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Cost Analysis of an Autonomous Low-Temperature Solar Rankine Cycle System for Reverse Osmosis Desalination

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Abstract: The present paper regards the design outlines and cost analysis, of a low temperature solar organic Rankine cycle system for Reverse Osmosis (RO) desalination. The thermal processing taking place is described briefly below:
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 vapour. The super-heated vapour is then driven to the expanders where the generated mechanical work produced by the processing drives the High 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 vapour at the expanders' outlet is directed to the condenser and condensates. HFC-134a condensation is necessary in the Rankine process. On the condenser's 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 pressurised by the HFC-134a pump. Such system can be considered as an alternative to PV-RO system or other thermal processing distillation methodologies since it is reliable, environmentally friendly, with low O&M cost and it is ideal to exploit low temperature thermal sources in a most efficient way.

Key-Words: Solar energy, ORC, RO desalination, solar collectors, cost analysis

1. Introduction

The present work regards the cost analysis of a Low Temperature Organic Solar Rankine system which generates energy for RO desalination. The cost analysis is based on the simulation results provided by the application of suitable softwares. A prototype system is going to be installed within the framework of COOP-CT-2003-507997 project, partly financed by EC.

2. Technical description of the system

The Low Temperature Solar Organic Rankine Cycle (LTSORC) system for RO desalination consists of the following sub-systems and components (Fig.1):

(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

The system operation is described briefly below:

Thermal energy produced by the solar array (1) preheats and evaporates the working fluid (HFC-134a) in the evaporator surface (3). The water temperature at collector inlet is about 70 ^{o}C and the outlet temperature about 77 ^{o}C. The super-heated vapour is driven to the expanders (5) where the generated mechanical work drives the RO high pressure pump high pressure pump, cooling water pump, HFC-134a pump (6) and circulating pump (2). The saturated vapour at the expanders' outlet is directed to the condenser (4). On the condenser surface, seawater is pre-heated and directed to the seawater reservoir (8). Seawater pre-heating is applied to increase the fresh water recovery ratio in a value not exceeding the temperature limit set by the membranes manufacturer. The seawater tank is insulated. The saturated liquid at the condenser outlet is pressurised by the pump (6). An energy recovery system (10) is coupled to the RO unit thus declining the energy consumption to 2.5 kWh/m^3 product. Fig. 1 represents schematically the above described system.

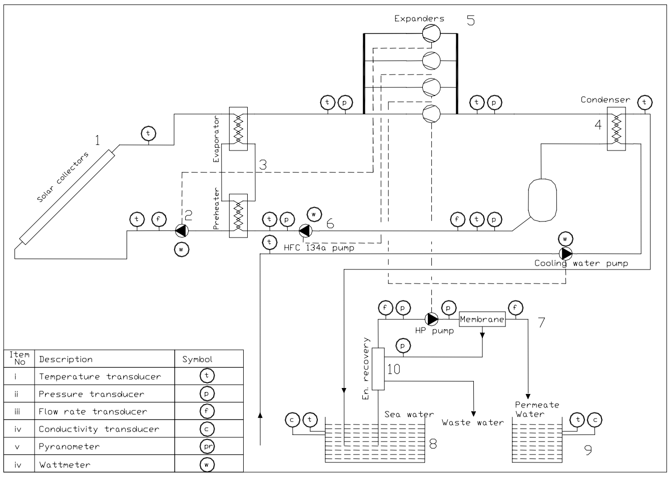

Figure 1: Schematic representation of the system

3. Assessment of system advantages

Significant advantages of using the proposed Solar Rankine system for RO desalination are:

- Use of market available components (expanders, heat exchangers, pumps) widely applied in heating and cooling industry available at low cost implies lower investment cost compared to other solar thermal technologies.
- Ideal exploitation of low temperature energy sources. This concerns the efficient utilisation of thermal wastes of industries, diesel generators and geothermal energy fields, as well as thermal energy coming from biomass or Municipal Solid Wastes.
- Mechanical work is driven directly to RO pumps so there is a direct efficiency gain from no transformation to electrical power.
- It can be easily standardised due to most of the system components are market available.
- Rankine cycle approaches the efficiency of Carnot cycle meaning maximum efficiency.
- Continuous and safe operation at low temperatures.
- The working fluid (HFC-134a) is not corrosive and environmentally friendly.
- Low maintenance cost since except the fact that most of the components are market available, they are characterized by long life time (e.g. expander >150000 hrs)
- Due to low O&M cost, simplicity in construction and reliable operation it fits perfectly for applications in isolated, not grid connected areas.
- Compared to PV-RO desalination system this system prevails in the following:
    - Water storage is used instead of batteries (electrical energy storage)
    - It is environmentally friendly since no batteries are used (problems of old batteries disposal).
    - The absence of batteries implies less maintenance (usually 5 years batteries' replacement). This is critical for installations in isolated areas where the maintenance is the key factor for long life-time.
    - Since no electricity is produced, the system is safer for the end users.
    - No qualified staff is needed for O&M.
    - The fresh water cost is expected to be at competitive level.
- Compared to thermal systems operating in the same temperature range the proposed one is characterised by a much higher efficiency and much less product water cost.
- Variable pressure working conditions in RO system, implies higher energy availability and higher efficiencies in the whole system, making it more flexible to the variability conditions of RES (solar).

