LIFE CYCLE COSTING AND PAYBACK PERIOD EVALUATION OF A SOLAR THERMAL DESALINATION SYSTEM

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ABSTRACT

Water is important for life and development. About 1.8 billion people will be living in absolute water scarcity by 2025.Non availability of safe drinkable water is the major source of diseases in the different regions of the world especially remote rural and coastal areas. About 97% of water on earth is comprised of seawater. Desalination of saline water is a prominent approach to handle the problem of water scarcity. Conventional desalination technologies cause economic and environmental problems due to their dependency upon fossil fuels. Solar flash desalination is one of the best desalination techniques in the developing stages. Solar energy, passive vacuum and recovery of latent heat of condensation make this system a sustainable option for desalination. In this paper, economic analysis of the solar thermal desalination system of saline water is presented. The unit cost of desalinated water is found to be US$ 0.0147 per litre. The energy and emission payback (EEP) period for vacuum chamber and solar collector has also been presented. The energy payback period of solar collector and vacuum chamber are found to be 1.3 years and 1.5 years respectively. The emission payback period of solar collector and vacuum chamber are found to be 1.8 years and 2.1 years respectively.

KEY WORDS: *Solar desalination; passive vacuum; life cycle cost analysis; energy payback period; emission payback period*

INTRODUCTION

Water scarcity, energy and environmental issues are among the most prominent issues in the world these days. Safe drinking water is necessary for health and development. The exponential growth in the population of the world, improvement in life styles and industrialization are among the main reasons behind the increasing demand of potable water. Natural processes cannot replenish the extraction and consumption of potable water from its reservoirs. The fresh water resources are unevenly distributed. The forecast of population growth in different regions of the world and total expected population growth is described in Fig. 1. It is clear that, world population is increasing drastically with expected value of about 8.9 billion by 2050. The graph also shows that the trend of increase in population in Asia is higher than the other regions of the world. About 97 % of total water on earth is seawater. Therefore, desalination of seawater is a promising approach to tackle the problem of water scarcity. The process of desalination involves the removal of dissolved salts from brackish or seawater.

Conventional desalination technologies are dependent upon fossil fuels to provide high grade energy. The burning of fossil fuels has a negative aspect in terms of economy and environmental pollution. Demira[1] and Ko[2] proposed a system consisting of a solar-natural gas hybrid power plant, thermoelectric generator (TEG), Rankine cycle to produce electricity and flash distillation unit to produce fresh water. The proposed ele plant uses solar driven volumetric pressurized air receivers as main power supply and uses natural gas to compensate power when the direct normal irradiance is below 900 W/m^2. Aberuee[3] proposed system is able to produce electric power, distilled water and hot water, concurrently. The performance of the main is modeled mathematically, and then evaluated at different working conditions using the second law of thermodynamics. Zubaira[4] studied the impact of the effectiveness of the humidifier and the dehumidifier, as well as, the number of collectors, were also studied. The analyses were performed for Dhahran, Jeddah, Riyadh, Sharurah, Qassim, and Tabuk to determine the effects of varying the geographical location.

The market share of different seawater desalination technologies is shown in Fig. 3[5]. The alternative renewable energy technologies can be applied for eco-friendly and economically viable seawater desalination system[6]. The contribution of the major factors of climate change

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on water quality was reviewed by I. Delpla[7]. Sun is the oldest renewable energy source utilized by human beings. The reflected heat of the sun was utilized by Archimedes to burn the roman fleet in Bay of Syracuse[8]. The use of solar energy for desalination was documented in sixteenth century. The installed capacity of desalination with the inception of growth on the industrial scale is increased exponentially in the past few decades as projected by the graph shown in Fig. 2. World Health Organization (WHO) sets availability of 1000 m^3 per capita per year as the lower limit for growth of economy and tolerable standards of living[9]. In this process, multi-stage flash (MSF) desalination system is modified to single stage and a pilot plant is designed to produce 50 liters of potable water for 8 hours of continuous operation with generation of vacuum passively and utilization of latent heat of condensation in order to pre-heat the saline water.

