SMALL AUTONOMOUS RO DESALINATION SYSTEMS POWERED BY RENEWABLE ENERGIES. TECHNOLOGICAL ADVANCES AND ECONOMICS

G. Papadakis*, E. Sh. Mohamed, D. Manolakos

***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 depends 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*

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.

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)	1. Reverse osmosis (RO)
2. Multiple effect boiling (MEB)	–RO without energy Recovery
3. Vapour compression (VC)	–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	

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 2.36x1012 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 CO2 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

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.

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)

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.

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 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.

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%

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 and 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.

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.

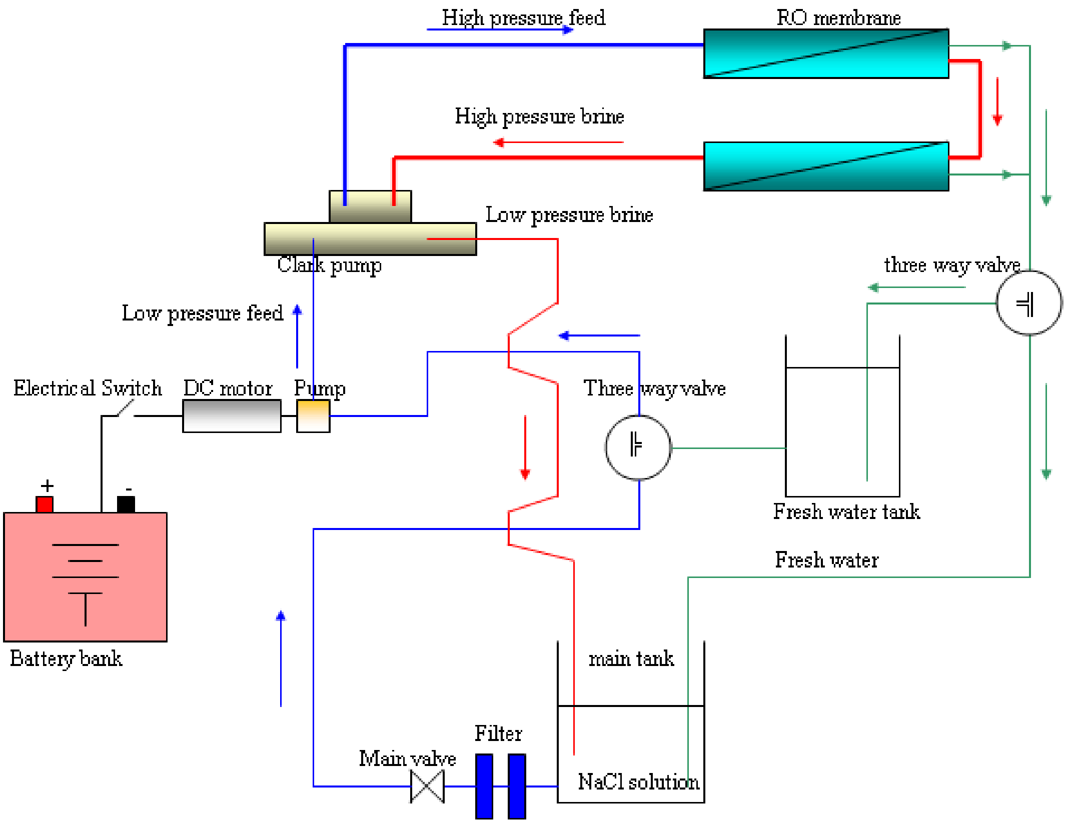

Figure 1. Schematic diagram of a PV-battery driven RO system equipped with energy recovery of the Clark pump type

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.

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).

