form of a tree in Fig. 1.

Solar thermal desalination plants utilizing indirect collection of solar energy can be classified into the following categories: atmospheric humidification/ dehumidification, multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC) and membrane distillation (MD).

Determining the appropriate desalination technology for remote areas where no electricity grid is available depends primarily on system features. The main desirable features for such systems are low cost, low maintenance requirements, simple operation, as well as high reliability. The selection of the appropriate desalination process depends on a number of factors including plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of the local renewable energy resource. Conventional membrane processes such as reverse osmosis (RO) and electrodialysis (ED) usually have lower energy costs but may require more chemicals and expertise in their operation.

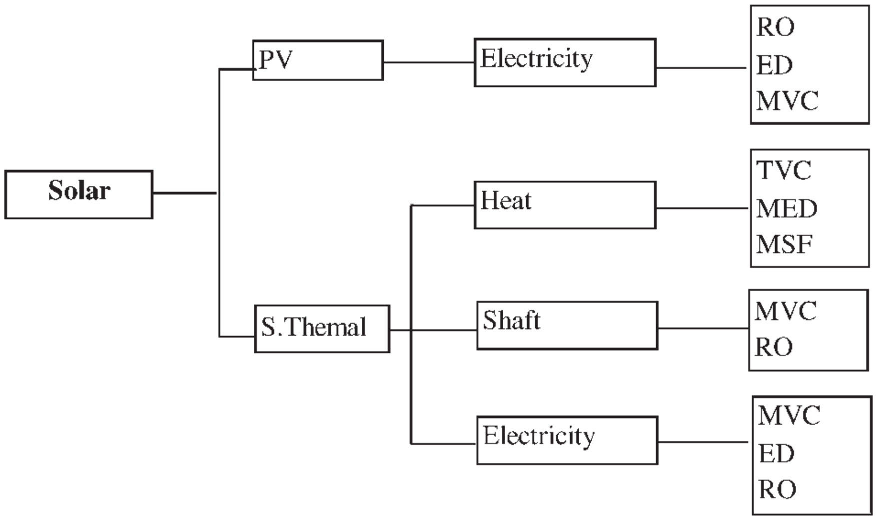

Figure 1. Solar energy-desalination technology combinations (European Commission 2002).

This study aims:

1. To review the existing solar energy collecting systems and their possible integration with membrane based processes.
2. To assess and identify membrane processes suitable for coupling with solar energy and to compare their energy consumptions.
3. To conduct a survey of existing solar powered membrane desalination processes

2. Solar Technologies

Solar technologies are developed enough for direct conversion to electricity using PV cells, low and medium temperature thermal application using solar concentrators. Concentrating solar power (CSP) technologies are well established. Commercial applications from a few kilowatts to hundreds of MW are now feasible, and plants totaling 354 MW have been in operation in California since 1980s. An investigation by Garzia-Rodriguez and Gomez-Camacho (2000) showed that parabolic trough collectors and salinity gradient solar ponds are the best choices for indirect solar desalination. The following is a brief on the available technologies for thermal or electricity generation that can be coupled with membrane based desalination plants.

2.1. SALINITY-GRADIENT SOLAR PONDS (SGSP)

A solar pond is a thermal solar collector that collects solar energy by absorbing direct and diffuse sunlight and stores thermal energy in its own storage system. Natural convective circulation in the pond is prevented by making the bottom water much denser than the surface water. By doing so, the solar radiation absorbed in the deep water can be stored (Garzia-Rodriguez et al., 2002a). Solar ponds usually consist of three layers; the top layer is usually fresh water about 0.8–1 m deep, the gradient zone where the temperature and salt concentration increase with depth (1–2 m) and the bottom layer which is dense and acts as a heat storage zone where the temperature can reach as high as 100ºC (Hussain, 2003). Heat is extracted by passing the brine from the storage zone through an external heat exchanger. This heat can be used in a special organic-fluid turbine to generate electricity, provide energy for desalination, and to supply energy for space heating in buildings.

The annual collection efficiency of useful heat for desalination is around10–15%. Larger ponds tend to be more efficient than smaller ones due to losses at the pond edge. Solar ponds are particularly suitable for desalination plants as waste brine from desalination can be used as the salt source for the solar pond density gradient. Using desalination brine for solar ponds not only provides a preferable alternative to environmental disposal, but also a convenient and inexpensive source of solar pond salinity. Many countries, such as Libya, are greatly dependent on seawater desalination and are provided with these characteristics. Using solar ponds instead of fossil fuel for heating the desalination plants would mean significantly lower production costs (Hussain, 2003).

2.2. FLAT-PLATE COLLECTOR (FPC)

FPCs are static solar energy concentrators that usually use water as heat transfer fluid, which circulates through absorber pipes made of either metal or plastic. The absorber pipes are assembled on a flat plate and they usually have a transparent protective surface in order to minimize heat losses. They may have different selective coatings to reduce heat losses and to increase radiation absorption. Thus the thermal efficiency increases but the collector cost also increases. Flat plate collectors have not been proved as a useful technology for desalination (Garcia-Rodriguez, 2002b; Belessiotis and Delyannis, 2001). Although they have been used for relatively small desalinated water production volumes, production of large volumes of water would require an additional energy source such as the desalination facility in Mexico which derives energy from flat plate collectors and parabolic troughs. There is a relevant example of MED flat plate unit located in Abu Dhabi (El-Nashar and Samad 1998). The plant was designed for an expected yearly average of 85 m^3/day. The plant started operation in 1984 for 13 years. The total cost of water produced from this plant ranged from about 7 $/$m^3$ to 10 $/$m^3$. El-Nashar and Samad (1998) concluded that for the production of 1 m^3/day the system would require 10-20 m^2 of FPC. Recently, FPCs have been used to supply membrane distillation modules in Jordan, Egypt and Morocco with the required thermal energy.

2.3. EVACUATED TUBE COLLECTOR (ETC)

Heat losses are minimized in ETCs by the evacuated cover of the receiver. This cover is tubular and made of glass. In addition, a selective coating of the receiver minimizes the losses due to infrared radiation. Usually a number of evacuated tubes are assembled together to form a collector. Evacuated tube collectors require more sophisticated manufacturing facilities than flat-plate collectors and cost $300-$550/m^2 as opposed to $80-$250/m^2 for flat plate collectors. Evacuated tube collectors are preferred to flat plate collectors as less land area would be needed for the same level of energy production. Because evacuated tube collectors produce temperatures of up to 200°C, they are particularly suited as an energy source for high temperature distillation (Belessiotis and Delyannis, 2001).

2.4. PARABOLIC TROUGH COLLECTOR (PTC)

Trough systems use linear parabolic concentrators to focus sunlight onto a receiver running along the focal line of the collector. The solar energy is absorbed in a working fluid usually heat-transfer oil. Parabolic troughs on average have concentration ratios of 10 to100, leading to operating temperatures of 100–400°C (U.S. Department of Energy, 2003). The parabolic trough collector systems usually include a mechanical control system that keeps the trough reflector pointed at the sun throughout the day.

Due to the high temperatures parabolic troughs are capable of producing high-grade thermal energy that is generally used to generate electricity (Belessiotis and Delyannis, 2001). Parabolic troughs could be a suitable energy supply for most desalination methods, but in practice, have mainly been used for thermal distillation as these methods can take advantage of both the heat and electricity troughs produce.

Garacia-Rodriguez et al. (2002b) have presented a comparison of static solar technologies as well as one-axis sun tracking for applications in seawater desalination under Spanish climatic conditions. The authors concluded that direct steam generation parabolic troughs are a promising technology for solar-assisted seawater desalination.

2.5. POWER TOWER SYSTEM

This is a field of large two-axis tracking mirrors that reflect the solar energy onto a receiver that is placed on top of a centrally located tower. The solar energy is absorbed by a working fluid and then used to generate steam to power a conventional turbine.

2.6. DISH/ENGINE SYSTEM

This uses a parabolic dish concentrator to focus sunlight onto a thermal receiver and a heat engine/generator, positioned at the focus of the dish to generate power.

Commercial solar plants have achieved costs about 10 cents per kWh, the lowest of any type of solar technology, and if reliability problems are solved the cost may fall as low as 5 cents per kWh (ESCWA 2001).

3. Membrane-Based Processes

Water desalination processes are classified into two groups: distillation based processes, which include MSF, MED, and VC, and membrane processes which include reverse osmosis (RO), electrodialysis (ED), and membrane distillation (MD). In membrane separation processes, material separation is achieved when the membrane acts as a semi-permeable barrier between two phases. Transport across the membrane occurs when a driving force such as pressure (RO), temperature (MD), or electrical potential (ED) is applied across the membrane. When the process operates selectively, certain components pass through the membrane into the permeate stream while others are retained. In the commercialized membrane processes, low capital costs, energy efficiency as well as compactness are definite advantages.

3.1. REVERSE OSMOSIS (RO)

3.1.1. *Operation principle*

Reverse osmosis is a pressure driven process where a pressure difference greater than the osmotic pressure is applied across a suitable semi-permeable membrane. Fresh water passes from the concentrated salt solution to the dilute one. In practice, the saline feed water is pumped into a closed vessel where it is pressurized against the membrane. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. At the same time, a portion of this feed water is discharged without passing through the membrane. The amount of the feed water discharged to waste in the brine stream varies from 20 to 70% of the feed flow, depending on the salt content of the feed water, pressure, and type of membrane. A typical recovery value for a seawater RO system is only 40% (Spiegler and El-Sayed 1994). An RO desalination plant essentially consists of four major systems:

- Pretreatment
- High-pressure pump
- Membrane assembly
- Post-treatment

To extend membrane life, extensive pretreatment is usually required to condition the feed seawater. Therefore, suspended solids must be removed and the water pretreated so that salt precipitation or microbial growth does not occur on the membranes. Usually, the pretreatment consists of fine filtration and the addition of acid or other chemicals to inhibit precipitation and the growth of microorganisms. The high-pressure pump supplies the pressure needed to enable the water to pass through the membrane and have the salts rejected. Pressurizing the saline water accounts for most of the energy consumed by RO. Since the osmotic pressure, and hence the pressure required to perform the separation is directly related to the salt concentration, RO is often the method chosen for brackish water, where only low to intermediate pressures are required. The operating pressure ranges from 15 to 25 bar (225 to 375 psi) for brackish water and from 54 to 80 bar (800 to 1,180 psi) for sea water with an osmotic pressure of 25 bar (Buros, 2000). Energy recovery from the high-pressure brine leaving an RO plant plays an important part in reducing the total energy consumption for desalination, especially in large-scale RO plants for seawater desalination.

3.1.2. *Membranes*

RO membranes are specified in terms of their rejection of NaCl at a specified pressure. This means that a 99.5% rejection membrane is substantially denser than a 95% membrane. A 95% membrane may be acceptable for the desalination of brackish water, but it will not be useful for single stage seawater desalination as the rejection of NaCl is much too low. Membranes are generally made from cellulose acetate (CA) (sometimes called thin composite organic membrane CTA) or thin film inorganic composite (TFC) materials. The CA membrane is made of organic cellulose and can fail due to bacteria contained in the water. Therefore, the CA membrane works best for treating pre-chlorinated water since chlorine kills bacteria growth and extends the life of the membrane. TFC membranes cannot be used to treat chlorinated water because chlorine will damage this membrane and shorten its life. In this case, granulated activated carbon or extruded carbon filters are used to remove the chlorine from the water. RO membranes for desalination generally come in two types: Spiral wound and Hollow fiber. Spiral wound elements are actually constructed from flat sheet membranes.

3.1.3. *Feed Water Quality*

The permeate quality of an RO unit depends on the quality of the raw water. If the brackish water contains less than 10 g/L of dissolved salts, the permeate can be used as drinking water without further treatment. Seawater (35 g/L) and water with a higher salt content must be desalinated in several stages in order to achieve a residual salt content of 0.5 g/L. Post-treatment usually involves pH adjustment, removal of dissolved gases such as carbon dioxide and hydrogen sulfide, and disinfection. Although in theory RO should remove all microorganisms, in practice there are often small leaks in the system, making disinfection a recommended protection.

3.1.4. *Energy Consumption*

Compared with thermal distillation processes RO consumes less energy (Table 1). The amount of pressure and thus the amount of energy required for desalination by RO depends primarily on the salt content of the raw water. This means that the power consumption for brackish water desalination by RO will be much lower than for seawater desalination because the operating pressure is much lower, 15–25 bar for brackish water and 54–80 bar for seawater desalination. Typical figures for power consumption range from 2–5 kWh m^3 for brackish water desalination to 5–15 kWh m^3 for seawater desalination (for small-scale plants). These figures are relatively low in comparison with other processes, especially distillation processes. A very important factor in keeping energy consumption at low levels is the recovery and reuse of energy in the brine reject stream. In desalination of seawater the water recovery is approximately 40%, which means that 60% of the feed water at high pressures of up to 70 bar is rejected as brine. This represents a very large part of the energy input to the process. Without recovery of this energy, the power consumption of seawater RO will be much higher than the figures mentioned above. Various designs were used to recover this energy including reverse running pumps, Pelton wheels and more recently pressure or work exchangers.

Some of these have efficiencies of up to 96% and have resulted in plants where energy consumption has been reduced to 2.5 – 3 kWh/m^3.

None of energy recovery systems in the market are available for small capacity RO plants. So, small RO plants are often built without any energy recovery system. They use a needle restrictor valve to provide the backpressure in the concentrate. This keeps the capital cost down but is very wasteful of energy. On average, 70% of the input power is wasted in the valve. As a result small RO systems usually consume more than 10 kWh/m^3 making them expensive to operate.

TABLE 1. Estimated energy consumption of the major desalination processes (ESCWA 2001, Ribeiro et al. 2005)

Process	**Heat (MJ/m^3)**	**Electrical (kWh/m^3)**	**Total electric equivalent (kWh/m^3)**
MSF	250-300	3.5-5	15-25
MED	150-220	1.5-2.5	8-20
VC			
Thermal (TVC)	220-240	1.5-2	
Mechanical (MVC)	None	11-12	11-12
RO			
Seawater	None	5-9	5-9
Brackish water		0.5-2.5	0.5-2.5
ED	None	2.6-5.5	2.6-5.5

3.1.5. *Advantages and Disadvantages*

The high share of recovered product water (up to 55%), the modularity of the systems, and the low unit investment costs all add to the advantages of RO process. Disadvantages are the sensitivity of the membranes to fouling, the high costs of maintenance and repair, the risk of disruptions in supply, and the lower product water quality (compared with thermal processes). However, advances in membrane and pretreatment technology have contributed to the increased use of RO.

3.1.6. *Coupling with Solar Energy*

The capacity of RO plants ranges from several 1,000 cubic meters per day to the 12 liters-per-day units which are used to supply the small household. The use of renewable sources of energy for power generation to operate an RO-plant has recently caught attention. The most promising candidates are wind and solar energy. However, solar radiation and wind are intermittent, non-dispatchable sources of energy. The operation of RO-plants, on the other hand, requires the supply of a constant load; fluctuating loads would wear out plant components; in particular, it would severely reduce the membrane life. Moreover, if wind and solar energy is used on a stand-alone basis, a constant power supply can only be maintained through energy storage or back-up systems, which would significantly increase the costs of this solution.

In practice if the demand of water is no higher than 1-2 m^3/day, a photovoltaic plant is also an economical energy supply option. Since photovoltaics convert solar energy directly into electrical energy, this technology is best suited for coupling with reverse osmosis or mechanical vapor compression. However, since reverse osmosis generally requires less energy than vapor compression, in practice reverse osmosis has been greatly favored for coupling with photovoltaics. Since solar resources are quite variable these reverse osmosis systems often include either battery storage of photovoltaic energy or are connected to an alternate energy source such as a generator. Debatably, either case would limit the potential for process sustainability. If batteries are to be used as an energy source when solar resources are not available and to provide constant operating conditions over the course of a day, then, for a desalination plant operating at full capacity 24 hr/day, the photovoltaic system would have to be at least four times larger than if batteries were not used. Typically lead-acid batteries are used for photovoltaic-desalination systems but have proved to be particularly problematic as they must be replaced as frequently as every 2 years, particularly in warm climates, and do not reliably have efficiencies greater than 75% (Thomson et al. 2002; Miranda and Infield 2002). Additionally, there are significant life-cycle problems with lead-acid batteries leading to reduced overall sustainability benefits from photovoltaics. In any event, qualified personnel and a good supply of spare parts are necessary for RO plants. On-going research and development on the subject of combining RO with solar energy predict a good possibility of finding a cost-effective solution. Among the suggested solar driven plants are RO desalination driven by solar produced steam (Garzia-Rodriguez, 2000). For large plants, however, a diesel generator is a cheap source of electricity. Despite this, reverse osmosis is competitive with large-scale distillation and dominates in regions without cheap sources of energy.

Many demonstrations of photovoltaic- (PV) energy-powered RO systems have been built. These systems require some degree of technical skill to protect the membranes from fouling and to maintain pumps. The following section profiles case studies of solar energy-powered RO systems.

In conjunction with Murdoch University in Western Australia, the RO manufacturer Venco has developed a PV-powered RO unit which can produce up to 400 liters/day from brackish water up to 5000 ppm TDS and is designed for use in remote areas. Several units have been sold. Unlike most PV -powered systems, Venco's uses no batteries. Instead, the 120 peak Watt PV panels, with the aid of a power maximizer, supply power to a DC motor which operates a positive displacement piston pump at variable speed. The system operates therefore with variab1e flow rates, albeit constant pressure. Recovery rates range from 16% to 25% depending upon salinity and flow rate. The system is designed to operate unattended and when maintenance of the membranes or pumps is needed, they can be detached and sent back to the manufacturer for maintenance. An ultraviolet disinfection system can also be added. The capital cost is listed at \$15,000/m^3/day, including the PV system. The unit includes a 25 μm and a 5 μm pre-filter, corrosion-proof cylinder, and energy recovery (Butler, 1997). Although the claimed water production rate may be slightly overstated, the system is of great interest for its efficient use of solar energy and easy operation in remote locations.

Extensive research has been conducted by the Energy Research Institute of King AbduJaziz City for Science and Technology (KACST) on a PV - battery-inverter RO system in Sadous, Saudi Arabia. Installed in November 1994, the RO system produces on average 5.7 m^3/day, converting brackish water from 5,700 ppm TDS to 170 ppm TDS with an average 30% recovery rate. The entire desalination system consists of pumps (booster, chemical, high-pressure, and distribution), building accessories (ventilation fan, lighting), control system, and a UV sterilization system (Hasnain, 1995; and Smiai and Rafique, 1995). Intermittent operation was well tolerated but continuous operation for long periods in hot weather resulted in overheating of the motors. Membrane fouling is an on-going problem, requiring membrane replacement every six months.

The Florida Solar Energy Center (FSEC) installed a PV -powered RO facility at the St. Lucie Inlet State Preserve off the coast of Florida in March, 1995 (Thomas 1997). The island facility uses duplicate RO units produced by Recovery Engineering to desalt 0.64 m^3/day for use by visitors to the nature reserve. The 2.7 kW PV array supplies energy to the 1050 amp-hour battery bank, which powers the supply well pump, the two RO units, chlorine injection pump for disinfection of the desalted water, product water distribution pump, and lighting. The only pretreatment used is filtration. The RO units consume 13 kWh/m^3 and frequently produce more water than is actually needed by the visitors. As originally designed, the excess water spilled to the ground.

In (Herold and Neskakis, 2001) a small PV-driven RO desalination plant with an average daily production of 0.8-3 m^3/day is presented. The authors investigated the influence of feed pressure on product water quality, on plant productivity and on energy consumption. At feed water pressure of 48 bars the specific energy consumption of the plant was 16.3 kWh/m^3. Productivity of the plant was 124 L/h with permeate concentration of 450 ppm. When the feed pressure was increased to 63 bar, the specific energy consumption dropped to 15 kWh/m^3, and productivity increased to 155 L/h with permeate concentration of 330 ppm.

Ahmad and Schmid (2002) presented a design for a PV powered small-scale desalination system to be operated in remote areas of Egypt. It is estimated that the cost of producing 1 m^3 of fresh water from the PV-RO system is 3.73 $.

Richards and Schafer (2003) reported on the design and field-testing of a photovoltaic (PV)-powered desalination system. The system described was intended for use in remote areas of the Australian outback. The system was based on a hybrid membrane configuration, with an UF module for removing particulates, bacteria and viruses and a NF or RO membrane for removing salts. The system produced clean drinking water from a variety of feed waters, including high salinity (3500 mg/L) water. The specific energy consumption ranged from 2 to 8 kW h/m^3 of disinfected and desalinated drinking water, depending on the salinity of the feed water and the system operating conditions.

In Fiorenza et al. (2003) the water production cost for seawater desalination by RO powered by a photovoltaic field was estimated. The results obtained showed that the cost of water produced can be lowered from 2.7 $/$m^3$ for plants of 500 m^3/d capacity to 2 $/$m^3$ for plants of 5000 m^3/d capacity.

With regard to solar desalination facilities, Garzia-Rodriguez (2002a) summarized the reverse osmosis plants driven by photovoltaic cells.

3.2. ELECTRODIALYSIS (ED)

3.2.1. *Operation Principle*

In this process, ion selective membranes are used to separate an assemblage of cells in an alternate order of cation and anion permeability. The process removes ions from water by forcing their migration through a membrane with a D.C. electric field. Cations such as Na^+ move through cation selective membranes and the anions such as Cl^- move through the anion selective membranes. Since the feed solution passes between parallel membranes, it becomes alternately more concentrated and more dilute in ions. Therefore a concentrated brine and purified water stream (dialysate) are withdrawn.