The sustainability of the process has a key role in the planning of the process, especially when it is concerned with essential needs such as desalination of water. The conversion of seawater into potable water in a sustainable way is one of the most instant tasks for the service of humanity. The continuous technological development must be carried out without conceding their projections for upcoming generations for the survival of human being on earth. The evaluation of economic aspect of the desalination system in terms of unit cost of the desalinated water is also necessary. Life cycle cost analysis is one of the important tools which are used to evaluate the economic feasibility of a system. It is helpful for making decisions in the design, development and use of the product.

Sustainable development of a desalination system must be focused on economy, environment and society[10-11]. Kalogirou[12] estimated that for every one dollar invested in desalination, there is an economic return of three to four dollars. The aim of new developing desalination technologies is to primarily focus on minimizing the cost and consumption of energy as well as reducing the impacts on the environment. The energy and emission payback (EEP) periods play a key role in the evaluation of a sustainable solar thermal desalination system. In this work, the cost of the desalinated water is evaluated by using life cycle cost analysis (LCCA). Moreover, the payback period for vacuum chamber and flat plate solar collector (FPSC), in terms of energy and emission, are also evaluated.

Brief History of Solar Desalination

Aristotle described the open solar distillation system in his water cycle. In 1870, the first patent on solar desalination by Wheeler and Evans was accepted. The first large solar desalination plant was fabricated by Carlos Wilson. Alexander described that seawater was boiled and converted into potable water by sailors[12]. The concept of solar desalination using low grade heat and passive vacuum flash technique was proposed by S. Alkharabsheh and Goswami[13]. It is an innovative and energy efficient concept in the field of desalination. Theoretical simulation analysis of this concept for different production rate has been carried out by Gude et al[14]. M. Abutayeh, S.C. Maroo and Goswami[15] carried out the theoretical analysis of thermal desalination system consisting of single and two stages. The steady state modelling of the solar desalination system was carried out by J.H. Beamer and D.J. Wilde[16]. Moreover, E. Howe[17] described the basic principles of multi stage flash desalination system. Feasibility of seawater desalination technology using renewable energy and natural vacuum was presented by T. Ayhan and H. Al Madni[18]. The economic feasibility of solar stills at different energy efficiencies was evaluated by K.R. Ranjan and S.C. Kaushik[19]. The sustainable development of different pre-treatment processes for seawater desalination using life cycle assessment was described by M. Beery et al.[18]. The current status and future prospects of solar desalination in the world are presented by Tiwari et al.[20]

Process Pattern of Desalination System

The process pattern of the solar thermal desalination system is shown in Fig. 4. The system consists of a feed water circulation pump, a condenser, a FPSC, evaporation chamber, brine water tank (BWT) and fresh water tank (FWT). Atmospheric pressure and natural force of gravity will be utilized by the system for generation of passive vacuum in the evaporation chamber and condenser shell. Latent heat of condensation of vapours is utilized to pre-heat the feed saline water which cause in increase in the energy efficiency of the system.

In vacuum generation step, pump is used to fill the water to remove air from the system. Feed water valve and valve on the top of evaporation chamber are kept open until the condenser and evaporation chamber are completely filled by water. After that, pump is turned off and valves of barometric columns of fresh water and feed saline water are opened. Water flows under the action of gravity, thus generating the vacuum on the head space.

In continuous operation, water is first pumped in the condenser for pre-heating and then enters in FPSC, where it is heated up to 80^0C and then flashes in the evaporation chamber after passing through the expansion valve. The reduced temperature inside the evaporation chamber cause a portion of water to be evaporated by a flashing mechanism leaving the concentrated brine behind. These vapours flow towards the shell of the condenser due to pressure gradient. The latent heat of condensation of the vapours is utilized to pre-heat the feed water in order to enhance the energy efficiency of the solar thermal desalination system. Condensate and concentrated brine flow towards the fresh water tank (FWT) and brine water tank (BWT) respectively under the action of gravity.