Several applications of solar Rankine cycle are referred in the literature. Most of them concern the cycle application for electricity generation or heat production. Ying You et al [1] proved that re-heat generative Rankine cycle is suitable for parabolic solar collectors. B.J. Huang and al [2] investigated an integral type solar assisted heat pump consisted of a Rankine refrigeration cycle. V.M Nguyen et al [3] developed a small-scale solar Rankine system designed to operate at low temperatures for electricity generation with 4.3% efficiency.

The international state-of-the art shows that scientific efforts of Solar Rankine Cycle have been so far concentrated to heat or electricity generation. No RTD efforts for seawater desalination are mentioned. The application of this thermodynamic cycle for RO desalination represents a significant step forward beyond state of the art.

4. System design

The system design concerns, as a first step, the definition of the size and technical specifications of the technologies involved in the system that is the solar collectors and their circulator, the heat exchangers (pre-heater, evaporator, condenser), the expanders, the HFC-134a pump, as well as the RO unit with the energy recovery system. The prototype system is going to be installed at a location near Athens, so the required meteorological data to be used for the design can be those of Athens without significant error. Well known softwares such as TRNSYS simulation software and other commercially available, provided by manufacturers of systems' components were applied [4]. A brief description of the design procedure is provided below.

4.1 Solar collectors array

The SOLAMAX direct flow evacuated solar energy collector manufactured by Thermomax Ltd. has been considered. For the assessment of solar array behaviour TYPE 71: EVACUATED TUBE SOLAR COLLECTOR of TRNSYS 15.0 is applied. In table 1 the basic data of the collectors array are presented.

Table 1: Characteristics of solar collector's array

Manufacturer	Thermomax Ltd.
Type	SOLAMAX
No. of tubes/collector	30
Capacity (l)	6
No. of collectors	56
No. of collectors connected in series	2
Slope (^{o})	40
Efficiency coefficients (aperture area) a_0(-), a_1(W/m^{2}C, a_2(W/m^{2}C^2)	0.769, 1.61, 0.0032
Maximum rate of energy gain (kW)	100.1
Maximum flow rate (l/min)	196.8
Inlet temperature (^{o}C)	70
Outlet temperature (^{o}C)	77.3

4.2 Solar collectors' circulation pump

Table 2 presents the circulation pump characteristics:

Table 2: Collectors circulator characteristics

Pump type	Centrifugal-1 stage
Flow rate (l/min)	200
Head (m)	18
Efficiency (%)	75
Nominal power (kW)	1.85
Rotation speed (rpm)	2850

4.3 Heat exchangers

4.3.1 Preheater and evaporator

For selecting the suitable preheater and evaporator, selection software provided by CIAT heat exchangers manufacturer is used. Table 3 presents the basic technical characteristics of the preheater and evaporator.

Table 3: Preheater and evaporator characteristics

	Preheater	Evaporator
Manufacturer	CIAT	CIAT
Model	EXL-1440	EXL-1440
Dimensions (Lxwxh, mm)	129x265x528	129x265x528
Duty (kW)	40	65
Fluids, hot/cold	Water/HFC-134a	Water/HFC-134a
Pressure drop, hot/cold (mmWG)	237/2140	237/2140
Type	Counter flow	Counter flow
Flow rate hot/cold (m^3/h, kg/h)	11 m^3/h	11 m^3/h

4.3.2 Condenser

CIAT software is also applicable for condenser's selection. The selected condenser has the following characteristics (Table 4).

Table 4: Condenser characteristics

Manufacturer	CIAT
Model	FKM 273 20 2U
Dimensions Lxwxh (mm)	2165x279x415
Duty (kW)	100

	Tube side	Shell side
Fluid	Sea water	HFC-134a
Inlet/outlet temperature (^{o}C)	25/33	-
Discharge temperature (^{o}C)	-	75
Condensing temperature (^{o}C)	-	34.8
Pressure drop (mmWG)	399	-
Flow rate	11 m^3/h	1700 kg/h

4.5 HFC-134a pump

Table 5 presents the Freon pump characteristics.