Each stage in ED system has a salt removal rate of about 50%. Therefore several stages are often needed, depending on the feed water salinity and the desired product water quality. As the cost of the system increases dramatically with the number of stages required, ED systems are most cost-competitive for brackish water desalination.

Pretreatment depends upon the quality of feed water. Post-treatment involves pH adjustment and disinfection. Routine maintenance includes cleaning of membranes to control scale and biofouling, usually by flushing the system with base and then with acid. Membranes must be replaced about every 10 years. Electrodes can degrade over time due to oxidation.

Operation can be in continuous or batch mode; continuous mode is more common. ED systems can be operated intermittently without any significant decrease in membrane life or efficiency, making them suitable for use as deferrable load. The membranes of ED units are subject to fouling, and thus some pretreatment of the feed water is usually necessary. The electrodialysis reversal (EDR) process was developed to help eliminate membrane fouling. In the EDR process, the membrane polarity is reversed several times an hour. This has the effect of switching the brine channels to freshwater channels, and the freshwater channels to brine channels, and breaks up and flushes out deposits (Buros, 2000).

Because electrodialysis operates by removing ionic solutes from the feed water, it has no effect on non-ionic solutes, such as organic matter, silica, and microorganisms. Therefore it cannot disinfect water. For water supplies with high silica levels, pretreatment is necessary to remove the silica. In such cases, RO might be a better choice than ED. Because electrodialysis is only cost effective for brackish water desalination, it accounts for only 5.7% of world desalting capacity and comprises only 12.8% of desalination installations (Wangnick, 1995).

Electrodialysis has been in commercial use since 1954, over ten years before RO. Since then, this process has seen widespread applications for a number of purposes including the production of potable water which is one of the most important. Due to its modular structure, ED is available in a wide range of sizes, from small (down to 2 m^3/d) to large product water capacities (European Commission 2002). ED is widely used in USA with 31 % of the total installed capacity. In Europe ED process accounts for 15% while in the Middle East for 23% of the total installed capacity.

3.2.2. *Energy Consumption*

Like RO the energy required to separate the ions increases with concentration, thus ED is more economical for low salinity and brackish water (not more than 6,000 parts per million (ppm) of dissolved solids). Similarly, ED process is not suitable for water with less than 400 ppm of dissolved solids because the energy requirement increases due to low conductivity. In general, the total energy consumption, under ambient temperature conditions is in the range of 2.6-5.5 kWh/m^3. In addition, pumping energy requirements are minimum.

3.2.3. *Advantages and Disadvantages*

Electrodialysis is frequently compared with reverse osmosis, its competitor membrane desalination technology. ED operates under low pressures so reducing the operational hazard of high-pressure systems; unlike RO, the product water stream is under slightly higher pressure than the concentrate stream, reducing the chance of contamination; flushing the membranes with desalted water after each shut-down is not necessary; and its membranes have a lifetime more than twice that of RO membranes. The disadvantages of ED compared with RO are that ED cannot remove non-ionic solutes such as microorganisms and silica; ED systems take up more space than RO; and ED becomes significantly more expensive at salinity above 5.000 ppm.

3.2.4. *Coupling with Solar Energy*

The use of PV arrays to power electrodialysis plants for brackish water desalination makes sense in arid and semi-arid regions. In such regions there is often an inadequate water and energy supply infrastructure together with good levels of solar radiation. A positive aspect is that electrodialysis plants need no inverter for the direct current given by the PV arrays. As such, solar energy using PV modules is an ideal power source for the ED process in remote locations.

Few demonstrations of PV-powered ED systems have been built and the literature published on the use of solar energy for electrodialysis is limited. Al-Madani (2003) reported that Abdul-Fattah had reviewed the various methods of utilizing solar energy for water desalination using reverse osmosis and electrodialysis, as well other processes. Recently, several PV-powered pilot plants have been built, some of which are described below.

Ishimaru, (1994) studied the reliability of an electrodialysis system operated by photovoltaic cells in remote areas to desalinate a feed water with TDS value of 1500 ppm. A 65 kW PV array supplies enough energy to produce an average of 200 m^3/day of potable water. Battery storage of 1.200 amp-hours (10 hours of storage) provides constant power. A 30 kVA inverter supplies AC power to the pumps, while the electrodes are powered by a DC bus. The 200 m^3/day unit was reported to produce drinking water of satisfactory quality during the 2-year period of study. Due to natural fluctuations in feed water salinity and temperature, the water production rate and energy requirements fluctuated between 130 and 370 m^3/day and 0.6 and 1.0 kWh/m^3, respectively.

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

Al-Madani (2003) reported on a small-scale commercial-type electrodialysis stack powered by photovoltaic cells. The stack consisted of 24 cell pairs, arranged in four hydraulic stages and two electrical stages. The feed water was fed from two sources, the first were sodium chloride solutions prepared in the laboratory and the second was groundwater of medium salinity. The experiments were done at temperatures ranging from 10 to 40 °C and product flow rates ranging from 50 to 300 gallons/day. Salt removal was as high as 95% for groundwater and 99% for NaCl solutions at low product flow rates of 150 gal/day.

3.3. MEMBRANE DISTILLATION (MD)

3.3.1. *Operation Principle*

Membrane distillation is a hybrid of thermal distillation and membrane processes best described as a trans-membrane evaporation. The driving force is a temperature difference between the feed water and permeate which results in a vapor pressure differential across a hydrophobic porous membrane (in contrast to pressure as driving force for RO and electrical potential as driving force for ED). Vapor evolved from the feed solution passes through the pores of the membrane and is collected on the other side. Since liquid does not penetrate the hydrophobic membrane, dissolved ions are completely rejected by the membrane.

Methods for collecting the vapor permeate include immediate condensation within a colder liquid flowing on the second side of the membrane or condensation on a cold surface located at some distance from the membrane. In the latter situation, vacuum can be applied to draw more vapor through the membrane. The materials used most commonly to produce hydrophobic membranes suitable for membrane distillation are polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinyldeneflouride (PVDF). Nonetheless, the number of commercial applications of membrane distillation is small but growing. Desalination plants were built in Florida and Cayman Islands but are no longer operated.

3.3.2. *Advantages and Disadvantages*

The main advantages of membrane distillation over conventional distillation process are: lower operating temperatures, compact modules, mist elimination, production of ultra pure water, and the possibility of overcoming corrosion problems by using plastic equipment. The process can use such available energy resources as solar energy or waste energy in industrial processes.

Table 2 summarizes the main characteristics of the membrane-based desalination processes.

Membrane distillation can readily tolerate fluctuating and intermittent operating conditions. Membrane distillation is a salt tolerant process and can operate with different levels of salt concentration. In addition, maintenance requirements are low. The main limitation of the process is the risk of liquid entering the membrane pores. Any liquid can be pressurized enough to wet the membrane. Since the surface tension of pure water is high, this is not a concern for many mixtures. Nonetheless, the portion of the feed water that evaporates and permeates through the membrane is relatively small, resulting in relatively small recoveries and large brine recycle streams.

3.3.3. *Coupling with Solar Energy*

Few demonstration projects using solar-thermal membrane distillation have been built. Hogan et al. (1991), at the University of New South Wales in Australia, describe a 0.05 m^3/day system using 3 m^2 of solar collectors. Their system, which was tested in Sydney, consisted of a hollow-fiber membrane module for MD and a heat recovery exchanger for reducing capital costs. This solar powered membrane distillation (SPMD) unit was found to be technically feasible, with the membrane process being compatible with the transient nature of the energy source. The calculated efficiency of 17 liters per day per square meter of collector area compares favorably with solar MSF and MED plants. The researchers calculated that the process requires 55.6 kWh/m^3 (thermal and electric).

Bier et al. (1995) constructed another SPMD using an air gap membrane distillation (AGMD) module instead of the direct contact membrane distillation (DCMD) module tested in the SPMD pilot plant constructed by Hogan et al. The latent heat recovery process in this late pilot plant was integrated with MD in a spiral-wound membrane module. However, the additional mass transfer resistance created by the air gap resulted in a large reduction in the trans-membrane water flux. Recently, Koschilkowski et al. (2003)] used a similar membrane module to that used by Bier et al. in their study of a SPMD pilot plant. According to their calculations, without heat storage, the plant can distill 150 L/d of water in the summer in a southern country.

TABLE 2. Summary of the main characteristics of the membrane-based desalination processes

Parameter	RO	ED	MD
Operating temperature range (^oC)	15-40	15-40	40-90
Operating pressure range (MPa)	2-8	Atmospheric	Atmospheric
Sensitivity to feed water quality	High	Medium-high	Low
Pretreatment requirements	Extensive	Medium	Low
Feed water salinity range	Brackish and seawater	Brackish water only	Brackish and seawater
Product water quality (ppm)	1-500	250-500	1-40
Product water recovery ratio (percentage)	25-50	--	3-10
Scaling/fouling and corrosion potential	Low-moderate	Low	Low
Spare parts replacement rate	High (high pressure pumps and membranes)	Low (Membranes)	Low (Membranes)
High technology components	High pressure pumps, membrane, instruments and control	Membranes	Membranes
Maintenance requirements	High	Medium	Low
Operators' skills requirements	Medium	Medium	Low
Potential for further process developments	Medium	Low	High
Market potential for the next 10-15 years	High	Low-moderate	High

Banat et al. (2002) integrated a MD module with a solar still to produce potable water from simulated seawater. In their investigations the solar still was used for both seawater heating and potable water production. The effect of some factors affecting flux of the membrane module was also investigated. Their experimental studies showed that the contribution of the solar still in the distillate production was no more than 20% of the total flux.

The Water Re-use Promotion Center in Tokyo, Japan, installed a demonstration solar-powered membrane distillation plant in 1994 that produces 40 liters per hour. Automatic controls start up the desalination system whenever sufficient sunlight is present to provide hot water and electricity for pumping from the solar collectors and PV panels (Thomas 1997).

A solar-powered membrane distillation system was installed in the Canary Islands in 1988. The system produced 14.5 liters per day per square meter of collector area, and operated intermittently according to the availability of sunlight (Thomas 1997).

The desalination performance and O&M procedures of an air-gap type membrane distillation system was tested by Walton et al. (2004) using low-grade thermal energy (between 13 and 75ºC) supplied by a salt-gradient solar pond. The entire system (an air gap membrane distillation module, 2.94 m^2 plus controlling pumps and heaters) built by SCARAB (Swedish firm http://www.hvr.se) was used in this study. Hot brine was pumped from the bottom of the solar pond and passed through a heat exchanger to supply heat. Cold water from the solar pond surface was passed through a heat exchanger to provide cooling. High and low temperatures for system operation were obtained by changing the flow rates for solar pond hot and cold water. The permeate flux was fluctuating and reached a maximum of 6 $L/m^2.hr$.

Theoretical calculations, based upon measured results, indicate that membrane distillation with latent heat recovery can be easily implemented and that this modification would make MD competitive with other thermal technologies in terms of energy use. The researchers found that membrane distillation is only competitive relative to reverse osmosis when low cost heat energy is available and/or when the water chemistry of the source water is too difficult for treatment with reverse osmosis.

With the aid of a computer simulation program Ding et al. (2005) concluded that for a certain solar collector area, heat recovery from the permeate to the feed is the only way to improve energy efficiency of the system, and in this way plant capacity can be promoted.

In the activities of the SMADES project funded by the EC three small scale and one large scale stand alone solar-powered MD pilots were installed in Morocco, Egypt, and Jordan. The small scale plants have been in operation for periods ranging from 2-6 months. Whenever sufficient sunlight is present to provide hot water and electricity for pumping from the solar collectors and PV panels the unit starts to produce distillate permeate. The production rate of the unit installed in Jordan reached as high as 120 L/d with a distillate quality of 4 μS/cm. The large unit with a production rate of 1000 L/d has been installed in Aqaba-Jordan with seawater as the feed solution. Preliminary results showed that the unit is capable of producing distillate with a quality of 2-4 μS/cm.

4. Summary

Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible, and where the water scarcity is severe. Solar energy can be used for seawater desalination either by producing the thermal energy required to drive the phase-change membrane distillation process or by producing the electricity required to drive the RO and ED membrane processes.

The proven RO and ED technologies require only electrical (no thermal) input energy while MD requires both thermal and electrical energy. ED is the most energy-efficient desalination method for brackish water with low non-ionic solute content, while RO can be used for brackish or seawater as long as the water has low potential for fouling the membranes. More research is needed to determine the competitiveness of membrane distillation with the more proven desalination technologies.

Photovoltaic-powered reverse osmosis (PV-RO) is considered one of the more promising approaches, particularly for small systems where other technologies are less competitive. In practice however, solar power is intermittent and variable while RO plant is generally designed to run continuously and at constant flow. Batteries are often proposed, and indeed used, to address this, but batteries are very problematic in the field. In addition, energy recovery in small scale PV-RO system is a challenge.

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SMALL AUTONOMOUS RO DESALINATION SYSTEMS POWERED BY RENEWABLE ENERGIES. TECHNOLOGICAL ADVANCES AND ECONOMICS

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Abstract. The supply of fresh water is becoming an issue of increasing importance in many areas in the world. In arid areas potable water is very scarce and the lives of people in these areas strongly depend on the amount of available water. Seawater desalination requires large amounts of energy and if this energy is produced by fossil fuels it will harm the environment. Therefore, renewable energy sources coupled to desalination offer an attractive solution. Considerable research is under way to optimise the matching of renewable energy technologies with the corresponding desalination technologies and especially to reduce the energy required per unit volume of fresh water produced. The present paper gives emphasis to the following technologies: 1) RO powered by PV and 2) Solar collectors for powering RO through a Rankine cycle. These systems are reviewed and recent developments are presented. Finally the economics of the systems are analysed and overall figures of the present fresh water cost are given.

Keywords: Renewable energies, photovoltaics, solar collectors, reverse osmosis, hydraulic energy recovery, Rankine cycle

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1. Introduction

The origin and continuation of mankind is based on water. Water is one of the most abundant resources on earth, covering three-fourths of the planet's surface. However, about 97% of the earth's water is salt sea water, and only 3% is fresh water. This small percentage of the earth's water -to satisfy most of human and animal needs-, exists in ground water, lakes and rivers. The only nearly inexhaustible sources of water are the seas which, however, are of high salinity. It would be feasible to address the water-shortage problem with seawater desalination; however, in order to subtract the salts from seawater requires large amounts of energy which, if produced from fossil fuels, will harm the environment. Therefore, there is a need to utilize environmentally-friendly energy sources to desalinate seawater.

Renewable energy sources (RES) coupled to desalination offer a promising prospect for covering the fundamental needs of power and water especially in remote regions, where connection to the public electricity grid is either not cost effective or not feasible, and where the water scarcity is severe.

2. Desalination Processes

Desalination can be achieved by using a number of techniques. Desalination technologies use either phase change or involve semi-permeable membranes to separate the solvent or some solutes. Desalination techniques may be classified into the following categories: (i) phase-change or thermal processes; and (ii) membrane or single-phase processes. In TABLE 1, the most important technologies in use are listed (Delyannis and Belessiotis, 1995).

TABLE 1. Desalination processes

Phase-change processes	Membrane processes
1. Multi-stage flash (MSF) 2. Multiple effect boiling (MEB) 3. Vapour compression (VC)	1. Reverse osmosis (RO) –RO without energy Recovery –RO with energy recovery (ER-RO)
4. Freezing	2. Electrodialysis (ED)
5. Humidification/ Dehumidification	
6. Solar stills –Conventional stills –Special stills –Cascaded type solar stills –Wick-type stills –Multiple-wick-type stills	

3. Desalination and Energy Requirements

Desalination processes require significant quantities of energy to achieve separation of salts from seawater. This is highly significant as it is a cost which few of the water-short areas of the world can afford. The installed capacity of desalinated water systems in year 2000 is about 22 million m^3/day, which is expected to increase drastically in the next decades. The dramatic increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by the use of fossil fuels. It has been estimated that the production of 22 million m^3/day requires about 203 million tons of oil per year (about 8.5 EJ/year or 2.36×10^{12} kW h/year of fuel), (Kalogirou, 2005).

Considering the environmental problems related to the use of fossil fuels, if oil was much more widely available, it is questionable if we could afford to burn it on the scale needed to provide everyone with fresh water. Given current understanding of the greenhouse effect and the importance of CO_2 levels, this use of oil is debatable. Thus, apart from satisfying the additional energy demand, environmental pollution would be a major concern. If desalination is accomplished by conventional technology, then it will require burning of substantial quantities of fossil fuels and given that conventional sources of energy are polluting, sources of energy that are not polluting will have to be deployed. Fortunately, there are many parts of the world that are short of water but have exploitable renewable sources of energy that could be used to drive desalination processes.

TABLE 2 presents typical energy consumptions of the most common desalination processes, (Tzen and Morris, 2003).

TABLE 2. Energy consumption of the main desalination processes

Feed Water	Desalination process	Thermal energy (kJ/kg)	Electrical energy (kWh/m^3)
Seawater	MSF	190 – 290	4 – 6
	MED	150 – 290	2.5 – 3
	VC	-	8 – 12
	RO with energy recovery	-	3 – 5
	RO without energy recovery	-	7 – 10
Brackish water (1500-3500 ppm TDS)	RO	-	1 – 3
	ED	-	1.5 – 4

4. Renewable Energies and Desalination

The first patent on desalination was submitted in 1870, (Birkett, 1984, Delyannis and Belessiotis, 1995). In this patent the basic principles of solar distillation were described. Solar desalination is used by nature to produce rain, which is the main source of fresh water supply. All available man-made distillation systems are small-scale duplications of this natural process.

Renewable energy systems produce energy from sources that are freely available in nature. Their main characteristic is that they are friendly to the environment, i.e. they do not produce harmful effluents. Although renewable energy powered desalination systems cannot compete with conventional systems in terms of the cost of water produced, they are applicable in certain areas and are likely to become more widely feasible solutions in the near future.

Solar desalination systems can be classified into two categories, i.e. direct and indirect collection systems. As their name implies, direct collection systems use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and one for desalination).

The most promising and applicable renewable energy systems (RES) desalination combinations are shown in TABLE 3. Over the last two decades, numerous desalination systems utilizing renewable energy have been constructed. Almost all of these systems have been built as research or demonstration projects and were consequently of a small capacity. It is not known how many of these plants still exist but it is likely that only some remain in operation. The lessons learnt have hopefully been passed on and are reflected in the plants currently being built and tested.

Still there are many problems to overcome to bring to a successful coupling renewable energies and desalination systems. A major problem regards the variation of the produced renewable power as wind speed or level of solar irradiance varies and since most renewable energy systems lack an inherent energy storage mechanism, the produced power has to be consumed directly or else it will be lost. Another problem is that, desalination systems (for example the popular Reverse-Osmosis one) have traditionally been designed to operate with a constant power input to ensure continuous operation without interruptions. Unpredictable and non-steady power inputs, such as the renewables, force the desalination system to operate in non optimal conditions (variable and intermittent) and cause operational problems.

TABLE 3. RES desalination combinations, (Desalination Guide Using Renewable Energies 1998)

RES technology	Feed water salinity	Desalination technology
Solar thermal	Seawater	Multiple effect boiling (MEB)
	Seawater	Multi-stage flash (MSF)
Photovoltaics	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Brackish water	Electrodialysis (ED)
Wind energy	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Seawater	Mechanical vapor compression (MVC)
Geothermal	Seawater	Multiple effect boiling (MEB)

The addition of an energy storage sub-system results to both cost increase and also system complexity. The above reasons explain why the great majority of RES powered desalination systems developed or installed today are combinations of "conventional" RE systems with "conventional" desalination systems, (Desalination Guide Using Renewable Energies, 1998, Lindemann, 2004, Kalogirou 2005, Tzen and Morris 2003). Only few research trials are found in literature where the whole system (renewable technologies and desalination technologies together) is designed as a "complete" system, e.g. see (Thomson and Infield, 2002) while only one publication is found regarding the effects of variable and intermittent operation on reverse osmosis membranes, (Gotor, 2003).

RO and ED can be powered by electricity produced by photovoltaics (PV) or wind turbines. The direct current (DC) or alternating current (AC) produced through converters -where appropriate- can be used to drive electromechanical devices such as pumps or other devices necessary to operate the desalination system. A major advantage of PV is that it can be used to power small to medium size desalination systems especially in the areas where solar energy is available but both grid electricity and fresh water are not.

TABLE 4. Desalination processes used in conjunction with renewable energy

RO	62%
ED	5%
MSF	10%
MED	14%
VC	5%
Other	4%

TABLE 5. Renewable energy sources for desalination

Solar PV	43%
Solar thermal	27%
Wind	20%
Hybrid	10%

TABLE 3 shows that the most promising desalination method to be combined with PV is RO, especially when energy recovery is used because the specific energy consumption is small. Hence PV driven RO is the usual choice in most cases. This is also proven from TABLE 4 and TABLE 5 below, (Tzen and Morris 2003). PV is particularly good for small applications in areas with high solar potential.

5. RO Systems and Hydraulic Energy Recovery

In **large** RO plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery reverse osmosis systems. Unfortunately brine turbines cannot be engineered for **small** RO plants due to the low brine flow rate, (Garcıa-Rodrıguez, 2003).

A key to minimize the cost of the produced fresh water from PV driven RO is to minimize the electrical energy consumed per unit volume of fresh water produced i.e. the specific energy consumption (kWh/m^3) and thus the introduction of an energy recovery system of high efficiency is still a matter that needs further investigation.