The major problem in the sustainability of passively generated vacuum is the increase of non-condensable gases in the evaporation space with the passage of time. The area of the evaporation chamber is increased so that the pressure build up by these gases does not exceed the atmospheric pressure till 8 hours of continuous operation for which system is designed. The pressure of the flash tank and condenser increases with the buildup of non-condensable gases. The larger the rate of vapor generation, the larger will be the buildup of non-condensable gases.

MATERIAL AND METHODS

Life Cycle Cost Analysis

Life cycle cost analysis involves the evaluation of the product over the total duration of its life cycle. It is used as a monetary tool which involves the integration of the engineering art and science to make reasonable commercial decisions. The evaluation of important parameters such as amortization factor, interest rate, plant availability, and life cycle cost to evaluate the cost per liter of the potable water is very important. The cost analysis must include the fixed cost as well as operation and maintenance cost. In most remote and isolated coastal areas, where the grid electricity is scarce or not available, the use of Diesel or gas engine to power the conventional desalination plants are less economical as compared to the solar desalination systems.[8] Economic analysis of solar thermal desalination system has been carried out. The initial investment required for installation of the pilot plant of 50 liters output of desalinated water is given in Table 1.

The cost of water produced from the solar thermal desalination system is determined using amortization. In business terminology, amortization involves the distribution of payments over multiple periods of time. However, in accounting, it involves attainment of cost subtraction from the incorporeal properties in regular style over their projected beneficial economic life in order to describe their consumption or expiry due to their use or passage of time. The amortization factor can be determined from Eqn. (1).

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (1)$$

where is amortization factor,is interest rate compounded annually (which is taken as 5 %), and is lifetime of plant (which is taken as 20 years). Putting values in Eqn. (1), the amortization factor is determined to be 0.080843. The total cost of the pilot plant of desalination system can be evaluated using Eqn. (2).

$$E_{total} = E_{initial} + E_{replacement} + E_{O\&M} \qquad (2)$$

where; is the estimated operation and maintenance cost of the pilot plant. The total expenses of the pilot plant are estimated to be US$ 3000. The specifications of the pilot plant for analysis are summarized in Table 2. Annual capital, operating, maintenance and replacement cost and unit product cost can be determined using Eqn. (3) and Eqn. (4) respectively.

$$A_{total} + E_{total} \; X \; a \qquad (3)$$

$$Unit\ Product\ Cost = \frac{A_{total}}{M \times f \times 365} \qquad (4)$$

where; M is amount of potable water in kg produced per day, which is 50 kg/day, is plant availability, which is taken as 90 % and is US$ 24.7278. Putting values in Eqn. (4), the unit cost is determined to be US$ 0.0147 per kg of desalinated water.

Energy Payback Period Evaluation

The energy consumption for the production of 1 m^2 area of FPSC and its frame for support is about 7 GJ[21]. The required area of FPSC is 34.4 m^2, so total energy consumption for production of FPSC is 240.8 GJ. If annual energy collected by total area of FPSC is 189.2 GJ on basis of 5.5 GJ/m^2 per year, which will be used for desalination purpose. Therefore, the energy payback period of FPSC is about 1.3 years.

The energy consumption for the production of vacuum chamber is about 27.5 MJ per Kg of hot dip galvanized steel[22]. The vacuum chamber cross sectional area and length required is 0.1256 m^2 and 2 m respectively. The total mass required for vacuum chamber is 63.75 kg, therefore, total energy consumption for production of vacuum chamber is 1.753 GJ. The specific energy of 64 kJ/kg can be saved by desalination under passive vacuum (at P= 20 kPa) .conditions. So total energy saved for production of 50 kg of potable water per day, will be 1.168 GJ per year. So, the energy payback period of vacuum chamber is about 1.5 years.