Table 5: HFC-134a pump characteristics

Type	Piston Diaphragm
Flow rate (kg/h)	1920
Suction Pressure (bar)	9
Discharge pressure (bar)	22
Power (kW)	0.9
Efficiency (%)	80

4.6 Expanders

Three expanders are used for the operation of HP pump of RO system, HFC-134a circulation pump, cooling water pump and collectors' circulator. The total power to be distributed to the above mentioned consumptions is 7 kW.

4.7 RO-desalination plant with Energy Recovery System

For the analysis of the RO system the ROSA 6.0 software supplied by FILMTEC™ Company is applied. The system details are illustrated in the table 6 below:

Table 6: RO configuration

No. of stages	1
Element model	SW30HR-320
No. of pressure vessels	1
No. of elements	3
Recovery (%)	20
Water temperature (^oC)	25
Water classification	Seawater (open intake) SDI<5
Energy recovery system	Clark pump
Specific energy (without energy recovery) kWh/m^3	8.36
Specific energy (with energy recovery) kWh/m^3	2.50
HP pump power (kW)	2.50

4.8 Results and discussion

The following table summarizes the energy and mass balance of the specific system. These results are derived from the simulation programme running for one year.

Table 7: Basic energy and mass results

Collectors' energy gain (MWh/y)	101.3
HFC-134a pump (MWh/y)	0.89
Energy for condensation (MWh/y)	90.83
Energy for preheating (MWh/y)	35.5
Energy for evaporation (MWh/y)	65.8
Energy from expansion (MWh/y)	7.10
System efficiency (%)	7
Energy for desalination (MWh/y)	2.53
Fresh water produced (m^3/y)	1012
Specific energy consumption (kWh/m^3)	2.5

5. Economic analysis

5.1. The cost of desalinated water, based on the total annual cost of the system and on the specific cost of the investment

The quantity of water that system produces is 1,012m³/year. The cost of the whole system for each year, taking into account that the economic life period is 20 years is approximately 15,000€, while the cost per cubic meter is 15.21€.

5.2. Appraisal of the investment according to the specific conditions

The system is installed in Marathon, near Athens. The necessary land is 0.1 hectares where the 56 solar collectors will be installed. The building requires an area of 10m². Taking into account the weather conditions of the specific region, the capacity of the system is 1,012m³/year of fresh (desalinated) water. System's economic life is estimated in 20 years and taking into account the prices of the year 2005 and using an interest rate of 5% it's equal annual cost is approximately 15,000€. Table 8 shows the partially cost of the system while in pie of figure 2 these costs are compared to the total cost. Operation and maintenance costs have been estimated as 2% of the total cost each while insurance as 1%.

Table 8: The cost of the system

	Total cost (€)	**% of total**
Building (10m²)	**5000**	**2.61%**
Land Rent (0.1 hectare)	**300**	**1.95%**
Energy System		**50.59%**
Collectors part		**35.00%**
Solar collectors (100.1kW)	**50400**	23.24%
Collectors Pipes and installation	**25000**	11.53%
Collectors pump	**440**	0.23%

Rankine cycle part		**15.59%**
Preheater (40kW)	**2700**	1.41%
Evaporator (65kW)	**2700**	1.41%
Condenser (100kW)	**5500**	2.87%
Freon pump (0.9kW)	**7600**	6.40%
Pipes	**1500**	0.78%
Expander (7kW)	**1236**	0.64%
Rankine labour	**4000**	2.09%
Desalination System		**32.37%**
(RO unit 1m³/h)		
Membranes	**4000**	7.33%
All other components	**40000**	25.04%
(Labour included)		
Civil works	**8000**	**4.17%**
Others		**8.31%**
Instrumentation	**5000**	3.13%
Tanks	**800**	0.42%

The pie in Figure 2 gives an indication of cost sharing of different cost parts. The solar collectors' part gets a percentage of 35% over the total 51% of the cost of the energy and is the main reason for the high cost of fresh water produced.

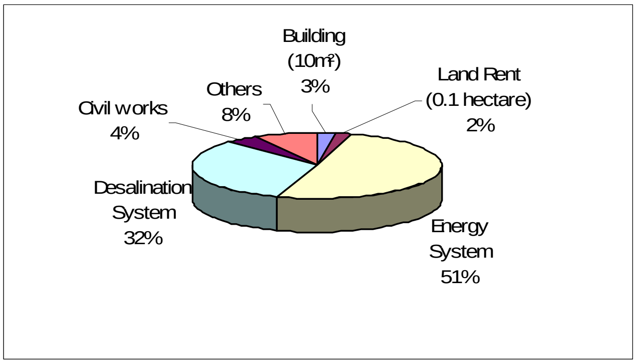

Fig. 2: Division of the cost in the different parts

5.3. Comparison with a system which uses a conventional source of energy

Compared to a system coupled to a constant thermal source supply (all other parameters remaining stable) there are the following differences:

- The energy system doesn't include the solar collectors' part
- The installation cost decreases
- Fresh water capacity increases from 1012 m³/year to approximately 8200 m³/year due to constant energy supply during the whole year.
- The cost of water produced is 1.18€/m³, really low compared with that of the innovative system.