In the last few years much research is being done to develop energy recovery systems compatible with **small** RO plants. Some companies have developed systems to directly recover the hydraulic energy contained in the high pressure brine, (Spectra Water Makers–USA, www.spectrawatermakers.com, 2005). Both systems have been tested and performed well with efficiencies in the range of 80% to 90%, e.g. see Garcıa-Rodrıguez, (2003). RO plants equipped with such hydraulic energy recovery systems achieved overall specific energy consumptions lower than 4 kWh/m^3 (Thomson and Infield, 2002), however their reliability is still unconfirmed for **long** time operation. Nevertheless the market requires overall specific energy consumption lower than 3 kWh/m^3. Such low specific energy consumption values are difficult to accomplish when **small** RO plants are to be operated by a **batteryless** photovoltaic system, (Mohamed, 2004).

Danfoss company, (http://nessie.danfoss.com/products/pumps.asp, 2005), has recently developed the Nessie® series of high pressure pumps which are based on the axial piston principle (positive displacement) making the pumps light and compact. The pumps have very high efficiency (over 90%) which makes them very promising for RO systems for both feeding the salt water to the RO membranes but also for hydraulic energy recovery: The pump can be operated in reverse mode, that is as hydraulic motor driven by the high pressure brine water coming out from the membranes. In this way the hydraulic motor can be connected directly to the motor shaft and thus recover the energy from the high pressure of the brine.

6. Small Autonomous RO Systems Powered by PV

Stand-alone PV systems are used in areas that are not easily accessible or have no access to main electricity. A stand-alone system is independent of the electricity grid, with the energy produced normally being stored in batteries. A typical stand-alone system would consist of PV module or modules, batteries and charge controller. An inverter may also be included in the system to convert the direct current (DC) generated by the PV modules to the alternating current form (AC) required by normal appliances.

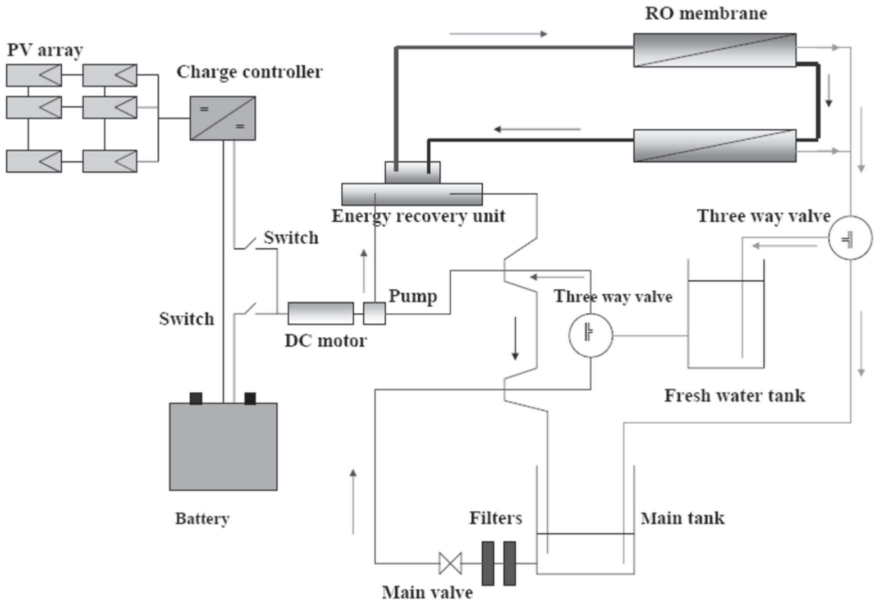

Figure 1. Schematic diagram of a PV-battery driven RO system equipped with energy recovery of the Clark pump type.

A typical arrangement of a DC pump driven RO system through PV (with batteries), equipped with energy recovery, of the Clark pump type is shown in Figure 1 (Mohamed et al. 2005). The system is installed at the Agricultural University of Athens. Various configurations of the electricity supply of this RO system are being tested such as, 1) hybrid (PV and wind) to charge batteries and then supply the pump DC motor through the batteries, 2) direct connection of the PV to the pump DC motor either through a linear current booster or without. All configurations offer advantages and disadvantages. A major advantage of the battery system is that it allows RO membrane operation at constant pressure although batteries increase maintenance requirements and also can cause environmental problems. A major disadvantage of the batteryless system is the operation of the membranes at variable pressure although this system is much simpler than the one equipped with batteries.

7. Solar Thermal Power Driven RO

An alternative to the PV driven RO is the solar thermal power driven RO that uses a low temperature solar organic Rankine cycle to produce mechanical power to drive the RO pump, see Figure 2, (Manolakos et al., 2005).

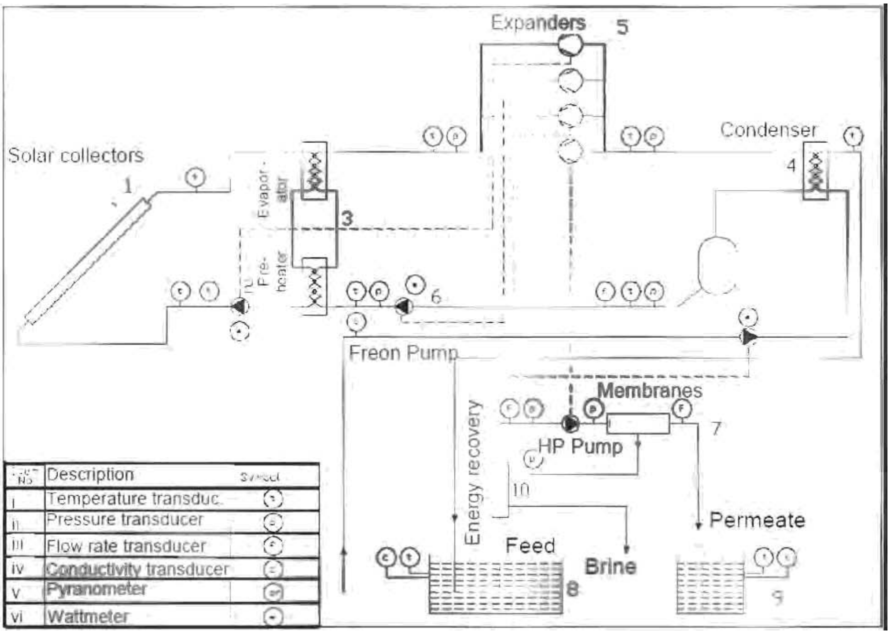

Figure 2. Schematic diagram of the solar thermal Rankine RO system. System components: 1) High efficiency vacuum tube solar collectors' array, 2) Circulator, 3) Evaporator, 4) Condenser, 5) Expanders, 6) HFC-134a pump, 7) RO unit, 8) Insulated seawater reservoir, 9) Fresh water reservoir, 10) RO energy recovery system.

Thermal energy produced from the solar collectors array evaporates the working fluid (HFC-134a) in the evaporator surface, changing the fluid state from sub-liquid to super heated vapor. The super-heated vapor is then driven to the expanders where the generated mechanical work produced by the process drives the pressure pump of the RO unit, circulation pumps of the Rankine cycle (HFC-134a, cooling water pump), and the circulator of the collectors. The saturated vapor at the expanders' outlet is directed to the condenser and condensates. HFC-134a condensation is necessary in the Rankine process. On the condenser surface, seawater is pre-heated and directed to the seawater reservoir. Seawater pre-heating is applied to increase the fresh water recovery ratio. The saturated liquid at the condenser outlet is then pressurized by the HFC-134a pump. In this system solar energy is used indirectly and does not heat seawater while the RO system is driven by direct mechanical work produced from the process. The energy recovery sub-system utilizes the Nessie® series Danfoss pumps. This system may also utilize any low temperature energy source like thermal wastes. The system is currently being tested at the Agricultural University of Athens.

8. Economics

The cost of the desalinated water varies according to the desalination technology, the size of the plant and the cost of the energy input to the plant. For large plants (several thousands of cubic meters per day) the cost is roughly 1 €/m^3, (Desalination Guide Using Renewable Energies, 1998). For smaller plants powered by renewables (e.g. wind or photovoltaics) the cost varies from 1.5 to 5 €/m^3, (Voivontas et al., 2001, Tzen and Morris, 2003, Zejli et al. 2004), while for very small plants the cost is usually reported to be above 5 €/m^3, (Desalination Guide Using Renewable Energies, 1998, Tzen and Morris, 2003). Recently a value of about 3.5 €/m^3 was reported for a PV driven (with batteries) RO plant, of a production capacity of 2.2 m^3/day, (Mohamed 2005). This good result was due to the use of an energy recovery system of Spectra Water Makers (of Clark pump type) that reduced the specific energy consumption down to 3.7 kWh/m^3.

According to Manolakos et al. (2005), solar thermal power Rankine - RO systems utilizing vacuum tube solar collectors, of a capacity of about 1 m^3/h and at a specific energy consumption of 2.5 kWh/m^3 are estimated to have a fresh water cost of about 12.5 €/m^3 while if thermal effluents are used the cost can be reduced dramatically down to 0.5 €/m^3.

9. Conclusions

There is an increasing need for renewable energy powered desalination systems as this seems to be the sole environmental friendly alternative to the conventional fossil fuel powered systems. RO seems to be particularly suitable for combining either direct electricity producing technologies (such as PV and wind turbines) or indirect such as solar collectors. Nevertheless there is a need to accelerate the development of novel water production systems from renewables. Particularly there is a need for a much stronger effort in R&D currently inadequate in Europe, which should include closer collaboration between the industry and research institutions as well as co-operation between Europe and the countries of the Mediterranean area and the Middle East.

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DESALINATION WITH WIND AND WAVE POWER

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Abstract. Seawater desalination can be an attractive alternative to ensure a secure source of water. However, the energy requirements for that process are high and can be a problem, mainly in isolated areas. Renewable energies are the best way to supply the energy needs, because can be available near the desalination plants and avoid environmental/availability problems associated with fossil fuels. In this paper two forms of renewable energies particularly suited for desalination are described: wind power and wave power.

Keywords: desalination; energy consumption; renewable energies, wind power; wave power.

1. Introduction

Desalination is a treatment process that removes salts from water. A typical desalination plant consists of a water pre-treatment system, the desalination unit, and a post-treatment system.

The most important desalination processes are split into two main categories, thermal (or distillation) and membrane processes[1]. The most widely used thermal processes for seawater desalination are: multistage-flash distillation (MSF), multiple effects distillation (MED or ME) and vapor compression (VC) processes. Membrane processes consist of reverse osmosis (RO) and electro-dialysis (ED) processes. Electro-dialysis is

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confined to the desalination of brackish water while reverse osmosis can be used for either brackish or for seawater desalination.

Osmosis is the movement of a solvent through a semi-permeable membrane into a solution of higher solute concentration that tends to equalize the concentrations of solute on the two sides of the membrane. Reverse osmosis is a method of producing pure water by forcing salt water through a semi-permeable membrane (which allows some molecules through, but not others) that salt molecules cannot pass through (Figure 1).

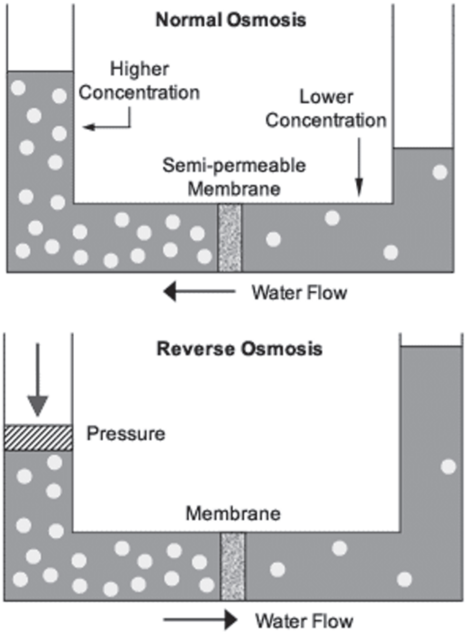

Figure 1. Normal and reverse osmosis. Source: Vision Engineer.

Electro-dialysis is an electro-membrane process in which ions are transported through ion permeable membranes from one solution to another under the influence of a potential gradient (Figure 2). The electrical charges on the ions allow them to be driven through the membranes fabricated from ion exchange polymers. Applying a voltage between two end electrodes generates the electrical field required for this process. The membranes used in electro-dialysis have the ability to selectively transport ions having positive or negative charge and reject ions of the opposite charge. In this way changing the concentration, removal, or separation of the salts can be achieved by electro-dialysis.

In the thermal desalination or distillation the principle is to reproduce the natural phenomenon of water evaporation and condensation as rain, while concentrating this phenomenon both in space and in time. Used with all types of seawater, thermal desalination only requires minimal pretreatment. Multiple effects processes have been optimized in order to reduce the high level of energy consumption involved in producing the heat required to vaporize the water.

These improved processes enable the energy released during condensation to be recovered and reused. Among these one of the most used process is the mechanical vapor compression (Figure 3), in which the sea water is evaporated after having been preheated in a heat recovery exchanger.

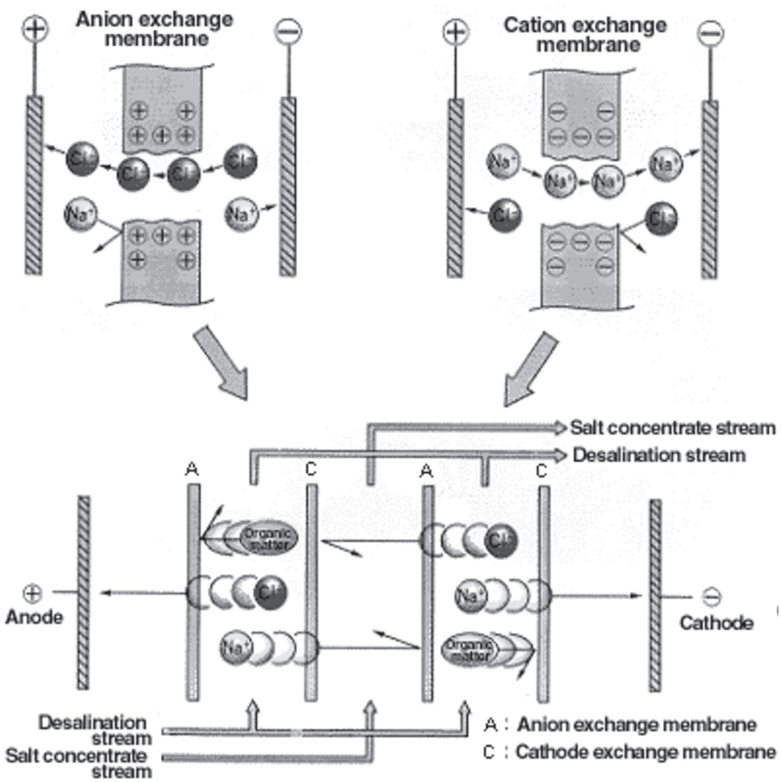

Figure 2. Principle of electrodialysis. Source: Astom Corporation.

Desalination processes require significant quantities of energy to achieve separation of salts from seawater[2]. This is a highly significant cost, representing in average 40% of the total costs. The energy consumption is about 3-8 kWh/m^3 of fresh water produced for the reverse osmosis process, 20-25 kWh/m^3 for the distillation process and 0.7-2.5 kWh/m^3 for the electro-dialysis (used mainly for brackish water).

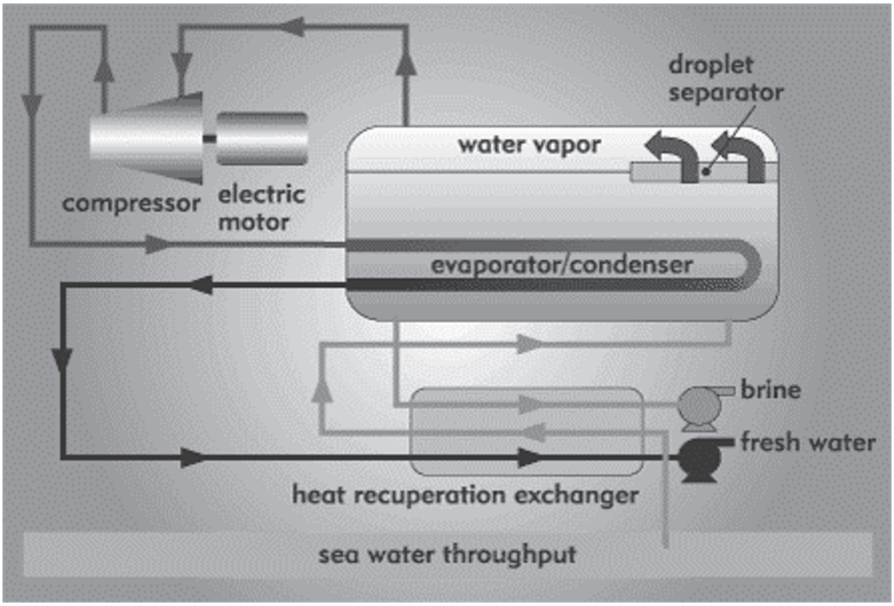

Figure 3. Mechanical vapour compression. Source: French Atomic Energy Commission.

If desalination is accomplished by conventional technologies, then it will require burning of substantial quantities of fossil fuels, while desalination with renewable energies offers an interesting possible solution, avoiding environmental problems. It often happens that the geographical areas where water is needed are well gifted with renewable energy sources, be it solar, wind, waves, etc. Thus, the obvious way is to combine those renewable energy sources with a desalination plant, in order to provide water resources as required[3].

A renewable desalination plant can be designed to operate coupled to the grid, and off-grid (standalone or autonomous). The latter case poses the problem of renewable energy variability because most renewable energy systems lack an inherent energy storage mechanism. However, because water can be stored cheaply in large quantities and for long periods, this lack of firmness does not seem to be a serious potential problem in most locations. With a renewable energy resource, like wind or wave power, the energy can be provided in form of electric energy or directly as mechanical energy[4,5].

2. Wind Power

The potential for the increased use of wind energy is huge (Figure 4). The estimated potential (onshore and offshore) for the wind energy in Europe is about 4800 TWh per year and worldwide some 53000 TWh per year.

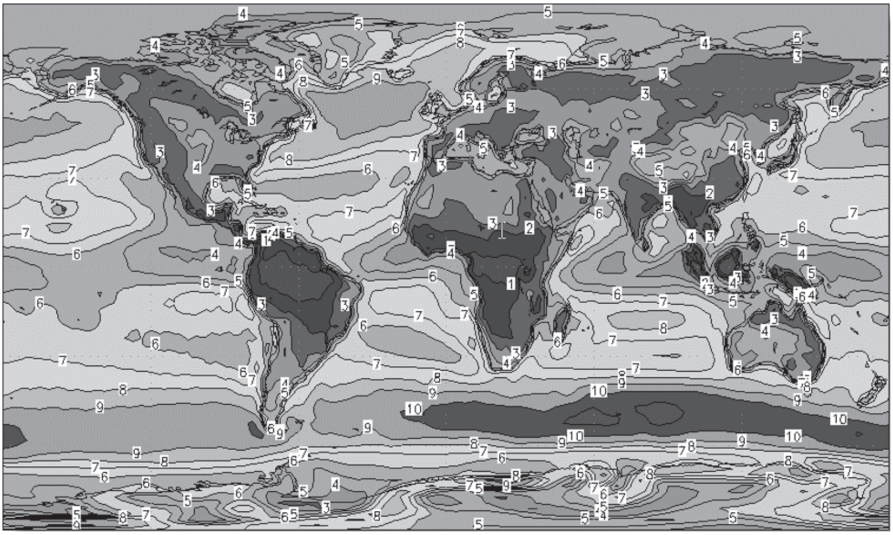

Figure 4. Wind Atlas of the World (wind speed in ms^{-1}). Source: Risoe National Laboratory.

A wind turbine is comprised of a tower (Figure 5), topped by an enclosure called a nacelle, and the rotor, which is the propeller-like structure connected to the nacelle. The nacelle houses an electrical generator, power control equipment and other mechanical equipment (typically a gearbox), which is connected to the rotor.

Wind energy became a significant research area in the 1970's during the energy crisis and the resulting search for renewable energy sources. Modern wind turbine technology has made significant advances over the last 30 years. Today, attention has remained focused on this technology as an environm-entally sound and convenient alternative. Generally, individual wind turbines are grouped into wind farms containing several turbines. Many wind farms are MW scale, ranging from few MW to tens of MW. Wind farms or smaller wind projects may be connected directly to utility distribution systems. The larger wind farms are often connected to the transmission network.

Wind power is becoming popular in many countries due to the fast and simple installation and low maintenance requirements once installed. Also, the land can still be used for animal grazing and some agriculture operations. Utility-scale turbines range in size from 50 to 5000 kW. Single small turbines, below 50 kW, can be used for remote loads.

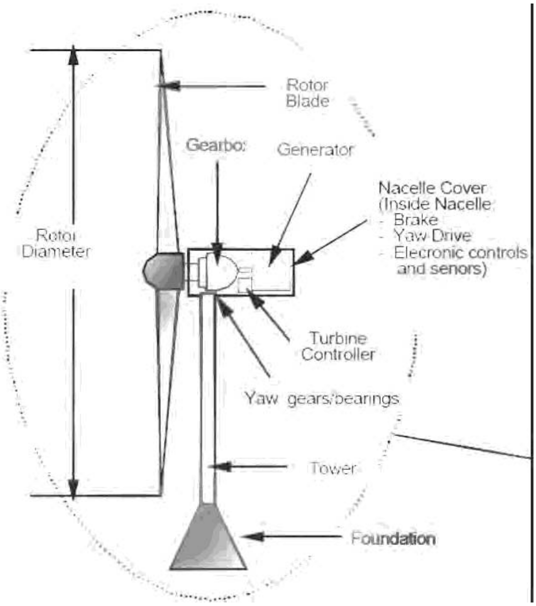

Figure 5. Horizontal axis wind turbine.