Emission payback period

The global warming potential (GWP) of 1 m^2 area of FPSC is estimated to be approximately 722 kg equivalent of CO_2. The annual equivalent of CO_2 saved due to use of heat energy collected by FPSC for desalination is estimated to be 407 kg equivalent of CO_2; on the behalf of specific global warming factor of 0.0657 kg equivalent of CO_2 per MJ of valuable thermal energy[22]. The equivalent CO_2 emission for production of FPSC is about 24.85 tons, on basis of 722 kg equivalent of CO_2. So, the GWP of FPSC for the desalination system will be recuperated in 1.8 years with yearly CO_2 equivalent emission savings of 14 tons.

The GWP for production of 1 kg of hot dip galvanized steel is estimated to be approximately 2.5 kg equivalent of CO_2[18]. The equivalent CO_2 emission for production of vacuum chamber using galvanized steel is about 0.16 tons, on basis of 63.75 kg mass of vacuum chamber. The annual equivalent of CO_2 saved due to use of thermal energy saved by vacuum chamber for desalination is estimated as 76.74 kg equivalent of CO_2; using the specific global warming factor of 0.0657 kg equivalent of CO_2 per MJ of valuable heat energy[22]. Hence, the GWP of vacuum chamber for thermal desalination system will be recuperated in about 2.1 years with yearly CO_2 equivalent emission savings of 0.0767 tons.

RESULTS AND DISCUSSION

The economic analysis of the investments and energy and emission payback (EEP) periods of the thermal desalination system are evaluated for a pilot plant of 50 litres per day with 8 hours of operation. The cost comes out to be US$ 0.0147 per kg of desalinated water. EEP period for FPSC is 1.3 years and 1.8 years respectively. EEP period for vacuum chamber is 1.5 years and 2.1 years respectively. The cost of desalinated water (US$ 0.0147/L) is less than the half of the value of desalinated water from the solar stills (US$ 0.034/L)[15]. The EEP periods of FPSC and vacuum chamber are also lesser than the total estimated life of the plant. Therefore, the evaluated system has better economic feasibility and less environmental degradation as compared to those of conventional desalination systems.

Table 1: Break down cost of solar thermal desalination system

Sr. No	Item	Description	Qty	Cost (USD)
1	Evaporator	0.1256 m2 cross sectional area , 1 m length	1	120
2	Condenser shell	0.1256 m2 cross sectional area , 1 m length	1	120
3	Condenser Cu-Ni coil	3 meter length and 0.984 mm inner diameter	1	10
4	Ball Valves	1.97 mm outer diameter	5	10
5	Sockets	1.97 mm inner diameter	5	5
6	Vacuum gauge	1.97 mm outer diameter	1	10
7	Pipe with small holes	0.75 meter length, holes of 0.984 inch diameter	1	5
8	PVC piping	25 m length and 1.23 mm inner diameter	1	25
9	Storage tanks	50 litre capacity	4	40
10	Solar heater	200 litre capacity	7	1910
11	Pumps	12 V DC, 500 W, pump	1	25
12	Structure	10 m height	1	65
13	Labour	For machining and welding	-	30
Total Cost				2,600

Table 2: The specifications of the pilot plant

Sr. No	Quantity	Estimated Value	Unit
1	Desalinated water	50	L/day
2	Initial Investment	2600	US$
3	O&M Cost	300	US$
4	Replacement Cost	100	US$
5	Salvage Value	0	US$
6	Plant Availability	90	%
7	Interest Rate	5	%
8	Amortization Factor	0.080843	-
9	Annual Instalment	24.7278	US$
10	Payback Period	20	Years