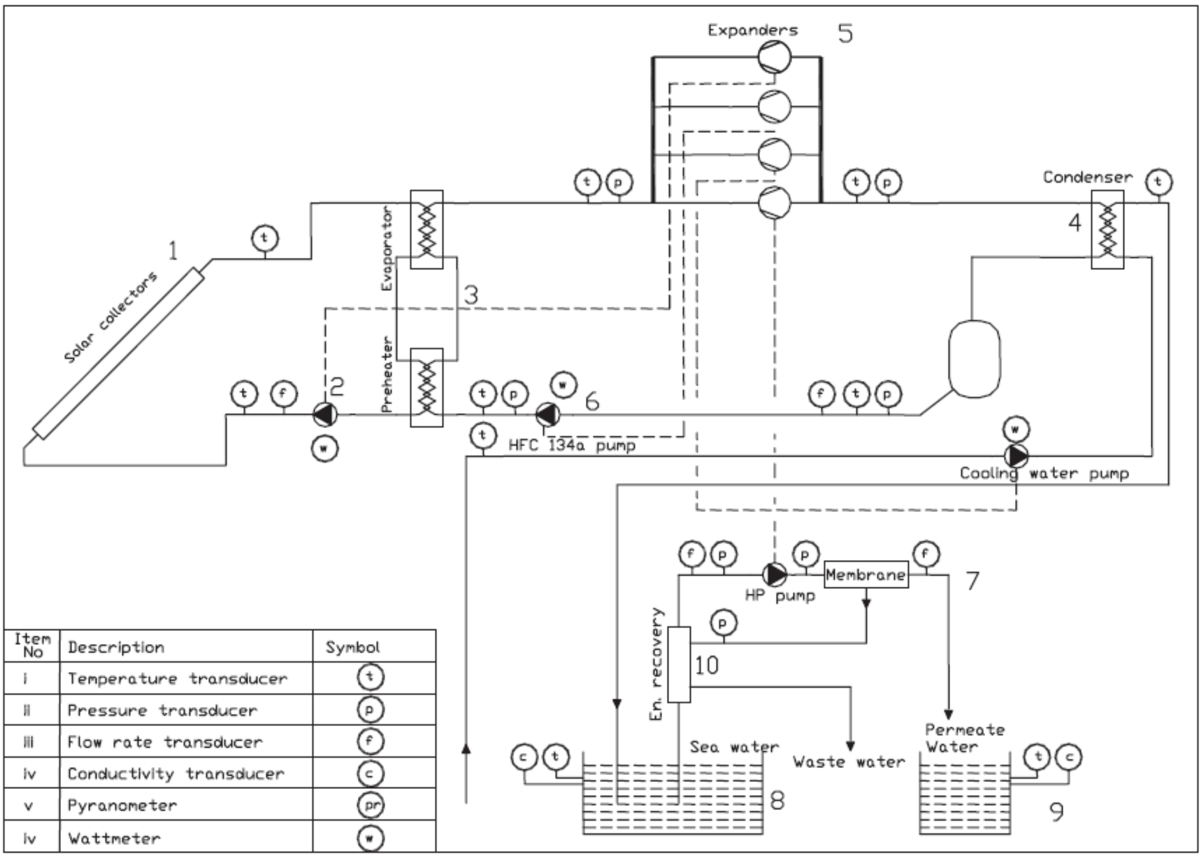

Figure 2. Schematic diagram of the solar thermal Rankine RO system. System components: 1) High efficiency vacuum tube solar collectors' array, 2) Circulator, 3) Evaporator, 4) Condenser, 5) Expanders, 6) HFC-134a pump, 7) RO unit, 8) Insulated seawater reservoir, 9) Fresh water reservoir, 10) RO energy 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.

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.

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.

REFERENCES

[1]. Birkett D. J., 1984. A brief illustrated history of desalination, *Desalination 50: 17-52.*
[2]. Delyannis E., Belessiotis V., 1995. Methods and Desalination Systems-Principles of Desalination Process. Athens (In Greek).
[3]. Desalination Guide Using Renewable Energies, 1998. THERMIE Programme, CRES, Greece, ISBN 960-90557-5-3.
[4]. Garcıa-Rodrıguez Lourdes, 2003. Renewable energy applications in desalination: state of the art. *Solar Energy 75: 381–393.*
[5]. Gotor Antonio Gomez, De la Nuez Pestana Ignacio, Espinoza Celso Argudo, 2003. Optimization of RO desalination systems energies powered by renewables. *Desalination 156: 351.*
[6]. http://nessie.danfoss.com/products/pumps.asp (site accessed in 2005).
[7]. Kalogirou A. Soteris, 2005. Seawater desalination using renewable energy sources. *Progress in Energy and Combustion Science 31: 242–281.*
[8]. Lindemann H. Johannes, (2004). Wind and solar powered seawater desalination. Applied solutions for the Mediterranean, the Middle East and the Gulf Countries. *Desalination 168: 73-80.*
[9]. Manolakos D., Papadakis G., Mohamed Sh. E., Kyritsis S., Bouzianas K., 2005. Design of an autonomous low-temperature solar Rankine cycle system for reverse osmosis desalination. *Desalination 183: 73-80.*
[10]. Mohamed Sh. Essam and Papadakis G., 2004. Design, simulation and economic analysis of a stand alone reverse osmosis desalination unit powered by wind turbines and photovoltaics. *Desalination 164: 87-97.*
[11]. Mohamed Sh. Essam, and Papadakis G., 2004. A TRNSYS dynamic simulation model for a stand alone photovoltaic system powering directly (without batteries) a reverse osmosis desalination unit with energy recovery. *Proceedings "19th European photovoltaic solar energy conference and exhibition", Paris, France, 7-11 June 2004*.
[12]. Mohamed Sh. Essam, Papadakis G., Mathioulakis E. and Belessiotis V., 2005. The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; An experimental and economical evaluation. *Desalination 184: 241-246.*
[13]. Thomson M. and Infield D., 2002. A photovoltaic powered seawater reverse osmosis system without batteries. *Desalination 153: 1-8.*
[14]. Tzen E. and Morris R., 2003. Renewable energy sources for desalination. *Solar Energy 75: 375–379.*
[15]. Voivontas D., Misirlis K., Manoli E., Arampatzis G., Assimacopoulos D., Zervos A., 2001. A tool for the design of desalination plants powered by renewable energies. *Desalination 133: 175-198.*
[16]. www.spectrawatermakers.com (site accessed in 2005).
[17]. Zejli D., Benchrifa R., Bennouna A., Zazi K., 2004. Economic analysis of wind-powered desalination in the south of Morocco. *Desalination 165: 219-230.*

ABOUT THE AUTHORS

G. Papadakis, Agricultural University of Athens, Dept. of Natural Resources and Agricultural Engineering, Iera Odos street 75, Athens 11855, Greece. e-mail: gpap@aua.gr
E. Sh. Mohamed. Agricultural University of Athens, Dept. of Natural Resources and Agricultural Engineering, Iera Odos street 75, Athens 11855, Greece

D. Manolakos. Agricultural University of Athens, Dept. of Natural Resources and Agricultural Engineering, Iera Odos street 75, Athens 11855, Greece