Technology improvements already achieved have lowered wind energy costs to less than US$1000/kW and wind power is one of the least expensive forms of renewable energy generation. Each part of the wind turbine is being subjected to research in order to improve efficiency and reduce costs. Several organizations are working to improve wind turbine generators to be more efficient. Some of the new technologies that are being developed use power electronics devices to allow for variable rotor speed operation to improve efficiency, and to improve power quality.

The airfoils for the wind turbine blades are also being improved to increase energy capture, and improvements have been made to the aerodynamics control devices that are built into the turbine blades to adjust the aerodynamic driving forces, optimize energy capture, control mechanical loads and control rotor speed.

The next major development in the wind industry is expected to be in achieving significant exploitation of the offshore resource. Much higher and more continuous winds at sea, combined with more advanced technological development shall compensate the higher investments needed to build offshore facilities and connect them to the electrical grid. But the economic viability of offshore wind farms will depend heavily on the quality of sites.

Offshore turbines will have to be larger (above 2 MW) than their counterparts on land to compensate for the sizeable additional costs of laying foundations and the grid connection, and thus to enable economical operations. Such turbines have to be adapted to marine conditions and prove their reliability. In the case of the desalination use of the wind energy, the offshore turbines have an important opportunity due to the localization of the energy consumption close to the place of generation.

Wind energy conversion devices and some desalination units can be chosen from a number of alternatives: reverse osmosis, electro-dialysis, and vapor compression[6,7]. In all these alternatives, the energy supply can come from a single wind turbine or from a wind farm.

Due to the random nature of the wind power, appropriate power control and conditioning systems are required for matching of the input power to the desalination load. The power supply must provide alternate current for reverse osmosis and vapor compression, while electro-dialysis requires direct current.

Power matching requires some form of energy dissipation or storage devices. Hence, in all cases the power control system may include dump loads, flywheels, or storage in batteries. A number of such plants have actually been operated, mainly for research purposes.

Enercon has recently launched a reverse osmosis desalination system (Figure 6). This technology uses directly the mechanical energy produced by the wind turbine to drive a high pressure pump and new energy recovery system.

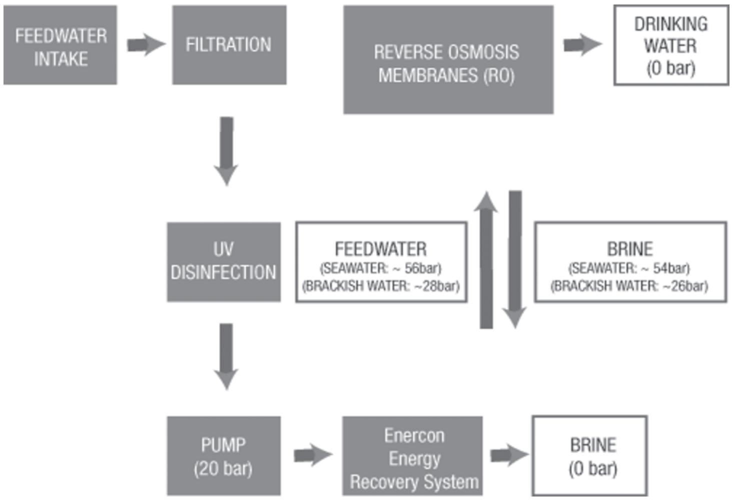

Figure 6. Basic functionality of Enercon's reverse osmosis desalination plant. Source: nercon.

In this process pressurized seawater flows through a membrane that retains the dissolved salts, producing drinking water. After passing the membrane, a three-piston system recycles the energy of the remaining seawater pressure with virtually no loss (Figure 7). Thus desalination and energy recovery occur in a continuous complementary process, forming a cycle.

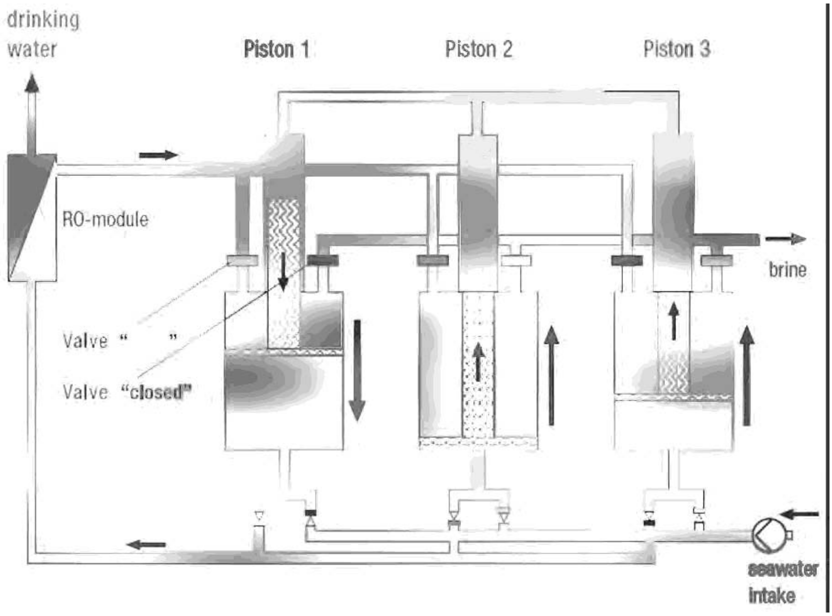

Figure 7. Enercon's energy recovery unit. Sorce: Enercon.

In this system, feedwater flows through filters and a UV disinfection system to the energy recovery. The pump pressure of 20 bar is transferred to sea water (56 bar) or brackish water (28 bar) and flows to the reverse osmosis membranes. Here, feedwater separates into drinking water and brine. Drinking water leaves the system and the brine, still under pressure, flows back to the energy recovery system to support the process.

The company's energy recovery unit consists of a low pressure pump (max. 20 bar) and a three-piston system, which raises the pressure up to 70 bar and simultaneously recovers energy from the pressurized brine. This system avoids that 75% of the energy input are lost (only 25% of the energy is used to produce drinking water), decreasing the energy consumption to less than 2.5 kWh/m^3 of desalinated water.

Enercon plants have no fixed operating point, enabling that the water production range between 12.5% and 100% of nominal capacity by adjusting the piston speed in the energy recovery system, according to demand. This means that output can be adjusted to match water demand, without shutting down the plant and that the plant can be powered by a fluctuating energy supply, like wind turbines.

3. Wave Power

Several types of ocean energy sources with different origins exist, the most developed being: tidal energy, thermal energy, marine currents and ocean waves. Wave energy can be considered a concentrated form of solar energy, because winds are generated by the differential heating of the earth, and, as a result of blowing over large areas of water, part of their kinetic energy is converted into waves. The power in a wave is proportional to the square of the amplitude and to the period of the motion, commonly exceeding 40-50 kW per meter of the width of the oncoming wave[8]. The global wave power potential was estimated to be more than 2 TW that is the same order of magnitude of the world consumption of electrical energy. Increased wave activity is found between the latitudes of 30º and 60º on both hemispheres i.e. the coasts of the Americas, Europe and Australia/New Zealand, with annual average power levels between 20 and 70 kW/m or higher (Figure 8).

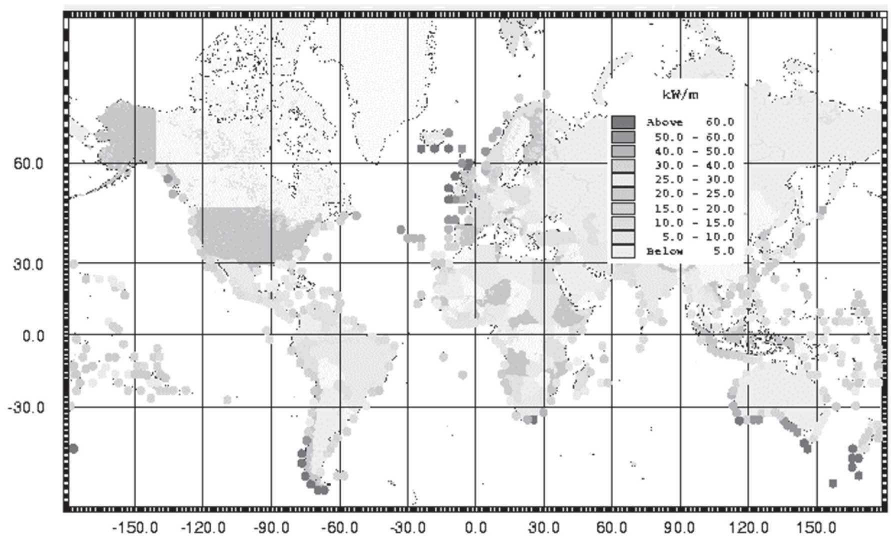

Figure 8. Global costal wave power estimates. Source: Oceanor.

The power present in ocean waves has been recognized for millennia although mostly in terms of its destructive potential. The research on wave energy conversion started in the 1970s when the oil crises provoked the exploitation of a range of renewable energy sources. Several research programmes with government and private support started thenceforth, mainly in the United Kingdom, Portugal, Ireland, Norway, Sweden and Denmark, aiming at developing industrially exploitable wave power conversion technologies in the medium and long term. Different schemes have proven their applicability on a large scale, under hard operational conditions, and a number of commercial plants are currently being built in Europe, Australia, Israel and elsewhere. Recent designs are rated at power levels ranging from a few kW up to 4 MW. Massive power production can be achieved by interconnection of large numbers of devices.

The wave energy devices can be divided in three different types: shoreline, nearshore and offshore devices[9,10]. Shoreline devices are fixed to or embedded in the shoreline making easier the installation and maintenance. Offshore devices exploit the more powerful wave regimes available in deep water (more than 40 m depth). The above devices are intended for electricity production but desalination is another potentially important use of wave energy devices.

3.1. SHORELINE DEVICES

3.1.1. *Oscillating Water Column*

The oscillating water column (OWC) device is a partially submerged hollow structure (Figure 9), which is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which alternately compresses and expands the air column generating a reciprocating flow through a Wells turbine, which is capable of maintaining constant direction of revolution irrespective of the direction of the air flow passing through it. The turbine is coupled to an alternator to generate electricity.

The Energetech device (Figure 10) is an onshore OWC with major improvements in the design of the system, the turbine, and in the project construction techniques. The system employs a parabolic wall to focus wave energy on to an OWC chamber. The motion of the waves causes an oscillatory water motion within the chamber, which in turn forces a high-speed airflow past a unique controllable turbine, which drives an induction generator to produce electrical power.

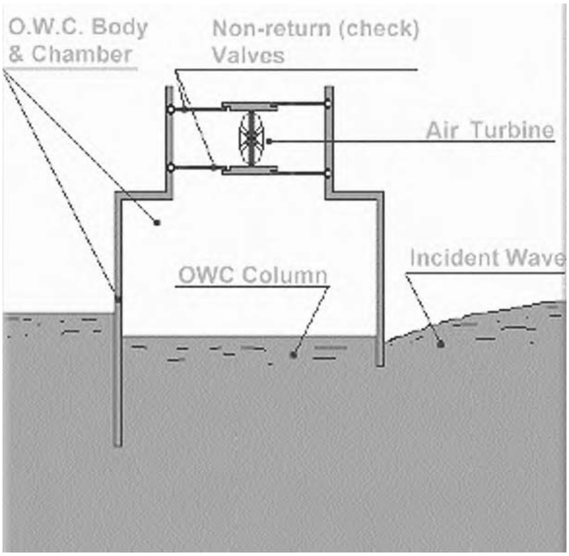

Figure 9. Oscillating water column device. Source: Daedalus Informatics Ltd.

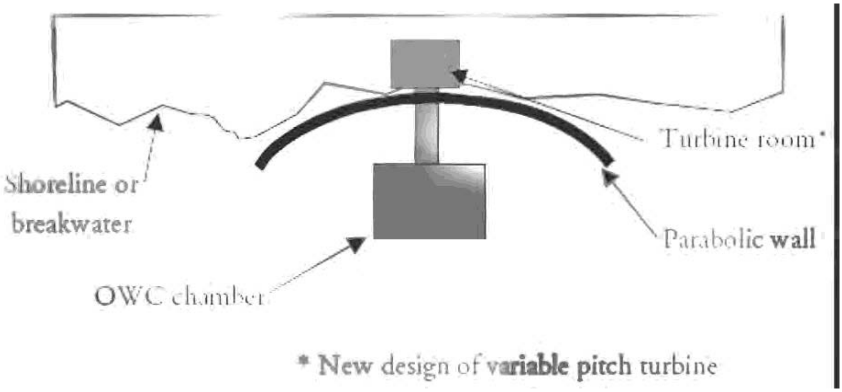

Figure 10. Energetech device. Source: AEA Technology.

3.1.2. *Tapchan*

The Tapchan (tapered channel system) device (Figure 11) consists of a reservoir built into a cliff a few metres above sea level. Leading into its structure, a gradually narrowing channel with wall heights above mean water is located. Incoming waves increase in height as they move up the channel, eventually overflowing the lip of the channel and pouring into the reservoir. In this way the kinetic energy of the wave is converted into potential energy, which is subsequently converted into electrical energy by a turbine coupled to a generator, as the water is fed back to the sea through a pipe.

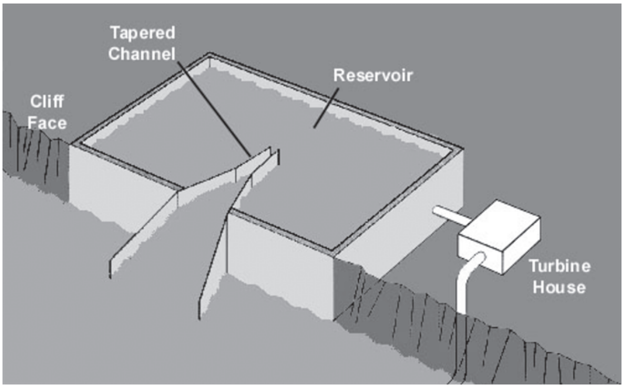

Figure 11. Tapchan device. Source: Oxford University.

3.1.3. *Pendulor*

The pendulor wave-power device (Figure 12) consists of a rectangular box, which is open to the sea at one end. An oscillating flap, moving like a pendulum, is hinged over this opening, so that the action of the waves causes the flap to swing back and forth, powering a hydraulic pump and a generator.

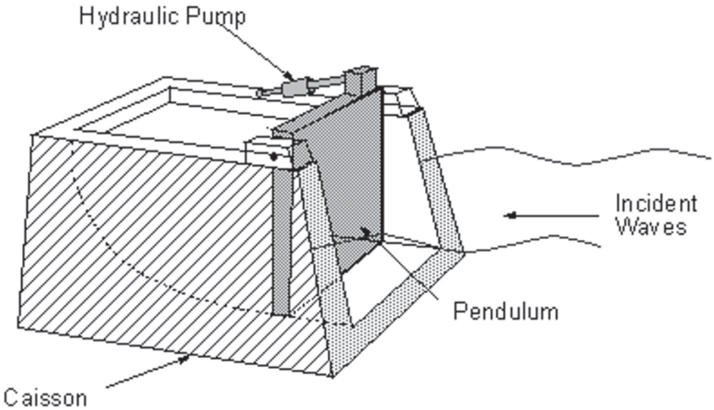

Figure 12. Pendulor device Source: EC ATLAS Project.

3.2. NEAR-SHORE DEVICES

3.2.1. *Osprey*

Osprey device (Figure 13) is a single chamber OWC, designed for installation in a water depth of approximately 14 m, with hollow steel ballast tanks fixed to either side. These tanks focus the waves towards the opening in the collector chamber. The air flow from this chamber passes through two vertical stacks mounted on the chamber with contra-rotating Wells' turbines. Behind the collector chamber and power module is a conning tower on which can be mounted a wind turbine.

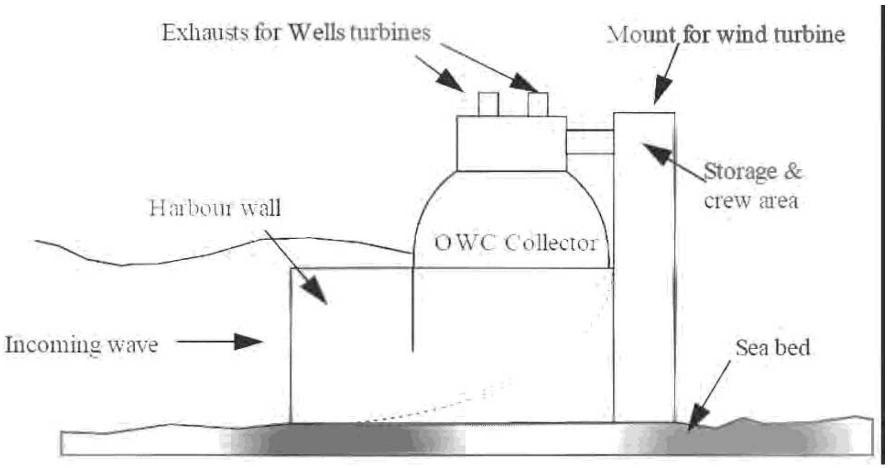

Figure 13. Osprey device. Source: Wavegen

3.3. OFFSHORE DEVICES

3.3.1. *Archimedes Wave Swing*

The Archimedes Wave Swing (AWS) wave energy converter (Figure 14) consists of a bottom-fixed air-filled cylindrical chamber which is fully submerged beneath the waves. As a wave crest approaches, the water pressure on the top of the cylinder increases and the upper part or 'floater' compresses the air within the cylinder to balance the pressures on both sides of the chamber. Its volume oscillates due to the reciprocating piston-like motion of its top part or "floater". The reverse happens as the wave passes trough and the cylinder expands. The relative movement between the floater and the fixed lower part or 'basement' is converted directly to electricity by means of a linear generator.

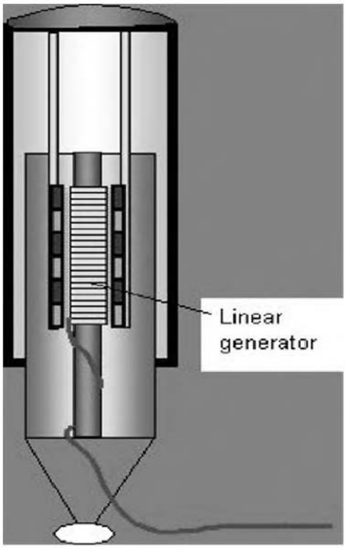

Figure 14. Archimedes wave swing device. Source: Teamwork Technology.

3.3.2. *McCabe Wave Pump*

The McCabe Wave Pump device (Figure 15) consists of three rectangular steel pontoons, which are hinged together across their beam. The pontoons move relative to each other with the waves. A damper plate is attached to the central pontoon, which ensures that it stays still as the fore and aft pontoons move relatively to the central pontoon by pitching about the hinges, allowing the system to vary its alignment in order to head into the oncoming waves. Energy is extracted from the rotation about the hinge points by linear hydraulic pumps mounted between the central and two outer pontoons near the hinges.

3.3.3. *Floating Wave Power Vessel*

The Floating Wave Power Vessel device (Figure 16) is similar to the Tapchan (tapered channel system) described in 3.1.2. The system is an overtopping device based in a steel floating platform, supported by ballast tanks in four sections, containing a sloping ramp, which gathers incoming waves into a raised internal basin. An anchor system allows the orientation of the vessel to the most energetic wave direction. The water flows from this basin back into the sea through low-head turbines.

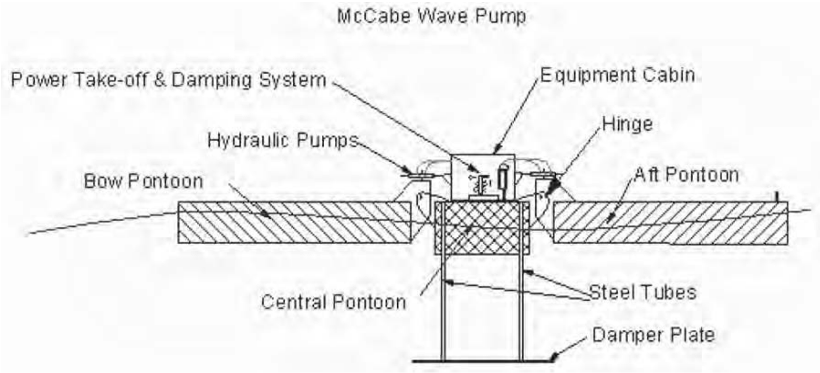

Figure 15. McCabe wave pump device. Source: Northern Ireland Assembly.

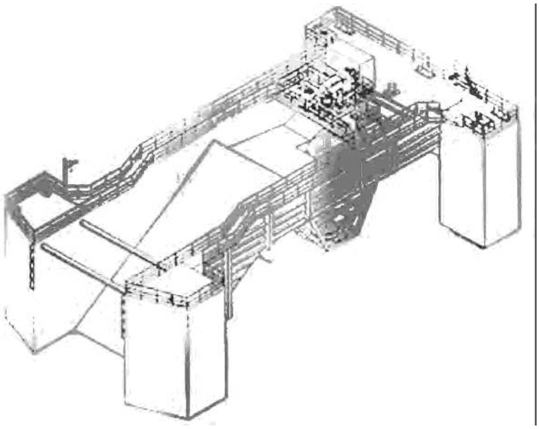

Figure 16. Floating Wave Power Vessel device. Source: Sea Power International.