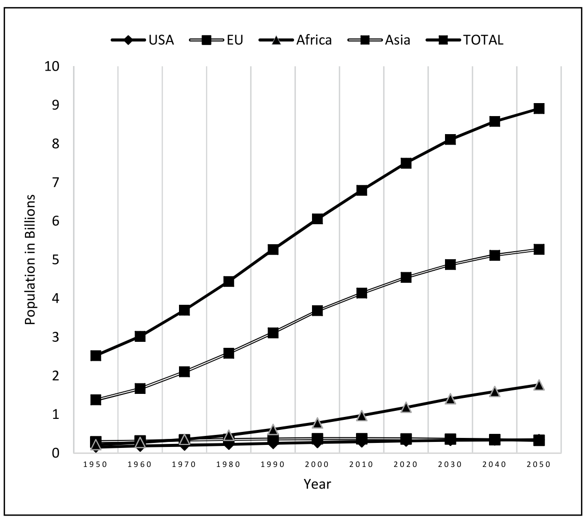

Fig. 1: Forecast of population in the world[6]

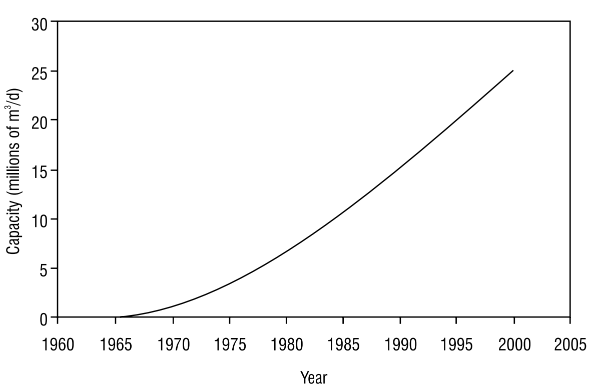

Fig. 2: Installed desalination capacity in the world[4]

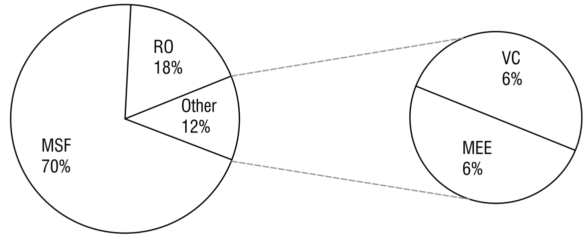

Fig. 3: Market share of different seawater desalination technologies[1]

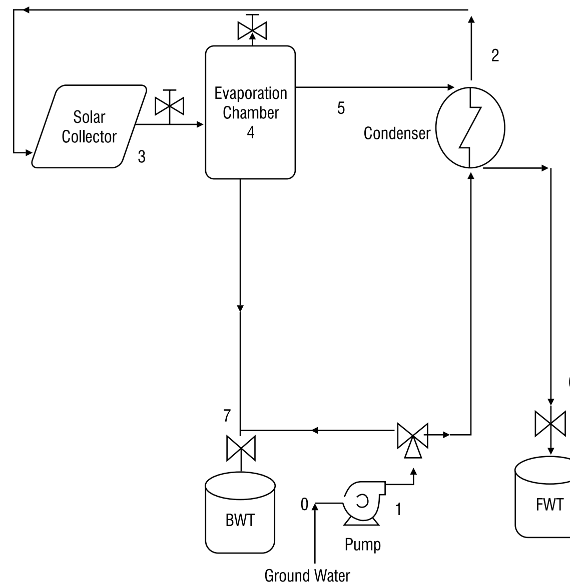

Fig. 4: Process pattern of desalination system

CONCLUSION

The LCCA and EEP analysis of major components of system show that system is economically viable and environmentally friendly as compared to other conventional desalination systems especially for islands, coastal and remote arid areas where grid electricity is not available. The utilization of solar energy, latent heat of condensation and passive vacuum concept are found to be a promising approach to address the problem of water scarcity in efficient, economic and sustainable manner. Therefore, it is one of the potential cleanest sources of conversion of seawater into potable water as compared to conventional desalination systems.

REFERENCES

1. *Demira, M.E., Dincera, I., (2017), "Development of an integrated hybrid solar thermal power system with thermoelectric generator for desalination and*

power production", Desalination, Vol. 404, pp. 59–71

2. Ko, M. J., (2015), "Analysis and Optimization Design of a Solar Water Heating System Based on Life Cycle Cost Using a Genetic Algorithm", Energies, Vol. 8, pp.11380-11403.