The pie of Figure 3 expresses the allocation of different costs for the system which uses a constant thermal source of energy (e.g. geothermal).

In Figure 3 it is evident that the main cost concerns the installation of the desalination system (52%), while the cost of the energy system has decreased to 25% of the overall cost.

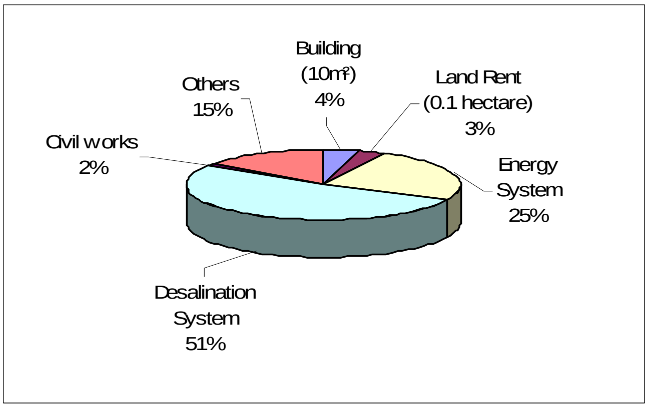

Fig. 3: Allocation of the cost for the same system using conventional source of energy

5.4. Comments on system's cost

Figure 4 depicts the cost of water produced per month in correlation with the fresh water production. It is obvious that these two lines will be inversely related, as when the fresh water production increases, the cost of water produced decreases and vice-versa. What is not obvious is that when a similar system is installed in a region with solar radiation much higher than that of Greece, especially for the winter months, due to better weather conditions, the cost of water produced can decrease even more, probably near or less than 10€/m³. Regions which suffer from water scarcity are those that have high solar radiation, like many African countries, where the desalination systems are necessary for the population supply with potable water.

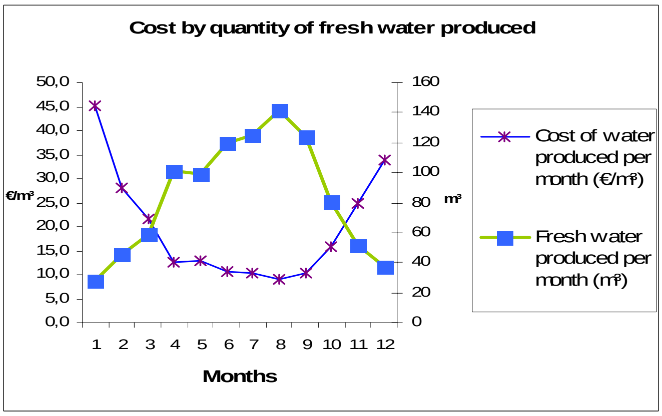

Fig. 4: Fresh water cost as a function of production in monthly base

6. Conclusions

From technical point of view, the Organic Solar Rankine System for RO desalination can be successfully applied for fresh water production from both sea and brackish water. Particularly, compared with PV-RO systems, is more environmentally friendly, with less O&M needs and simpler.

The results show that a system efficiency of about 7% is achieved. The efficiency is directly related to the selected temperature level of operation. The higher the temperature difference between high and low temperature reservoir, the higher the efficiency. But the scope of research is to examine the behaviour of Rankine system at temperatures in the range of 70 to 80 ^oC, so as to extract valuable results about the exploitation of low temperature thermal sources. Although this value of efficiency does not seem attractive at first sight, it is comparable to the efficiency of a PV system for RO desalination. Taking into account the above mentioned advantages, the system becomes an attractive alternative technology for both exploitation of low temperature thermal sources and generation of fresh water from solar energy.

The results of this paper concerning the cost evaluation of the system can be summarized as following:

1. The capacity of the system using solar collectors as providers of energy is 1,012m^3/year
2. The cost for fresh water which produced from the system using the solar stills is 15.21€/m^3
3. The cost of a similar system connected to a thermal source decreases to 1.18€/m^3, as the system has lower installation cost and desalinates water during the whole day, as it is independent of the solar radiation
4. System's cost can be lower if it is installed in regions with higher solar radiation than that of Greece, such in many African countries.

7. Acknowledgements

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