3.3.4. *Wave Dragon*

The Wave Dragon (Figure 17) is an offshore wave energy converter, also of the overtopping type, utilizing a wave reflector design to focus the waves towards a ramp and fill a higher-level reservoir. The basic idea of the Wave Dragon wave energy converter is to use well-known and well-proven principles from traditional hydropower plants in an offshore floating platform. The water overtopping Wave Dragon is stored temporarily in a large reservoir creating a head, i.e. the difference between the "normal" level of the water surface and the water surface in the reservoir. This water is let out of the Wave Dragon reservoir through several turbines and thus generating electricity like in hydro power plants. Wave Dragon is a very simple construction and has only the turbines as the moving parts, which is useful for operating offshore under extreme forces and fouling.

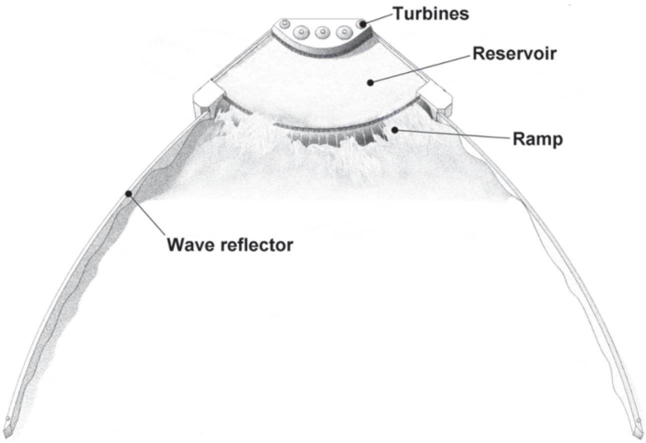

Figure 17. Wave dragon device. Source: Wave Dragon ApS.

3.3.5. *Mighty Whale*

The Mighty Whale device (Figure 18) is a floating oscillating water column that also makes use of hull motion for wave energy absorption. Alternately, floating devices may involve the use of a gyroscope to provide an inertial reference. The device has the double purpose of extracting wave energy and providing a calm waters area behind it.

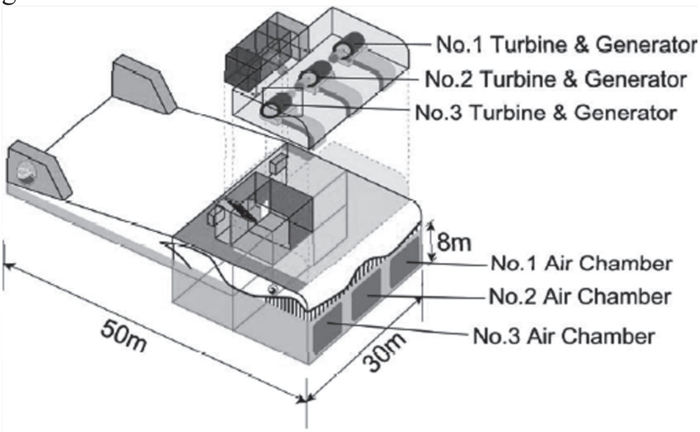

Figure 18. Mighty Whale device. Source: International Energy Agency.

3.3.6. *Pelamis*

The Pelamis (Latin for sea snake) is a semi-submerged device composed of hollow cylindrical sections linked by hinged joints (Figure 19). The sections point into the oncoming waves and move with respect to each other as the waves pass down their length. As waves run down the length of the device and actuate the joints, hydraulic cylinders incorporated in the joints pump high pressure oil to drive a hydraulic motor via an energy-smoothing system. Energy is extracted at the joints by hydraulic rams which drive the electrical generators.

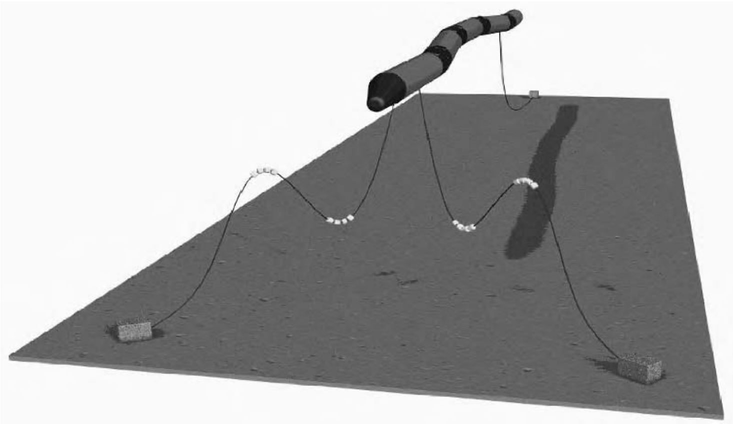

Figure 19. Pelamis device. Source: Ocean Power Delivery.

3.3.7. *Salter Duck*

The Salter Duck device (Figure 20), generate electricity through the harmonic motion of the floating part of the device, as opposed to fixed systems which use a fixed turbine which is powered by the motion of the wave. The device rise and fall according to the motion of the wave and electricity is generated through the motion. An important feature of this device is the capability of converting both the kinetic and potential energies of the waves, achieving thus very high absorption efficiencies. The latest 'Duck' consists of dozens of pistons fixed inside a cylinder which are pushed in and out by a ring of cams fixed to the moving float. This arrangement works by using highly specialized digital control hydraulics which juggles the pressure inside many hydraulic circuits, turning the slow bi-directional movement of the float into the constant high speed rotation of a generator.

3.3.8. *IPS Buoy*

The IPS Buoy device (Figure 21) consists of a flat plate with a curved head, which is inclined at an angle to the vertical, connected below to a weighted vertical tube. Inside the tube, which is open to the sea at both ends, there is a piston which extends upwards to the float. The buoy is held in position by an elastic mooring enabling it to move freely up and down against a damping water mass contained in the long vertical tube underneath the buoy. Out at sea, the float and tube move up and down more vigorously than the piston and the relative movement between the buoy itself and the water mass is transferred by a working piston in the acceleration tube into an energy conversion system located within the buoy hull.

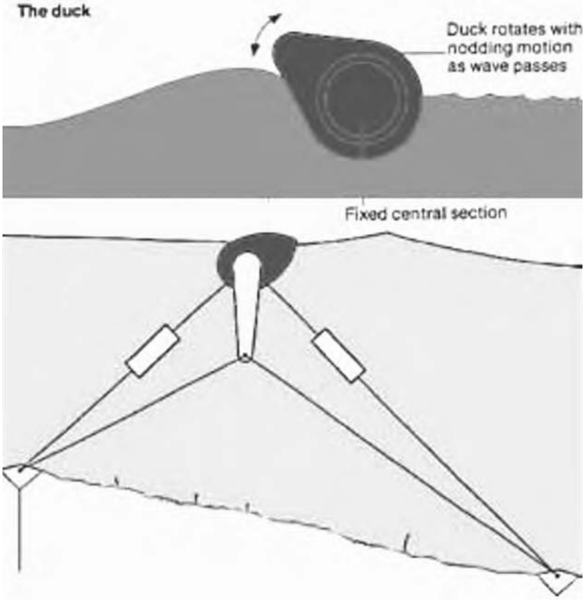

Figure 20. Salter Duck device. Source: Fujita Research.

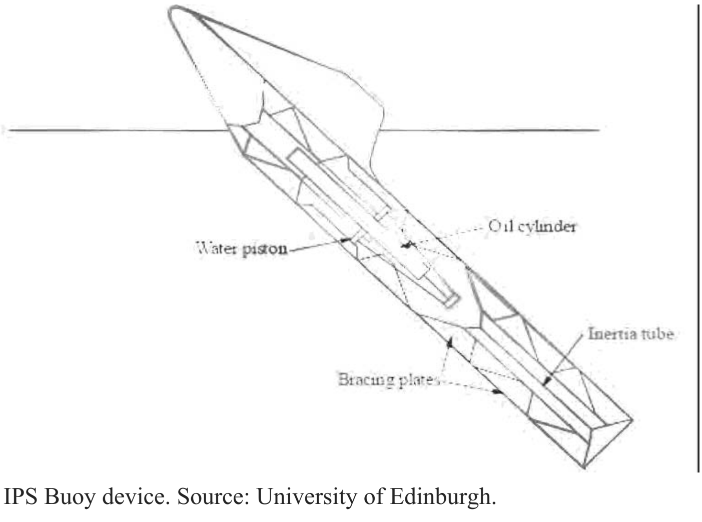

Figure 21. IPS Buoy device. Source: University of Edinburgh.

3.3.9. *PS Frog*

The PS Frog device (Figure 22) is a large buoyant paddle-shaped upper part, attached to a cylindrical lower part, which is designed to extract power from the Pitching and Surging (PS) motion. The upper part forms the working surface, whilst the lower part contains all the mechanical and electrical plant including a large reaction mass, which moves with respect to the hull. Hydraulic rams make the mass move and enable energy to be extracted via high pressure oil. The device adapts to the changing wave conditions from instant to instant, so as to resonate and allow it to capture large amounts of power while being physically small.

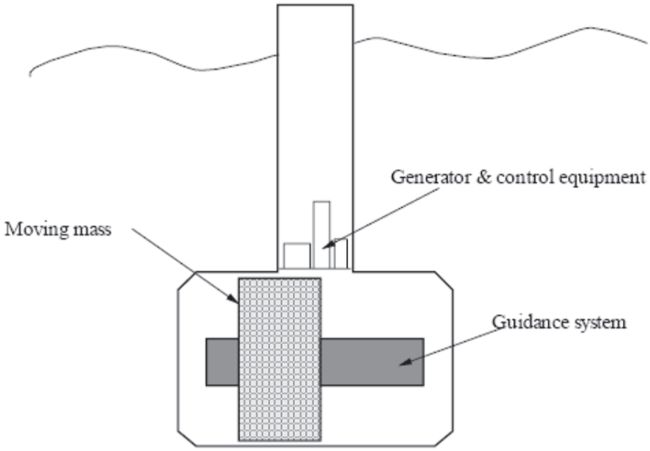

Figure 22. PS Frog device. Source: Lancaster University.

3.3.10. *AquaBuoy*

The AquaBuoy device (Figure 25) combines elements of two prior, successfully ocean-tested, technologies - the IPS Buoy and the Swedish Hose-pump. This consists of a slack-moored buoy floating on the surface, an ‘acceleration tube’, and an hydraulic power take-off on the sea bed. As the buoy rides the waves, the moving seawater drives a piston inside the tube, and the motion of the piston in turn drives a hose pump. As the hose elongates, its internal volume decreases to create a pressurized flow of seawater, which turns a Pelton wheel in the seabed assembly.

Figure 23. AquaBuoy device. Source: AquaEnergy Group.

4. Conclusions

Seawater desalination can be an attractive alternative to ensure a secure source of water. However, the energy requirements for that process are large and can be a problem, mainly in isolated areas. In some locations, particularly in islands, renewable energies can be the most sustainable way to supply the energy needs for desalination, because it can be available close to the desalination plants and avoid environmental/availability problems associated with fossil fuels.

Wind and wave power are two of the most abundant forms of renewable energy, which can be used for water desalination. In the last few years wind power technology had impressive developments, and is becoming cost-effective compared with fossil fuel alternatives. Wave power is not yet a mature technology and there is a variety of conversion systems which presently available and under development. The huge potential of these forms of energy can increasingly be used in desalination systems to meet the growing needs of fresh water in many parts of the world, lacking this precious resource.

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DESALTED WATER FROM A HYBRID RO/MSF PLANT WITH RDF COMBUSTION: MODELLING AND ECONOMICS

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Abstract. The hybrid process of seawater desalting couples the reverse osmosis with the multi-stage flash process. The hybrid process is usually planned to improve the performance of MSF and reduce the cost of desalted water. In this paper, we propose to apply a cogeneration system using a Refuse Derived Fuel to supply energy to this plant. Many researchers investigated the hybridization of RO and MSF technologies from different points of view. The present work is a trial to contribute in these efforts to throw more light on practicability of the hybridisation design through an optimization study, that is able to calculate the minimum water cost as function of the most important MSF plant parameters.

Keywords: RO, MSF, desalination, hybrid plant, cogeneration, RDF

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1. Introduction

The amount of fresh water resources in the Mediterranean countries is continuously decreasing, due to increasing needs and low rainfall. In Sardinia, in the last 30 years, the annual average rainfall is 500 mm, much less compared to those of 50 years ago (750 mm). So it's necessary to find other non-conventional sources, like reuse and desalination.

Economics of industrial desalination processes show that the most influent factors on water costs are both the energy and the capital cost. In the last 25 years, the introduction of technologies with low energetic consumption, favoured the diffusion of desalination processes, particularly in the industry.

The feasibility of desalination with low energetic cost may be reached by means of the following two options: (1) the optimization and minimization of energetic consumption and (2) the use of non-conventional energy sources.

Many researchers investigated the use of non conventional sources (i.e. renewable sources) for desalination processes. Several energy sources, which are available at a low price, like solar, wind, geothermic and combustion of refuse, are actually employed to produce energy and can also be used for desalination. In this work we calculate the process parameters that make minimum the water cost, for a dual purpose plant, where the desalination process occurs with an hybrid MSF-RO process. The energy is supplied to a co-generation plant using pre-treated MSW as fuel. In this way, it's possible to use economical fuel and, simultaneously, to improve the process economics of the conventional MSF process.

The addition of a RO plant, to be operated in parallel with an existing MSF plant, while sharing a common intake facility, is worth of consideration for future expansion in desalted water production[1]. A dual purpose plant, coupling a distillation (MSF, MED, TVC) and a RO plant, offers high flexibility in the cogeneration of desalted water and electricity, because the RO plant can fulfil water demand when the electric energy demand is low.

The impact of rising fuel prices of all energy sources has increased the use of RO technologies since its energy consumption is smaller in comparison to that of all the conventional desalination technologies. This couples with modern membrane technology that permits reduction of pre-treatment costs. The purpose of this work is the modelling of a hybrid desalination plant, which produces 10,000 m^3/d. This plant fulfils the demand of fresh water of a small town sited near the industrial area of Cagliari, where the MSW incinerator is located. A co-generation system is used to feed the hybrid RO/MSF desalination plant.

In fact nowadays, many researchers study co-generation processes since they permit to attain a higher thermodynamic efficiency than the conventional energy production plants. So, co-generation technology offers a larger energetic saving than a traditional energy plant, in agreement with the rising demand of ecology.

2. Plant Description

The plant consists of two desalination sections (multi flash MSF and reverse osmosis RO). A plant with co-production of electric and thermal energy, using a steam turbine, supplies the required energy.

2.1. CO-GENERATION PLANT

This plant includes a steam generator, a steam turbine, an alternator and a condenser.

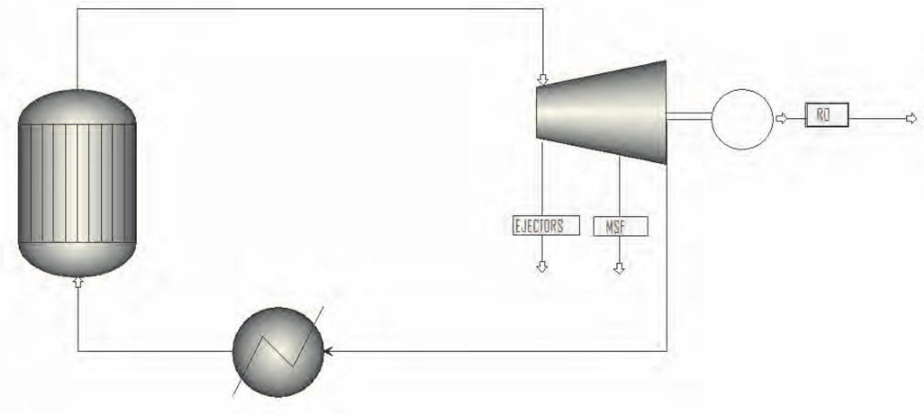

Figure 1. Scheme of the co-generation plant.

The steam generator produces superheated steam, with a pressure of 38 bar and a temperature of 472 °C. The outlet steam flow rate enters the steam turbine, connected with an alternator. Two steam flow rates leave the turbine. The first has a pressure of 6 bar and a temperature of 450 °C and feeds the ejectors in the MSF plant. The second has a pressure of 3 bar and a temperature of 120 °C and feeds the brine heater. The remaining steam expands in the turbine to produce electric energy and ends in the condenser. The electric energy is produced for both the MSF and RO plants.

Some air pollutants are produced during the MSW combustion. The SO_x and HCl removal occurs with a semi-dry process using aqueous lime suspensions. The NO_x is removed by using ammonia. The particulate is removed using a fabric filter.

2.2. MSF PLANT

The MSF process accounts for more than 60% of the global desalination industry and is the major source of fresh water in the Gulf countries. Treatment of the seawater is required in order to prevent foaming and scale formation.

The conventional MSF plant includes three sections: the brine heater, the heat recovery section and the heat rejection section. The last two sections are composed by a number of stages; the heat recovery section consists of more stages than the heat rejection section. The thermal energy surplus of the plant is removed throughout the heat rejection section in such a way that the distillate and the concentrated brine are cooled at the lowest possible temperature. After this section the seawater stream is partly discharged to the sea and partly fed to the heat recovery section together with the recycle brine. The brine enters each recovery stage as a superheated solution, so it is flashed to produce a stream of water vapour. This is condensed passing trough the tube bundle of the heat exchanger and falls on the product tray. Two streams are extracted from the last stage: the distillate and the brine stream that is partly recycled.

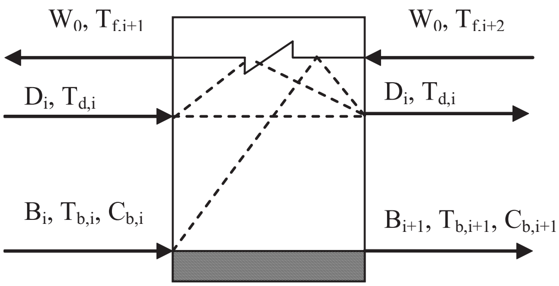

Figure 2. Scheme of the single flash in a MSF plant.

This work refers to a MSF-M (mixing) plant, where the brine circulation stream is made by mixing a part of the blow down brine with the feed stream.

The purpose of the brine recirculation is to decrease the flow rate of the feed seawater.

This simple configuration improves the thermal efficiency of the process, since the recycled stream contains higher energy than the feed seawater.

The main parameter used to estimate the process performance is the ratio between the distillate flow rate and the heating steam flow rate. This parameter is called the PR (performance ratio):

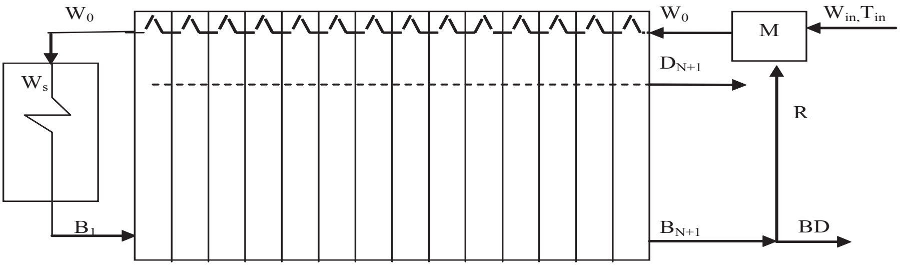

Figure 3. Scheme of a MSF-M plant.

$$PR = \frac{D}{W_S} \tag{1}$$

2.3. RO PLANT

The RO process is the most widespread used among the membrane processes[3-4]. These processes are preferred to all conventional methods in large-scale application due to their low consumption of energy.

The reverse osmosis process uses a semi-permeable membrane that operates under cross-flow conditions. Under pressure, there are two flows: a permeate with reduced ion concentration and a concentrate having a high level of ionic solute.

The RO feed water may contain a high concentration of suspended solids and dissolved matter, which can damage the membrane. So a pre-treatment of the seawater is needed to remove the larger particles. Moreover, the membrane damage can be caused by the system operation at very low pH values, high chlorine concentration or presence of other aggressive chemical compounds that would react and destroy the membrane material.

This kind of plant permits a partial energy recovery by using a hydraulic turbine, where the concentrated solution expands to the atmospheric pressure.

3. Mathematical Model

In this study the model developed by Soliman[5] for steady-state calculations of the MSF process was used. This model is based on the following assumptions.

- The distillate product is assumed to be salt free.
- The temperature profiles of all the streams flowing within the plant are linear.

- Each plant section has a constant value of the heat transfer coefficient, heat transfer area, boiling point rise and specific heat capacity of the brine solution.
- The latent heat of vaporization of water is constant and independent of temperature.
- The specific heat capacity of the brine solutions is a weak function of salt concentration.