3. Aberuee, M.J., Baniasadi, E., Rad, M. Z., (2017), "Performance analysis of an integrated solar based thermo-electric and desalination system", Applied Thermal Engineering, Vol. 110, pp. 399–411.

4. Zubaira, M. I., Sulaimana, Antara, M.A., Dinia, S.A., Ibrahim, N. I., (2017), "Performance and cost assessment of solar driven humidification dehumidification desalination system", Energy Conversion and Management,Vol. 132, pp., 28–39.

5. MacLaughlin, Candace, (2000), "IDA Worldwide Desalting Plants Inventory", International Desalination Association, USA.

6. Coroneos, C., Dompros, A., Roubs, G., (2007), "Renewable energy driven desalination system modeling", Journal of Cleaner Production, Vol. 15, pp. 449-464.

7. Delpla, I., Jung, A.-V., Baures, E., Clement, M., Thomas, O., (2009), "Impacts of climate change on surface water quality in relation to drinking water production", Environment International, Vol. 35, No. 8, pp. 1225–1233.

8. Fiorenza, G., Sharma, V.K., Braccio, G., (2003), "Techno-economic evaluation of a solar powered water desalination plant", Energy Conversion and Management, Vol. 44, pp. 2217–2240.

9. W. H. Organization, (2005). "Regional overview of wastewater management and reuse in the Eastern Mediterranean Region", Regional Office for the Eastern Mediterranean.

10. "Population: Annual time series", (2000). [Online]. Available: http://faostat.fao.org. accessed on 07/10/2014.at 14PST….

11. Matan Beery, Gunter Wozny, Jens-Uwe Repke, (2010). "Sustainable Design of Different Seawater Reverse Osmosis Desalination Pretreatment Processes", Computer Aided Chemical Engineering, Vol. 28, pp. 1069–1074.

12. Kalogirou, S., (2005). "Seawater desalination using renewable energy sources", Progress in Energy and Combustion Science, Vol. 31, No. 3, pp. 242-281.

13. Al-Kharabsheh, S., Goswami, D.Y., (2004). "Theoretical Analysis of a Water Desalination System Using Low Grade Solar Heat", Journal of Solar Energy Engineering, Vol. 126, No. 2, pp. 774-780.

14. Gude, V.G., Nirmalakhandan, N., Deng, S., Maganti, A., (2012), "Low temperature desalination using solar collectors augmented by thermal energy storage", Applied Energy, Vol. 91, pp. 466-474.

15. Maroo, S.C., Goswami, D.Y., (2009). "Theoretical analysis of a single-stage and two-stage solar driven flash desalination system based on passive vacuum generation", Desalination, Vol. 249, pp. 635-646.

16. Beamer, J.H., Wilde, D.J., (1971). "The simulation and optimization of a Single Effect MSF desalination plant", Desalination, Vol. 9, No. 3, pp. 259-275.

17. Howe, E., (1974)."Fundamental of Water Desalination", New York: Marcel Dekker.

18. Ayhan, T., Al-Madani, H., (2010). "Feasibility study of renewable energy powered seawater desalination technology using natural vacuum technique", Renewable Energy, Vol. 35, pp. 506-5014.

19. Ranjan, K.R., Kaushik, S.C., (2013). "Economic feasibility evaluation of solar distillation systems based on the equivalent cost of environmental degradation and high grade energy savings", International Journal of Low-Carbon Technologies, pp. 48.

20. Tiwari, G.N., Singh, H.N., Tripathi, R., (2003). "Present status of solar distillation", Solar Energy, Vol. 75, pp. 367-373.

21. Ardenate, F., Beccali, G., Cellura, M., Brano, V., (2005), "Life cycle assesment of a solar thermal

collector: sensitivity analysis,energy and environmental balances", Renewable Energy, Vol. 30, pp. 109-130.

22. *Bourg, R., (2011), "Life cycle assessment methodology report", World Steel Association.*