Equations

- Overall mass balance on each stage:

$$B_i + D_i = B_{i+1} + D_{i+1} \tag{2}$$

- Salt balance on each stage:

$$B_i C_i = B_{i+1} C_{i+1} \tag{3}$$

- Enthalpy balance on each stage:

$$A_{11} T_{f,i} + A_{12} T_{f,i+1} + A_{13} T_{f,i+2} = B_1 \tag{4}$$

where the coefficients are calculated with the followings equations:

$$A_{11} = \frac{\alpha_1 (D_i + B_i)}{1 - \alpha_1} \qquad A_{12} = -\frac{D_i + B_i}{1 - \alpha_1} - \frac{\alpha_1 (D_{i+1} + B_{i+1})}{1 - \alpha_1} - W_0$$

$$A_{13} = \frac{D_{i+1} + B_{i+1}}{1 - \alpha_1} - W_0 \qquad B_1 = (B_i - B_{i+1}) \Delta T_{in}$$

- Enthalpy balance on first stage:

$$W_0 \hat{C}_p (T_{f,2} - T_{f,3}) = D_1 \hat{C}_p T_{d,i} + B_1 \hat{C}_p T_{b,1} - D_2 \hat{C}_p T_{d,2} - B_2 \hat{C}_p T_{b,2} \tag{5}$$

- Mass balance on the splitter blow down:

$$BD = B_{N+1} - R \tag{6}$$

- Mass balance on the brine heater:

$$B_1 = W_0 \tag{7}$$

- Overall mass balance on the mixer:

$$W_0 = R + W_{in} \tag{8}$$

- Salt balance on the mixer:

$$R \cdot C_{b,N+1} + W_{in} \cdot C_{in} = W_0 \cdot C_R \tag{9}$$

- Enthalpy balance on brine heater:

$$W_0 \cdot \hat{C}_p \cdot \left(T_{b,1} - T_{f,2}\right) = W_S \cdot \lambda_S \tag{10}$$

- Enthalpy balance on the mixer:

$$W_0 \cdot \hat{C}_p \cdot T_{f,N+2} = R \cdot \hat{C}_p \cdot T_{b,N+1} + W_{in} \cdot T_{in} \tag{11}$$

This system may be split into two subsystems. The first one is tridiagonal system solved by using the Thomas method and calculates the brine temperature. The second system calculates the brine and the distillate flow rates, satisfying the material and enthalpy balances on each stage. The whole system is resolved by a trial and error method[1].

In this work the model formulated by Sourirajan cited by Helal[1] was used to describe the RO plant. This is a mechanistic model which assumes a micro-porous structure of the membrane and is based on the "preferential sorption-capillary flow" mechanism. The solvent is forced through the membrane pores by pressure difference. This model is the simplest amongst the mechanistic models, but it doesn't ignore concentration polarization.

In the current work the RO modeling is based on the following assumptions.

- The brine side has a uniform bulk concentration, which is equal to that of the feed. However, salt rejection at the membrane wall will result in a higher, yet uniform concentration.
- The water permeability in the stage is constant and independent of pressure.
- The mass transfer coefficient is constant.

Equations

- Overall mass balance:

$$M_F = M_P + M_B \tag{12}$$

- Overall salt balance:

$$C_F \cdot M_F = C_P \cdot M_P + C_B \cdot M_B \tag{13}$$

- Pure water flux:

$$N_B = 3600 \cdot A_w \cdot \rho \left\{ \Delta P - n \cdot \Theta \cdot R_g \cdot T \cdot 1000 \cdot \rho_B \cdot \left[\frac{(C_W - C_P)}{10^6 \cdot M_S} \right] \right\} \quad (14)$$

- Salt concentration at the membrane wall:

$$C_W = C_P + (C_{ro} - C_P) \, e^{\left(\frac{N_B}{3600 \cdot k \cdot C \cdot M_W} \right)} \quad (15)$$

- Salt flux:

$$N_A = 3600 \cdot K \cdot \rho_B \cdot \frac{(C_W - C_P)}{10^6} \quad (16)$$

- Mass balance on permeate:

$$W_P = A_m \cdot (N_A + N_B) \quad (17)$$

- Salt balance:

$$N_A A_m = \frac{W_P \cdot C_P}{10^6} \quad (18)$$

Our model is used to calculate the variables in each of the three stages, which make up the plant studied. The equations are solved with an iterative method, by supposing the value of the following variables: N_B, C_W e C_P.

4. Cost Calculation

The optimal values of some process parameters were evaluated minimizing an objective function given by the specific cost of the desalted water produced. This cost is calculated as the sum of the fixed and variable costs. The fixed cost is calculated as function of the capital cost. So, the total cost derives from the following parameters: depreciation of the plant, cost of the energy used and costs of manpower, materials and chemicals used in the process. A depreciation of 6 % over 30 years is assumed, so the amortization factor is 0.073.

The objective function is calculated as the sum of the specific cost of the three sections present in the whole plant:

$$C_{CMR} = C_{COG} + C_{MSF} + C_{RO} \quad (19)$$

For the co-generation section, we take into account the investment depreciation and the costs of manpower, chemicals and fuel used during the operation; the equation is the following:

$$C_{COG} = C_{fix,COG} + C_{l,COG} + C_{chem,COG} + C_{comb} \qquad (20)$$

The fixed cost includes all the equipment (steam generator, turbine, condenser and cyclone). The amount of the fuel used depends on its heat value and on the heat exchanged and the efficiency of the generator.

$$m_c = \frac{Q_S}{\eta_{GV} \cdot H_i} \qquad (21)$$

The thermal power exchanged in the generator depends on the enthalpy level of both the steam produced and the inlet water.

$$Q_S = m_v \cdot (h_2 - h_1) \qquad (22)$$

The mass flow rate of the steam is calculated by means of a mass balance, considering that it is used as the heat vector in the MSF, to feed the ejectors in the MSF, as well as to produce the electric energy for the pumps in both the MSF and RO plants.

The costs of the generator and the steam turbine are calculated as function of the electric power, using the following equations:

$$C_{GV} = 10^7 \left(\frac{P'_{el}}{27}\right)^{0,6} \; ; \quad C_{TV} = 4.3^6 \left(\frac{P_{el}}{27}\right)^{0.6} \qquad (23)$$

The cost of the condenser is calculated as function of its exchange surface. This cost also includes the cooling section:

$$C_{cond} = 12.1 \cdot 2.5 \cdot 10^3 \cdot S^{0.59} \qquad (24)$$

The cost of the cyclone depends on the rate and the density of the flue gas.

The cost of the MSF section depends on the costs of manpower and chemicals used as well as the capital cost:

$$C_{MSF} = C_{fix,MSF} + C_{chem,MSF} + C_{l,MSF} \, . \qquad (25)$$

The fixed cost is calculated from the total heat exchange surface and the rate of the desalted water produced[1].

The cost of the RO section is calculated using the same terms considered for the MSF section besides two peculiar contributions. One is the substitution cost of the membranes that can be very considerable. The second is the income due to the electric energy produced by the turbine that is placed after the RO plant.

$$C_{RO} = C_{fix,RO} + C_{sost,RO} + C_{chem,RO} + C_{l,RO} - C_{rec,RO} \qquad (26)$$

The capital cost of the RO plant is calculated from the purchase cost of the membranes. This can be considered equal to 60 % of the total capital cost[6]. The substitution cost is assumed as 10 % of the purchase cost. The recovery income is calculated considering that the energy produced is given by the following equation[7]:

$$E_{rec} = B \cdot P_B \cdot \eta_T \tag{27}$$

A cost of 0.075 €/kWh has been assumed in this calculation for the electric energy.

5. Results and Discussion

The following parameters were chosen to optimise the process: (1) the recycle ratio of the brine, (2) the exchange surface of each flash, (3) the surface of the brine heater, (4) the seawater feed rate and (5) the number of flash stages in the MSF plant. All these parameters are associated to the MSF equipment. No parameter of the RO plant was used for the optimization. It is well known that the cost of the desalinated water produced by a RO plant is strongly affected by the permeate quality. In our calculation this value was set in order to remain under 500 ppm so as to reach the Italian limitations.

The most important parameters of the plant used for our calculations are reported in table 1.

Table 1 – Parameters of the plant

MSF Section		RO Section		Cogeneration	
C_{in} [ppm]	32000	Stage number	3	P_{max} [bar]	38
Stage number	14	Pure water permeability [m/(s·atm)]	$8.33 \cdot 10^{-8}$	Max. temperature [°C]	472
T_{vap} [°C]	120	Solute permeability [m/s]	$3.51 \cdot 10^{-8}$	$\eta_{G.V.}$	0.9
T_{in} [°C]	30	Salt mass transfer coefficient [m/s]	$2.7 \cdot 10^{-5}$	$P_{\text{steam to ejectors}}$ [bar]	6
PR	8	Dissociation factor	0.9	$P_{\text{steam to brine heater}}$ [bar]	3
		R_g [m³·atm/(mol·K)]	$8.21 \cdot 10^{-5}$		
		ΔP [kPa]	7500		
		ΔP_{drop} [kPa]	69		
		T [°C]	25		

The minimum value of the objective function was calculated using a subroutine available in the literature[8]. This subroutine is able to minimize non linear functions with several variables.

For our calculations, we assumed the MSW rate of 250 t/d that is the amount produced daily in the city of Cagliari (Italy). A production of desalted water of 10,000 m^3/d, that is enough for a small town, was estimated from the heat power generated by this MSW rate combustion.

The calculation acts according to the following steps.

From the values assumed for all the parameters, the program calculates the rate of the desalted water produced by the MSF plant. The difference to 10,000 m^3/d is assumed to be the input rate for the RO plant.

The optimal value for the cost of the desalted water is attained for a recycle ratio equal to 1.06, the surface of the heat exchanger in each flash of 586 m^2, the exchange surface of the brine heater of 485 m^2 and a feed flow rate of 100.4 kg/s. The cost of the desalted water calculated at these conditions is equal to 3.39 €/m^3. The salt concentration in the permeate leaving the RO plant is 435 ppm. All the specifications, the parameters and the consumptions when the cost of the desalted water is minimum, are reported in the Table 1.

The specific cost of the desalted water as function of the recycle ratio (R) of the MSF plant, is reported in figure 4. All other parameters are fixed at their optimal value. A minimum value of the specific cost is attained when R varies. In fact, an increase of R involves an increase in distilled water production, but also an increase in energy consumption.

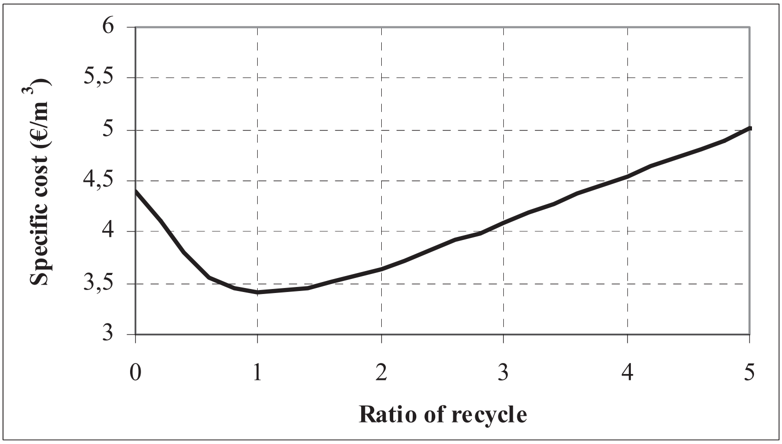

Figure 4. Specific cost of the desalted water as a function of the recycle ratio.

The trend of the specific cost as function of the heat exchange surface of each flash is reported in figure 5 for the values of both fuel cost and the cost of electric energy previously cited. All other parameters are kept at optimal values. The figure emphasizes the minimum value attained by the specific cost. It is important to mention that the specific cost is not very sensitive to this parameter for values higher than the minimum.

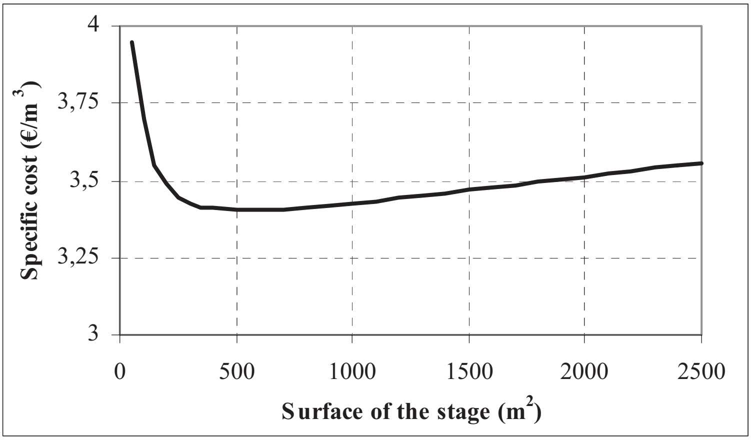

Figure 5. Specific cost as a function of the surface of the stage.

The influence of the heat exchange surface of the brine heater on the specific cost of the desalted water produced is reported in figure 6. All other parameters are the same, previously found as the optimal values. It is apparent that an increase of the surface involves a higher capital cost, but also an increase in the amount of distilled water produced. So, a minimum value of the specific cost is present also in this plot.

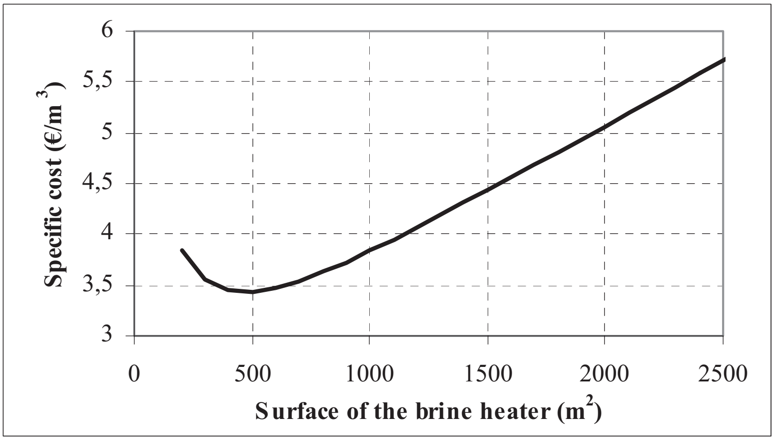

Figure 6. Specific cost as a function of the surface of the brine heater.

Figure 7 shows the trend of the specific cost as function of the feed rate sent to the MSF plant. Also in this case, all other parameters are fixed to the optimal values. The specific cost has a minimum value for a feed rate equal to about 100 kg/s, but is very sensitive to any variation of this parameter.

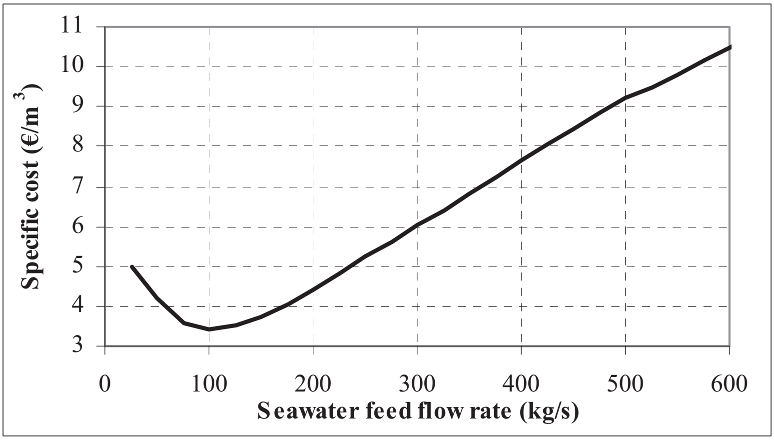

Figure 7. Cost as a function of the seawater flow rate sent to the MSF-M section.

A change in the specific cost for different values of the flash stage number, is reported in figure 8. We want to point out that the optimisation subroutine here used is able to calculate the optimal value only for real variables. So, each value of the plot was obtained as the cost calculated with that number of stages, keeping all other parameters to the optimal value previously calculated for the number of stages fixed (14). In any case, the optimal value of the stage number (18) is not far from that used in previous calculations.

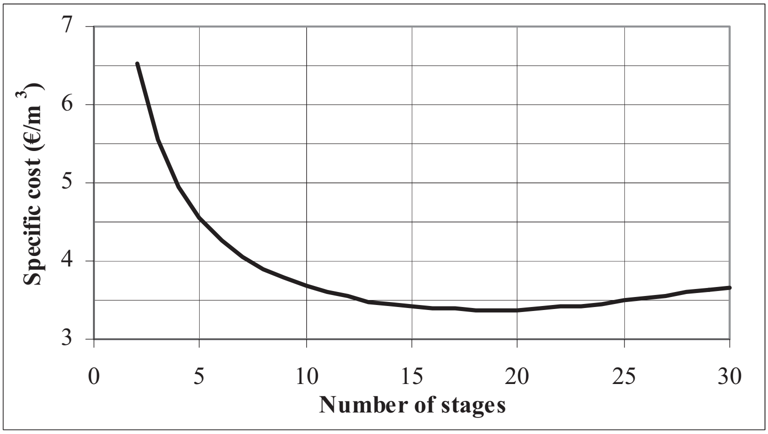

Figure 8. Cost of the desalted water as a function of the number of stages in MSF-M section.

6. Conclusions

The economic evaluation of a hybrid desalination process MSF – RO was carried out in this paper. All the thermal and electric energy required by this kind of process is produced by a co-generation plant. The value of several design parameters was calculated so as to minimize the cost of the desalted water produced. The rate of desalted water produced by the MSF plant at these optimal conditions is equal to 1,785 m^3/d, while the RO plant produces 8,215 m^3/d. These different rates are justified by the high cost of the MSF plant.

The results put in evidence the very high cost of desalted water produced. This value is essentially due to the high capital costs required, but the cost of the flue gas treatment has also a great influence. Moreover, it must be considered that the plant here studied uses the energy generated by the combustion of the MSW produced in the area of the city of Cagliari. So, the maximum amount that can be produced by the desalination plant cannot be higher than about 10,000 m^3/d of distilled water. A better result as to the specific cost of the desalted water, could be obtained with a higher production of desalted water. This can only be obtained if a larger amount of MSW is available.

Notation

A_m	membrane's surface in a single stage of the RO plant, m^2
A_W	permeability of the desalted water, m/(atm·s)
B	flow rate of the brine coming from the last stage of RO plant, m^3/s
B_D	flow rate of the brine coming from the MSF plant, kg/s
B_i	flow rate of the brine entering the i^{th} stage, kg/s
C	molar density of water, $kmole/m^3$
C_B	salt concentration in the brine stream coming from the RO plant, ppm
$C_{b,i}$	salt concentration in the brine stream coming from the i^{th} stage of the MSF plant, mass fraction
C_{cond}	cost of the condenser, €
C_F	salt concentration in the feed to RO plant, ppm
C_{GV}	cost of the steam generator, €
C_i	salt concentration in the feed to the i^{th} stage, mass fraction
C_{in}	salt concentration of the seawater entering the MSF plant, mass fraction
C_P	salt concentration in the permeate flow coming from the RO stage, ppm

$\hat{C}_p$	specific heat, kcal/kg/°C
C_{perm}	salt concentration in the permeate flow coming from the RO plant, ppm
C_R	salt concentration in the brine recycled to the MSF plant, kg/s
C_{ro}	salt concentration in the flow entering the RO plant, ppm
C_W	salt concentration at the membrane surface, ppm
D	total flow rate of the distilled water, kg/s
D_i	flow rate of the distilled water entering the i^{th} stage, kg/s
E_{recRO}	power recuperated with the turbine in the RO plant RO, W
h_1	enthalpy of the water fed to the boiler in the co-generation plant, J/kg
h_2	enthalpy of the steam produced in the co-generation plant, J/kg
H_i	low heat value of the fuel, J/kg
k	mass transfer coefficient of the salt, m/s
K	solute permeability, m/s
M_B	flow rate of the brine leaving the RO stage, kg/s
m_c	fuel consumption, kg/s
M_F	water fed to the RO plant, kg/s
M_P	permeate leaving the RO stage, kg/s
M_S	salt molecular weight, kg/kmole
m_v	steam produced, kg/s
M_W	water molecular weight, kg/kmole
n	number of ions resulting from dissociation
N_A	salt flux, $kg/(m^2 \cdot h)$
N_B	pure water flux, $kg/(m^2 \cdot h)$
P_B	pressure of the brine leaving the RO plant, Pa
Q_s	thermal power transferred to the steam, W
R	brine recirculation, kg/s
R_g	general gas constant, $m^3 \cdot atm/(mol \cdot K)$
S	exchange surface of the condenser, m^2
T	temperature of water in the RO process, °C
$T_{b,i}$	temperature of the brine entering the it^h stage, °C
$T_{d,i}$	temperature of the distilled water entering the it^h stage, °C
$T_{f,i}$	temperature of the seawater leaving the i^{th} stage, °C
W_0	seawater flow rate in the heat exchanger of the MSF plant, kg/s
W_{in}	seawater flow rate entering the MSF plant, kg/s
W_P	permeate flow rate from the RO stage, kg/h
W_s	heating steam flow rate, kg/s
ΔP	pressure loss across the membrane, Pa
η_{GV}	steam generator efficiency
η_T	turbine efficiency

λ_s latent heat of water, kcal/kg
ρ pure water density, (kg/m^3)
ρ_B density of saline water, kg/m^3
Θ dissociation factor

Abbreviations

MED Multiple Effect Desalination
MSF Multi Stage Flash
MSF-M Multi Stage Flash Mixing, with a partial brine recycle
MSW Municipal Solid Waste
PR Performance Ratio (see eq. 1)
RDF Refuse Derived Fuel, a fuel obtained from the treatment of a municipal or an industrial refuse
RO Reverse Osmosis process.
TVC Thermal Vapor Compression

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AUTONOMOUS DESALINATION UNITS BASED ON RENEWABLE ENERGY SYSTEMS - A REVIEW OF REPRESENTATIVE INSTALLATIONS WORLDWIDE

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Abstract. The ADU-RES co-ordination action is an EC funded project that aims to bridge the gap between successful R&D work and commercial applications of small desalination systems powered by renewable energy. This paper reviews installed units in order to define the state of the technology. Ninety-one plants were identified and sixteen of them were reviewed for their technical and economical performance. The examined units desalinate brackish or sea water and employ different technologies including: solar thermal distillation, wind energy or photovoltaic panels (PV) combined with revere osmosis (RO) as well as mechanical vapour compression driven by wind turbines. It was found that the technology has made significant progress over the past years. Still, cost-effective solutions have to be developed especially for the scaling of the membranes caused by the intermittent operation or the corrosion because of the high-temperatures. Also the energy efficiency and the controlling of the systems have to be further developed. The first products are in the market and will improve through competition and experiences resulting from implementation in real conditions for long periods.

Keywords: Desalination, Renewable Energy, Autonomous Operation, ADU-RES, Mediterranean

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1. Introduction

Many arid regions in Mediterranean countries have a great potential to cover part of their pressing water needs by renewable energy based desalination. However, the wide-scale implementation of this technology faces numerous technological, economic and policy barriers.

1.1. THE ADU-RES PROJECT

These barriers are studied and analysed by the ADU-RES (Autonomous Desalination Units powered by Renewable Energy Systems) co-ordination action. The consortium involves partners from 7 Mediterranean Partner Countries (MPC) as well as institutes and SMEs from 5 EU countries specialised in desalination and renewable energy systems.

In recent years, the research community has worked intensively on coupling desalination systems with renewable energy technologies in robust and cost effective desalination units. While both components of these set-ups are mature technologies in themselves, few commercial products in combination of those are available. ADU-RES strives to develop further integrated plant designs for mature and cost efficient renewable energy based desalination. The action brings together existing R&D work and the results of own technical, economic and policy research to design and present specific guidelines for ADU-RES plant construction.

The high capital costs involved make investors and decision makers reluctant to accept renewable energy powered desalination. However, comparison to alternative solutions shows that in many cases autonomous units powered by renewable energy are the most cost-effective option. ADU-RES analyses the schemes that can be used to finance such projects and suggests ways for lowering the capital cost of renewable energy based desalination.

The implementation of renewable energy based desalination is partly hindered by unfavourable socio-economic framework conditions. For example, in many regions conventional and environmentally harmful water supply is heavily subsidised while no public support can be found for desalination units. As a first step, the socio-economic and political framework conditions in Jordan, Algeria, Tunisia, Greece and Spain are analysed. Based on this analysis, a political strategy to boost decentralised renewable energy based desalination units will be developed. At the same time, the relevant EU legislation is being scrutinised, resulting in clear recommendations for improving the framework conditions in favour of enhanced implementation of desalination units.

1.2. REVIEW OF INSTALLED UNITS AND RESEARCH PROJECTS

The first action within ADU-RES was to define the state of the technology of autonomous desalination systems powered by renewable energy. The work involved analysis of installed pilot units and literature review of relevant research projects. This paper presents the results of the installations review.

Ninety-one desalination RES plants installed all over the world were identified and sixteen of them were reviewed for their technical and economic performance. The methodology and results are given in part 2 of this paper. The analysis of the reviewed plants and projects worldwide allowed a clear view on the status and the prospects of the technology. The discussion and the general conclusions of this work are presented in part 3.

2. Review of Installed Plants Worldwide

2.1. METHODOLOGY

A long list with abstract information on installations worldwide has been collated. Plants complying with the following characteristics have been included in the list:

- capacity of 50 m^3/day or less
- autonomous plants – not connected to the central electricity grid
- powered by renewable energy sources

The list includes 31 RES distillation plants, 56 RES membrane plants and 4 hybrid ones. In total there are 91 plants, some of which were installed for research purposes and are currently out of use. This list is a very useful tool in itself, as it offers a unique collection of the autonomous desalination installations.

Detailed questionnaires were prepared for collecting information from representative plants of the list. Several methods were used, including: literature review, internet research and personal communication either with the manufacturers or with the owners and operators of the various installations. In this paper sixteen of these plants are presented.

2.2. RESULTS

Figure 1 shows the technology combinations used in the installations identified within the ADU-RES research[1]. As is obvious from the figure, the most popular combination is PV – RO followed by wind – RO and solar distillation technologies like solar multi effect distillation (MED).

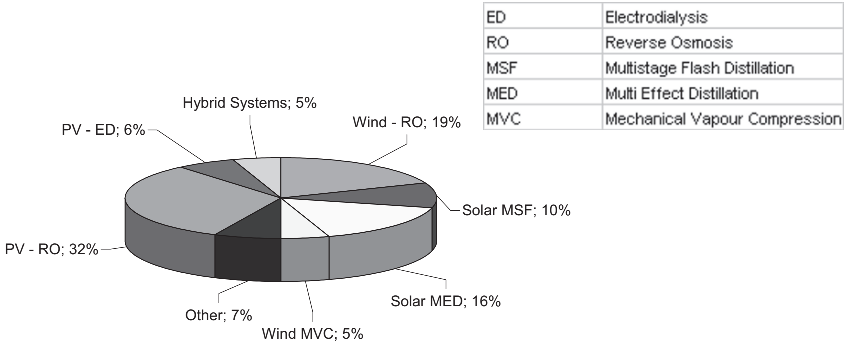

Figure 1. Technology combinations used in the installations identified.

From the identified plants, sixteen were reviewed in detail, employing the following technology combinations: distillation processes powered by solar collectors; Reverse Osmosis powered by Photovoltaic panels or by wind turbines (PV – RO or wind – RO) as well as Mechanical Vapour Compression powered by wind turbines (wind – MVC).

2.2.1. *Solar Thermal Systems*

Concerning solar applications, 6 distillation plants, listed in table 1, were examined in detail within the ADU-RES project.

TABLE 1. Solar distillation plants examined within the ADU-RES project

Plant Location	*Year of Commiss-ion*	*Water Type*	*Capacity* m^3/h	*Solar collector area* (m^2)
Hazeg, Sfax, Tunisia	1988	BW	0.04-0.05	80
Sfax, Tunisia	1989	BW	0.012-0.03	51
Almeria, Spain[2]	1993	SW	3	2,672
Pozo Izquierdo, Gran Canaria	2000	SW	0.025-0.029	50
Sultanate of Oman,[3]	2002	SW	0.042	5.34
Beni Khiar, Tunisia	2003	SW	0.007	108

SW: seawater, BW: brackish water

The water produced from the two units installed in Tunisia in 1988 and 1989 was used for greenhouse irrigation. Therefore, no post treatment process was required. The unit in Hazeg employed a single effect solar distillation process. The low efficiency resulted in very high costs and required huge areas of solar collectors for producing low quantities of water. However, the unit in Sfax with a multiple condensation evaporation cycle was more efficient, with simple operation and low cost materials. Still, the cost of the solar collectors is high, resulting in quite high cost for the product water.

The MED unit in Almeria, installed in 1993, is a larger installation than all the others examined here, still much smaller than conventional MEDs powered by oil. This experience showed the corrosion problem that distillation units have because of the high temperatures. It also clearly demonstrated that the distillation technology is subject to economies of scale and becomes more economical as the nominal output increases.

More recently, in Gran Canaria they tried to deal with the corrosion problem while increasing the efficiency. Corrosion free collectors were used and the feed-water flowed directly through them, so no heat exchanges were necessary. The results were positive; however the material used increases the overall cost.

The installation of a small-scale multi-effect submerged boiling distillation plant in the Sultanate of Oman was very interesting development. The main innovations consist in the water softener that was produced and the coating of the exchange surfaced made by plasma deposition technology. Thus, operations at temperatures as high as 100°C were achieved, allowing high-efficiency without corrosion problems. It was found that there was insufficient insulation in the piping. Better insulation will increase the efficiency in future applications. Finally, the plant operated under real conditions for over a month in the automatic control regime, including high-tech instruments like a solar tracking system.

2.2.2. *PV-RO systems*

As we have seen, the PV-RO combination is the most popular in demonstration plants. The gradual shift from distillation to RO follows the general trend of the desalination industry in the last decade. Moreover, the modularity of RO makes this technology suitable for small-scale applications. Here, the five plants presented in table 2 have been examined.

In Saudi Arabia, in 1994 an important pilot unit was built operating in real conditions, with energy autonomy and a fully automated control system. There are two independent PV systems; the one used for water pumping has no battery, only tanks to store the water, while the other used for the high pressure pump is connected to a battery bank. The RO unit operates intermittently to match demand and goes typically through six start-up shut-down cycles every day.

In general the unit was quite successful. The energy and control systems operated well and the system tolerated the intermittent operation. Actually when it operated for long periods in hot weather it resulted in overheating of the motors. The main problem was the fouling of the membranes caused by the intermittent operation, which resulted in cleaning or replacing requirements every six months. The repetitive starting also caused some other problems, like overload of the inverter and the need to flush the membranes after each stop of the RO.

TABLE 2. PV-RO plants examined within the ADU-RES project

Plant Location	*Year of Commission*	*Water Type*	*Capacity m^3/h*	*RES installed power(kWp)*	*Batteries (Ah)*
Riyadh, Saudi Arabia[4]	1994	BW	0.6	11.87	1100
Pozo Izquierdo, Gran Canaria	1998	SW	0.4	4.8	395
Coité-Pedreiras Ceará, Brazil[5]	2000	BW	0.25	1.1	100
Lisbon, Portugal[6]	2000	BW	0.0041-0.02	0,05-0,15	No
Loughborough, UK[7, 8]	2003	SW	0.5	1.54	No

In Brazil, a unit was installed in real conditions and ran for some months. Two different configurations were tested, one with a direct current (DC) motor and one with a three-phase induction motor. It turned out that the DC motor is not suitable for the hard operating conditions of a stand-alone plant while the three-phase motor is more capable of operating with less maintenance and reduces the specific energy consumption. Finally, in this project the importance of the community participation in all the stages of the unit installation and operation was demonstrated.

Another PV-RO unit reviewed is the one in the UK. This unit was installed in the premises of a research institute (CREST) in Loughborough. It ran for a long time with very interesting results regarding operation without the use of a battery where the flow and pressure of the system varies in direct response to the radiation. Batteryless operation was demonstrated as technically feasible. A separate speed control of the motors allowed for control of the energy drawn from the PVs for maximum power point tracking and control of the recovery ratio for maximum product flow. This way and with the use of an energy recovery system the unit used the energy very efficiently making up for the absence of batteries. The intermittent operation accelerated bio-fouling and this was dealt with by the annual replacement of the membranes.

2.2.3. *Wind Energy RO Systems*

As regards the coupling of wind turbines with RO, a number of units have been designed and tested. As early as 1982, a small system was set in

France (in Ile du Planier), with a 4 kW turbine coupled to a 0.5 m^3/h RO desalination unit. The system was designed to operate via either a direct coupling or batteries. Another case is that of Island of Drenec in France, in 1990 where a 10 kW wind turbine was used to drive a seawater RO unit.

The four plants selected for detailed examination, presented in Table 3, were all installed within the last decade.

TABLE 3. Wind-RO plants examined within the ADU RES project

Plant Location	*Year of Commission*	*Water Type*	*Capacity m^3/h*	*RES installed power*
Fuerteventura island, Spain	1995	SW	2.3	225 kW W/G, 160 KVA diesel, flywheel
Therasia island, Greece	1997	SW	0.2	15 kW W/G, 440 Ah batteries
Loughborough, UK[9]	2003	SW	0.5	2.5 kW W/G, no batteries
Pozo Izquierdo, Gran Canaria, Spain	2004	SW	0.8	15 kW W/G, 190 Ah batteries

The project on Fuerteventura Island has many interesting aspects. It is an autonomous system for energy and water provision. Initially there were some problems as the water demand was lower than expected resulting in an oversized RO unit. But since the design was corrected the system is operating well and has improved substantially the quality of life of the local people. This unit has demonstrated very well that if the local community, local authorities and research institutes cooperate in a well defined scheme such an installation can operate successfully in the long-term, in spite of any technical problems that may arise.

In Therasia, an autonomous unit was installed for providing water to the local community. There is a set of batteries only as a smoothing component – the RO unit operates only when enough wind is available. It was proven that the system had no major technical problems and that the presence of batteries was necessary to ensure that the start-up and shut down procedures of the RO unit were performed appropriately. The high pressure pump was driven by a DC unit. The system is characterised by high maintenance cost mainly because of the need for frequent replacement of the brushes of the DC motor.

An improved version of this system is now under operation in Pozo Izquierdo, Gran Canaria. With the same wind turbine, a higher energy efficiency and water production are achieved while the necessary battery storage has been reduced. The DC motor has been replaced by a three-phase one and an automatic control system has been incorporated. The system operates well with the exception of the membranes scaling because of the operation intermittency. The main focus is on further developing the control and operation system.

Finally, the plant in Loughborough University presented above as a PV-RO installation was also connected directly to a wind turbine. The interesting aspect here is that no battery at all was included in the system. It was demonstrated that this is technically possible and high energy efficiency can be achieved. However, the testing was too brief to be able to get a deeper understanding of the membrane behaviour under such conditions.

2.2.4. *Wind Energy MVC Systems*

Only a few applications of wind energy driving MVC desalination are known. A pilot plant was installed on the German island of Borkum in 1991 where a wind turbine with a nominal power of 45 kW was coupled to a 48 m^3/day Mechanical Vapour Compression (MVC) evaporator. The system was controlled by varying the compressor speed, and assisted by a resistance heating when the compressor ran at its speed limit. The experience was followed by another larger plant on the island of Rügen in 1995. The main disadvantage of these systems is the high-energy consumption of the MVC unit, which usually is in the order of 15 kWh/m^3.

The MVC plant examined within ADU-RES produced about 2 m^3/hour. The Wind MVC plant was installed in Gran Canaria in 1999 [10, 11]. The energy system consists of two 230 kW wind turbines and a 1,500 rpm flywheel coupled to a 100 kVA synchronous machine. This is connected to a Mechanical Vapour Compression (MVC) system. The main conclusion from this installation was that the start-up process is too long. Additionally, it was found that conventional MVC is not compatible with intermittent operation as a hard layer of scale develops within a few weeks time. Further development is required for successfully coupling it with wind turbines.

3. Discussion and Conclusions

The parallel analysis of the various units employing different technology combinations has given many interesting results and allows drawing some general conclusions. All combinations examined have proven that they are capable of producing autonomously safe drinking water without major technical problems. Only the wind-MVC combination still requires basic research work in order to become more energy efficient and overcome the scaling problems.

Still, RO and distillation units powered by renewable energy have some typical problems that installers have to keep in mind. Reverse Osmosis has to deal with the sensitivity of the membranes regarding fouling and scaling because of the start-stop cycles and partial load operation during periods of oscillating power supply[12], typical in wind turbines or PVs. Thus, the installer has to choose between an energy storage system and the frequent replacement of the membranes. The former increases the capital cost and the maintenance requirements while the latter increases the maintenance cost. Solar-MED plants suffer from corrosion due to the high temperature of operation. Also, they are characterised by high requirements of thermal energy and therefore become more cost-effective as the size increases. Solutions to the corrosion problem have been demonstrated, either by using corrosion-free materials or by processing the feed water and the exchange surfaces.

Careful design of the units based on the conditions of the specific sites guarantees the operation without major problems. The know-how for successful applications exists. However, in most of the cases at the end of research projects the units are abandoned and not used for supplying drinking water to the local populations. Consortia including companies that have the know-how, local stakeholders and financial institutions are needed for installing units that will provide the water to the communities, demonstrating further the applicability of the technology and boosting wide-scale implementation.

The cost of the product water in the examined units is in the range of 3 – 20€ per m^3, quite high compared to desalination units with similar sizes directly connected to the electricity grid. The latest energy efficient units can produce water with cost on the lower side of the range. Additionally, wide-scale implementation would push the costs further down. There are many niche markets where the water is being transported at much higher costs and the installation of autonomous desalination units would make commercial sense. There are also many communities without access to electricity or water that are very poor and could never face the costs for financing such units. It is the role of development agencies to support them. The research community has demonstrated that autonomous desalination powered by renewable energy is technically possible. The remaining problems can only be overcome with the impetus and resources that market applications will bring.

AUA, Agricultural University of Athens, Greece	**FM21**, Fondation Marrakech 21, Morocco
CDER, Centre de Développement des Energies Renouvelables, Algeria	**IAV**, Institut Agronomique et Vétérinaire Hassan II, Morocco
CRES, Centre for Renewable Energy Sources, Greece	**INRGREF**, Institut National de Recherche en Génie Rural, Eaux et Forets, Tunisia
CREST, Centre for Renewable Energy Systems Technology, Loughborough University, UK	**ISE**, Fraunhofer Institute for Solar Energy Systems, Germany
E.C. DG-JRC, Institute for Environment and Sustainability, Renewable Energies Unit, EU	**ITC**, Instituto Tecnológico de Canarias, Spain
ELARD, Earth Link and Advanced Resources Development, Lebanon	**PHG**, Palestinian Hydrology Group, Palestinian Authority
ETA–Renewable Energies, Italy	**RSS**, Royal Scientific Society, Environment Monitoring & Research Central Unit (EMARCU), Jordan
EWE, Egyptian Association for Water and Energy, Egypt	**WIP**–Renewable Energies, Germany

Figure 2. The ADU-RES consortium.

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ASSESSMENT OF MOST PROMISING DEVELOPMENTS IN SOLAR DESALINATION

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Abstract. Indirect solar desalination systems consist of a conventional desalination unit coupled to a solar conversion system, unlike systems as solar stills that integrates in the same device the desalination and the energy conversion processes. They are among the most developed systems of renewable energy-powered desalination. Their most significant possibilities of development in the near future are assessed in this paper. Particular emphasis is given to the efficiency of such systems since their cost mainly depends on the maturity of the technology and the production scale, factors which may change in the future in favour of more efficient systems. Considerable research has to be conducted on the technologies that have never been coupled before as they could be reliable and cost-effective options.

Keywords: Solar desalination; reverse osmosis; multi-effect distillation; multistage flash distillation; membrane distillation

1. Introduction

The status of renewable energy desalination was reviewed in detail by the author [García-Rodríguez 2002; 2003; 2004]. The most mature technologies are solar distillation and reverse osmosis (RO) driven by wind

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power or solar photovoltaic systems. There are also systems with interesting potentials but scarce operational experience and there are even significant improvements which have never been implemented as section 3 points out. Particular emphasis is given to the efficiency of such systems since their cost mainly depends on the maturity of the technology and the production scale, factors which may change in the future in favour of more efficient systems. Within the above framework, this paper proposes the most promising developments of solar desalination, from the author's point of view, depending on the particular features of the plant location and fresh water demand.

2. The Present Status of Indirect Solar Desalination

Indirect solar desalination systems consist of a conventional desalination unit coupled to a solar conversion system, unlike systems as solar stills that integrates in the same device the desalination and the energy conversion processes. A brief summary of the present status of indirect solar desalination is presented in this section. Tables 1 and 2 show solar distillation plants, whereas tables 3 and 4 present desalination plants driven by solar heated thermodynamic power cycles: Table 3 reports desalination systems connected to conventional solar electricity generation plants – dual purpose solar plants- and table 4 shows other solar desalination plants based on Rankine or Stirling cycles. Finally, table 5 reports the pilot experiences on PV driven ED plants, and table 6 presents some of the PV-driven RO plants, the most frequently implemented technology.

TABLE 1. Solar distillation plants driven by salinity gradient solar ponds

Plant location	**Desalination process**	**m^3/d**	**Solar collector**
Margarita de Savoya,Italia[1]	MSF	50-60	Solar pond
El Paso, Texas[2]	MSF	19	Solar pond
Islands of Cape Verde[3]	Atlantis "Autoflash"	300	Solar pond
University of Ancona, Italy[4]	ME-TC	30	Solar pond
Near Dead Sea[5]	MED	3000	Solar pond
Tunez, laboratorie of thermie Industrielle [6]	MSF	$8.6\cdot10^{-3}$ m^3/h	Solar pond
[1]: Delyannis, 1987; [2]: Lu and Swift, 1998; [3]: Szacsvay *et al.* 1998; [4]: Caruso and Naviglio, 1999; [5]: European Commision, 1998; [6]: Safi, 1998.			

TABLE 2. Solar distillation plants

Plant location	**Desalination process**	**m^3/d**	**Solar collectors**
La Desired Island, French Caribean [1]	ME- 14 effects	40	Evacuated tube
Abu Dhabi, U.A.E. [2]	ME- 18 effects	120	Evacuated tube
Kuwait[3]	MSF autoregulated	100	Parabolic trough
La Paz, Méjico[3]	MSF-10 stages	10	Flat plate + Parabolic trough
Arabian Gulf[3]	ME	6000	Parabolic trough
Al-Ain, U.A.E. [4]	ME- 55 stages MSF- 75 stages	500	Parabolic trough
Takami Island, Japan[3]	ME- 16 effects	16	Flat plate
Berken, Alemania[5]	MSF	20	-
Lampedusa Island, Italy[6]	MSF	0.3	Low concentration
PSA, Almería, Spain[7]	ME- Heat pump	72	Parabolic trough
Gran Canaria, Spain[8]	MSF	10	Low concentration
Area of Hzag, Tunisia[9]	Distillation	0.1-0.35	Solar collector
Al Azhar University, Gaza[10]	MSF	0.2	Solar collector+ PV (auxiliary energy)
Safat, Kuwait[9]	MSF	10	Solar collector
[1]: Madani, 1990; [2]: El Nashar, 1985; [3]: Delyannis, 1987; [4]: Hanafi, 1991; [5]: Papadakis, 1996; [6]: Palma, 1991; [7]: Zarza Moya, 1991; [8]: Valverde Muela, 1982; [9]: European Comisión, 1998; [10]: Abu-Jabal et al., 2001			

TABLE 3. Dual purpose solar plants

Plant location	**Desalination Process**	**Solar Collector**
Kuwait[1]	MSF (25 m^3/d)- OI (20 m^3/d)	Conventional solar power plant
PSA, Almería, Spain[2]	(72 m^3/d)	Conventional solar power plant
[1]: Delyannis, 1987; [2]: Zarza Moya, 1995		

TABLE 4. Desalination plants driven by solar-heated thermodynamic cycles

Plant location	**Desalination process**	**m^3/d**	**Solar collector**
Yanbu, (Saudi Arabia)[1]	Freezing	-	point-focusing collectors
Los Baños, California, USA[2]	OI	-	Solar pond
El Paso, Texas, USA[3]	OI	-	Solar pond
Cadarache, France[4]	OI (brackish water)	15	Flat plate collector (3 kW)
El Hamrawin, Egypt[4]	OI (brackish water)	54	Flat plate collector (10 kW)
[1]: Luft, 1982; [2]: Engdal, 1987; [3]: Lu et al., 2000; [4]: Libert and Laurel, 1981;			

TABLE 5. PV-driven ED systems

Plant location	**Desalination process**	**Plant capacity**
Thar desert, India[1]	ED- brackish water	0.120 m^3/h
Ohsima island, Nagasaki[2]	ED- sea water	10 m^3/d
Fukue city, Nagasaki, Japan[3]	ED- brackish water	8.33 m^3/h
Spencer Valley, New Mexico[4]	ED- brackish water	2.8 m^3/d
[1]: Adiga *et al.*, 1987; [2] : Kuroda et al., 1987; [3]: Ishimaru, 1994; [4]: Maurel, 1991.		

3. Most Significant Possible Developments

Section 2 pointed out the different status of maturity of the indirect solar desalination systems implemented. Some of them only require minor improvements on control systems in order to fit the solar energy resource or more extensive operational experience. Nevertheless, some other interesting technologies have been scarcely implemented.

Towards the maximum exploitation of natural resources, the most significant development should offer considerable decrease in specific solar energy consumption or high increase in desalination process recovery. Both of them result in much lower specific solar energy consumption and therefore, much lower specific investment cost of the solar system. Nevertheless the complexity of the system should be taken into account, unless it was designed for a developed area or for medium to high capacity range. For instance, in principle hybrid processes are not suitable for small capacity systems or remote locations since they may increase the complexity of the maintenance and the scale economy may be not favourable.

TABLE 6. Some reverse osmosis plants driven by photovoltaic cells, adapted from García-Rodríguez (2003)

Plant location	**Salt concentration**	**Plant capacity**	**PV system**
Cituis West, Jawa, Indonesia[1]	BW	1.5 m^3/h	25 kWp
Concepción del Oro, Mexico[2]	BW	1.5 m^3/d	2.5 kW peak
Doha, Qatar [1]	SW	5.7 m^3/d	11.2 kWp
Eritrea[3]	-	3 m^3/d	2.4 kWp
Florida St. Lucie Inlet State Park, USA[1]	SW	2x0.3 m^3/d	2.7 kWp + diesel generator
Hassi-Khebi, Argelie [1,4]	BW (3.2 g/l)	0.95 m^3/h	2.59 kWp
Heelat ar Rakah camp of Ministry of Water Resources, Oman[5]	BW	5 m^3/d (5 h/d operation)	3250 kWp
INETI, Lisboa, Portugal[6]	BW (about 5000 ppm.)	0.1-0.5 m^3/día	-
Jedd ah, Saudi Arabia [1,2]	42800 ppm.	3.2 m^3/d	8 kW peak
Lampedusa island, Italy[1]	SW	3+2 m^3/h	100 kWp
Lipari island, Italy[1]	SW	2 m^3/h	63 kWp
North of Jawa, Indonesia[2]	BW	12 m^3/d	25.5 kW peak
North west of Sicily, Italy[1]	SW	-	9.8 kWp + 30 kW diesel generator
Perth, Australia[1]	BW	0.5-0.1 m^3/h	1.2 kWp
Pozo Izquierdo- ITC, Gran Canaria, Spain[8]	SW	3 m^3/d	4.8 kWp
Red Sea, Egypt [1,7]	BW (4.4 g/l)	50 m^3/d	19.84 kW peak (pump) 0.64 kW peak (control)
Thar desert, India [1]	BW	1 m^3/d	0.45 kWp
University of Almería, Almería, Spain[1,9]	BW	2.5 m^3/h	23.5 kWp
Vancouver, Canada[1]	SW	0.5-1 m^3/d	4.8 kWp
Wanoo Roadhouse, Australia[1]	BW	-	6 kWp

BW, Brackish water; SW, Sea water.
[1]: European Commision (1998); [2]: Delyannis (1987); [3]: Thomson and Infield (2003); [4]: Kehal (1991); [5]: Al Suleimani and Nair (2000); [6]: Joyce et al. (2001); [7]: Maurel (1991); [8]: Herold and Neskakis (2001); [9]: Andújar Peral et al. (1991)

To gain maximum availability of desalination equipment on stand alone system, the annual mean of hours in operation has to be maximized by proper selection of the solar system and by optimizing the balance of solar system area and operation temperature, and energy storage and desalination plant capacities. If conventional energy backup is available, the solar fraction should be increased to achieve the minimum product cost of solar-driven operational mode.

The following subsections focus on different desalination technologies and point out the most significant improvements that every technology offers.

3.1. REVERSE OSMOSIS DESALINATION

Renewable energy-driven reverse osmosis (RO) normally consists of solar photovoltaic (PV) fields or wind turbines coupled to the RO plant which consumes the produced electricity. Solar RO desalination consists of either, solar photovoltaic fields or solar thermal-driven power cycles as section 2 reported – tables 3-4 -. The energy storage in such systems, if any, normally consists in batteries, although the use of batteries has several disadvantages: maintenance, limited lifetime and toxic wastes. If the RO system is designed for matching the available energy - batteries are not required -, the control of the process has to be carefully designed and tested. There are two possibilities:

- the design arrangement of the system consists of a set of desalination units in parallel working at nominal conditions which can be connected or disconnected.
- the desalination unit is able to match the energy input by suitable changes of working conditions. Simulations of such systems have to take into account that equipment does not operate in nominal conditions, in order to avoid estimations over actual experimental results. Fluctuations in operational conditions may result in damage to the equipment, experimental research on the influence on membrane behaviour of fluctuations in operational parameters is being carried out – pressure, volume, pH, conductivity, concentration of salts, temperature and recovery – [Gomez Gotor et al, 2003][de la Nuez Pestana et al., 2004]-.

On the other hand, energy recovery systems do not usually exist in RO plants powered by renewable energy which results in lower efficiency than that of conventional energy plants. Thomson et al (2002) described an energy recovery device, the Clark pump, specially designed for renewable energy applications to RO desalination, reporting a main energy consumption of 3.5 kWh/m^3.

The most suitable systems for driving solar stand-alone RO plants are salinity gradient solar ponds, dish/Stirling and photovoltaic systems. PV and dish/Stirling systems have the advantage of modularity whereas cost of solar ponds increases considerably in small capacity range. Trieb et al, (1997) presented a case study for solar electricity production comparison and reported specific investment cost of a 5 MW solar pond around one fourth of that of photovoltaic systems, while the cost of dish/Stirling systems are 20% lower. The resulting electricity cost reported for solar ponds are about one ninth of that of photovoltaic systems. Besides that, both, dish/Stirling and photovoltaic technologies permit less than a half of annual full load operational hours than solar ponds permit. On the other hand, some disadvantages of dish-Stirling systems and solar ponds should be taken into account such as their requirements of fresh water or the difficult stabilization of the salt gradient within the solar pond in windy areas.

With regard to efficiency, the thermal performance of commercial photovoltaic systems is around 10% on stand alone system. Nevertheless, solar dish/Stirling systems achieve more than 20% of thermal performance with the same features of modularity and distributed systems than PV ones. Solar electricity generation with paraboloidal dishes has lower costs than photovoltaic systems [Mills, 2004]. The experience on RO systems able to match the variability of the solar resources without batteries above mentioned is applicable to dish-Stirling collectors. In spite of the perspectives of dish-Stirling/RO technology it has not been implemented yet.

Other technologies for solar desalination are the distributed systems based on solar organic Rankine cycles driven by parabolic trough collectors. Such a technology, with evaporation temperature about 250-300ºC, is able to achieve thermal performances around 16% or more, even with heat rejection at temperature high enough to provide additional uses [Delgado Torres, 2004] – Toluene: 16%, boiling temperature, 300ºC; maximum temperature, 400ºC, condensation temperature, 113ºC, turbine efficiency, 75%.

Low temperature organic Rankine cycles have been mainly developed for geothermal energy systems. The thermal performance of electricity production with static solar collectors is of the same order as solar photovoltaic systems and the temperature of the heat rejection is not high enough to be valuable. High and medium temperature solar organic Rankine cycles permit the consumption of electricity by a reverse osmosis system and thermal energy by a distillation process, absorption chillers or other processes. Both possibilities, high and medium temperature solar systems, have been implemented – see tables 3-4 -, but only medium temperature plants based on parabolic trough solar collectors are suitable for distributed production of fresh water within a range of medium to low desalination capacities. None of such systems have been implemented. Mechanical and thermal powers delivered by such systems are able to supply basic needs such as electricity, water desalination, cooling and heating, etc.

Except for very small systems for water irrigation pumping, low to medium temperature solar-heated cycles for small or medium-size systems have not been deeply analysed or developed and very few implementations exist. With regard to desalination, only two designs of solar heat engine-driven RO were performed. All of them use commercial low temperature solar collectors and operate with top cycle temperature around 70ºC [Maurel, 1991; Libert and Laurel, 1981][Manolakos *et al.*, 2004]. The experimental research literature related to distributed power plants of medium temperature solar technologies (parabolic trough) or low temperature (stationary collectors) solar technology is also very scarce: In the early 1980´s, a 150 kWe organic Rankine cycle plant powered by parabolic trough solar collectors was demonstrated. Hassani and Price (2001) reported that the operation problems of this plant precluded further development of such systems. Nevertheless they carried out aa assessment of the technology taking into account the current significant improvements in both, solar and organic Rankine cycle technologies. Saitoh and Hoshi (2002) reported tests on a small electricity generation prototype with 7.6 kW in summer weather conditions, in a system powered by conventional compound parabolic solar concentrators.

3.2. MULTI-EFFECT AND MULTISTAGE FLASH DISTILLATION

Multi-effect and multistage flash processes are considered together in this section because their common features are more important than their differences, regarding their coupling to solar technologies.

There are three different possibilities of reducing the specific consumption of a desalination process: to lower the solar energy requirement of the main energy consumption or the auxiliary energy, or increase the recovery of the desalination process with similar thermal power consumption.

The selection of the solar thermal technology in a solar desalination system with conventional energy as backup should take into account the efficiency of the solar technology with reasonable solar fraction, thermal storage size and costs. With regard to stand alone system, for a given annual demand of fresh water, maximizing the possible annual mean of operation hours normally leads to the most economic solution since it requires the minimum nominal capacity of the desalination plant. In that sense, salinity gradient solar ponds are the best solar technology if the system capacity is not too small since they permit 4316 annual full load hours [Trieb, et al., 1997]. For systems with energy backup, medium temperature technology –parabolic trough collectors- are the most efficient. Among the solar thermal static collectors, compound parabolic concentrators showed to be superior in an assessment performed within Spanish climatic conditions of Plataforma Solar de Almería (CIEMAT) at Almería, Spain. Salinity gradient solar ponds, parabolic trough and compound parabolic concentrators, and evacuate tube and flat plate solar collectors were successfully connected to multi-stage and multi-effect distillation plants – see tables 1 and 2 -. In every case study, the top brine temperature on a multistage flash distillation as well as the number of effects on a multi-effect distillation should be carefully selected according to the solar technology selected in order to minimise the product costs.

The most efficient solar thermal technology and desalination process should be selected in order to decrease the solar energy requirement of the main energy consumption. An additional possibility is to recover the heat rejected by means of coupling other processes in order to achieve a decrease in the energy consumption of the process as a whole. Even a slight reduction of the auxiliary energy consumption is important because it does not require thermal energy, but electricity. Since both multi-effect and multistage flash distillation require a significant part of the auxiliary consumption for pumping the mass flow rate only required as coolant, special attention should be paid to that stream.

In order to maximise the efficiency of a multistage flash (MSF) process we could either increase the top brine temperature or decrease the minimum temperature. Both cases were analysed as follows:

- The minimum temperature is limited by the necessary heat rejection from the system to the ambient. Coupling to an absorption heat pump would allow cooling of the desalination process below ambient temperature, although the low pressure required and the high specific volume of the vapour in the last stages have to be considered. Even though these aspects could make it inadvisable to lower the minimum brine temperature below the values normally used, the coupling of the absorption heat pump (AHP) avoids the discharge of the cooling seawater, thus reducing the auxiliary energy required. Moreover, the main effect of coupling such a heat pump is the recovery of the heat otherwise rejected. Then, the main heat input of the desalination unit is reduced, although the temperature required for driving the heat pump is higher than that of the thermal energy delivered by it. This fact does not represent a disadvantage if solar parabolic through collectors drive the process. There is no experience of AHP/MSF although it is a promising technology for medium to large capacity solar desalination with conventional energy backup.

- The top brine temperature is limited by the feedwater pretreatment. Even more than 120ºC can be achieved with nanofiltration pretreatment [Hassan, 1998], which results in considerable increasing of the performance ratio of the process. Since the auxiliary energy consumption on a multistage flash process is high, it would be an important drawback to increase it even more.

3.2.1. *Coupling a solar-driven double-effect absorption heat pump to a multi-effect of multistage distillation unit*

There was an experience of multi-effect distillation process at the Plataforma Solar de Almería (CIEMAT), Spain, with the coupling of an AHP in order to recover the heat rejected on the end condenser. A prototype of LiBr-water double effect absorption heat pump (DEAHP) was coupled to an existing 3 m^3/h multi-effect distillation unit, SOL-14 plant [Zarza Moya, 1995]. The operation temperatures of the 14-effect remained unchanged but two heat exchangers were incorporated to preheat the feedwater with product and brine outlet streams. The viability of the system was shown and performance ratio around 20 was measured, although different improvement was identified to improve the reliability of the system. A second prototype has been recently coupled to the SOL-14 plant, which is expected to prove the reliability of such coupling obtaining twice performance ratio than that of the SOL-14 plant.

The DEAHP coupled to SOL-14 plant consumes about 108 kJ of thermal energy at 180ºC per kg of distilled water. This is less than one half of the thermal energy required at 70ºC in the multi-effect distillation unit. Let us compare the case study of solar desalination based on SOL-14 plant. Three main possibilities have to be taken into account: a) Medium temperature solar collectors - parabolic trough ones (PTC) - as heat source of a DEAHP coupled to the MED unit. b) Medium temperature solar collectors as direct source of the multi-effect unit. The solar field and the MED plant are connected by a steam generator. c) Low temperature solar collectors (LTC) connected to the multieffect distillation unit.

Table 7 shows the main energy consumption of the desalination system considered, both, the MED unit and the MED unit coupled to the DEAHP (DEAHP-MED).

3.2.2. *Using nanofiltration pretreatment on solar-driven multi-efect distillation*

The use of nanofiltration pretreatment on solar-driven multi-effect or multistage distillation has not been implemented yet. In principle, an increase in the top operation temperature would permit performance ratios around 20 on multi-effect distillation. An organic Rankine cycle with parabolic trough collectors would drive the nanofiltration system and use heat rejection to drive the thermal process with low solar energy consumption. Such systems have interesting perspectives but have never been implemented. Analysis performed on candidate working fluids suggest that only multi-effect distillation process coupled to nanofiltration exhibit interesting perspectives since multistage flash distillation requires quite high temperatures of the heat input in order to achieve significant increase in the performance ratio. None of such solar systems have been implemented.

TABLE 7. Thermodynamic assessment of three different solar desalination systems based on solar thermal collectors and a MED unit (PTC: parabolic trough collectors, LTC: temperature solar collectors)

Desalination system	**Main energy consumption, kJ/kg**	**Solar desalination system**	**Solar energy consumption(*), kJ/kg**
DEAHP-MED	108 (at 180ºC)	PTC-DEAHP-MED	142
MED	240 (at 70ºC)	PTC-MED	315
MED	240 (at 70ºC)	LTC-MED	545-1600 333-369(**)
(*) Efficiency of solar collectors at 800 W/m^2 (solar irradiance) (**) If evacuated absorber tubes are used			

3.2.3. *Coupling a membrane distillation system to a solar-driven multi-effect or multistage flash distillation units*

Coupling a membrane distillation process to recover part of the heat rejected by the warm blowdown also increases the recovery of the hybrid desalination process as a whole, with a negligible increase in auxiliary energy. Since the heat consumption of the membrane distillation process does not reduce the performance ratio of the multi-effect process, the economy of the process should be favourable. A precise assessment is not possible since costs of the membrane distillation process are not precisely defined in the literature, and also because the extrapolation or experimental results to different conditions are also difficult [Alklaibi and Lior, 2004].

The different possibilities of hybridation mult-stage flash and multi-effect distillation should be analysed and implemented. A deeper analysis is required in order to assess the limit of possible performance ratio of the hybrid system as a whole and the specific product costs.

3.3. MEMBRANE DISTILLATION

The coupling of a membrane distillation system to a solar-driven multi-effect or multistage flash distillation units in order to increase the overall performance ratio was discussed in section 3.2. Other hybrid desalination processes also have interesting potentials. Reverse osmosis desalination driven by solar-assisted power cycles provides the electricity consumption of the RO plant as well as the low grade thermal energy consumption of the membrane distillation process in order to distil the blowdown of the RO plant. To the author's knowledge, none of these hybrid desalination processes have ever been implemented.

In stand-alone solar desalination systems, the connection of a salinity gradient solar pond to a membrane distillation process has never been implemented. It could however be one of the most economic systems since a given membrane distillation system is able to operate at varying top brine temperature provided by the solar pond during the year. This fact guaranties the continuous and troublefree operation of the desalination system along the year, according to solar pond behaviour – see Al-Jamal and Khashan (1998) -. Only a slight decrease in the performance ratio should be exhibited in winter since the decreasing ambient temperature partially overcomes the decreasing temperature of the heat storage zone.

If a conventional thermal input is available as energy backup, an absorption heat pump provides a higher exergetic performance for the fossil fuel since the temperature of the required heat input is higher than that of the membrane distillation process. The coupling of a heat pump would also lower the temperature of the coolant below ambient temperature, thus increasing the performance of the membrane distillation process.

4. Conclusions

The main conclusions about future development of solar-powered desalination come from the assessment presented above:

- If the water demand in the near future is not predictable, modular systems are the best option. First of all reverse osmosis should be considered, although membrane distillation could soon be an economic option.

- If conventional energy is available as energy backup and the fresh water demand is not small, multi-effect or multistage flash distillation processes should be considered as important as reverse osmosis.
- If a stand-alone system is projected, firstly the use of salinity gradient solar ponds should be compared with reverse osmosis powered by dish/Stirling systems as the best options. Solar pond-powered desalination cost mainly depends on plant capacity since small solar ponds are much less cost effective than large ones. Solar ponds also permit the highest annual operation hours. The coupling of the solar pond to a membrane distillation process permits continuous operation during the year, although membrane distillation is not a mature technology. Other reasonable processes are multistage flash distillation, multi-effect distillation or reverse osmosis. Multi-effect and multistage flash distillation require careful analysis of the optimum number of effect and top brine temperature, respectively.
- If thermal energy is available as backup, organic Rankine cycles driven by parabolic trough collectors coupled to reverse osmosis are superior to conventional solar distillation processes. Nevertheless high efficiency thermal processes have to be considered, parabolic trough collectors coupled to:
    - multi-effect distillation driven by a double-effect absorption heat pump;
    - multi-effect distillation with nanofiltration pretreatment by means of organic Rankine cycles;
    - hybrid processes membrane distillation/multistage flash or membrane distillation/multi-effect distillation.

Considerable research has to be conducted on the technologies that have never been implemented before as they could be reliable and cost-effective options.

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ABBREVIATIONS

BW	Brackish water
BWRO	Brackish water reverse osmosis
COP	Coefficient of performance
DC	Direct current
ED	Electrodialysis
EU	European Union
FPC	Flat plate collector
GH	Green house
GOR	Gain output ratio
HDH	Humidification dehumidification
HP	Heat pump
MED	Multiple effect evaporation
MEH	Multi Effect humidification process
MENA	Middle East and North Africa
MES	Multiple effect stack
MD	Membrane distillation
MF	Microfiltration
MSF	Multistage flash desalination
MVC	Mechanical vapor compression
NF	Nanofiltration
PTC	Parabolic trough collector
PV	Photovoltaic
PX	Pressure exchanger
RO	Reverse Osmosis
ST	Solar thermal
STH	Solar thermal heat generation
STP	Solar thermal power generation
SW	Seawater
SWRO	Seawater reverse osmosis
UF	Ultrafiltration
WEC	Wind energy conversion

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