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Techno-economic analysis of solar stills using integrated fuzzy analytical hierarchy process and data envelopment analysis

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ABSTRACT

Desalination using solar stills is an ancient economic method for water desalination. Over the years, research and development in the area of solar still has resulted in increased distillate yield by means of integration of PCM (phase change material), photo-voltaic thermal (PVT), etc with the still. Nano-PCM is an upcoming technology which modifies the thermal performance of PCM. The aim of this research is to analyze the efficiency of 20 solar stills including nano-PCM based solar stills considering various input and output criteria using integrated fuzzy analytical hierarchy process (AHP) and data envelopment analysis (DEA). The efficiency derived here is relative with regard to the parameters and stills considered in this study. The result infers that, even though the productivity of stepped solar still with sun tracking system was high, but when techno-economic aspects were considered it is not among the top solar stills. The analysis indicated pyramid type solar still, single slope solar still with PVT, solar still with NPCM (paraffin + copper oxide), solar still with NPCM (paraffin + titanium dioxide) and solar still with PCM (paraffin) occupies the top five positions with relative efficiency of 100, 100, 88.47, 88.46 and 76.93% respectively.

1. Introduction

Solar desalination is a type of desalination process in which evaporation and condensation processes are driven by solar energy. Among the various types of solar desalination processes, solar stills are significant because of their low environmental impact, technical simplicity, low capital and maintenance cost (Dsilva Winfred Rufuss et al., 2016). Solar still can be used in extremely adverse environments, where there is no source of power for running the otherwise efficient desalination process (Dsilva Winfred Rufuss et al., 2016). Various researchers have modified the conventional solar still to improve its productivity. However this led to an increase in capital and maintenance cost. Studies carried out by earlier researchers (El-Bialy et al., 2016; Kabeel et al., 2010) determined the various costs of solar stills. However, there is no study found in the literature review so far which presents an optimized multi-criteria decision model (MCDM) that considers various criteria such as cost, employee's skill, productivity and technical features of solar stills. These aspects need to be considered to ascertain the importance of each criteria for the selection of an ideal solar still that can be taken up for commercialization. This paper focuses on the MCDM approach to analyze the relative efficiency of solar stills based on various input and output criteria using an integrated fuzzy analytical hierarchy process (AHP) model.

There are various criteria/parameters influencing a solar still such as atmospheric condition, design and economics. Atmospheric condition includes weather, ambient temperature, location, and latitude/longitude degrees. The design aspect includes area, glass cover inclination, brine depth, solar intensity, productivity, salt concentration and insulators. Economic aspects include present capital cost, annual maintenance/operational cost, annual salvage value and cost of distilled water per litre. Hence selection of a solar still for commercialization needs to be done by considering such parameters as mentioned above. In this paper, fuzzy analytical hierarchy process (AHP) and data envelopment analysis (DEA) techniques are used to optimize some of the above mentioned parameters to arrive at an efficiency for each still relative to the parameters considered. Generally, technical (thermodynamic) efficiency will be used in the comparison of solar stills which considers only the technical aspects. In this study in addition to technical aspects other parameters are considered and the efficiency is obtained relative to the parameters and the stills considered. Technical efficiency is an absolute efficiency that can be compared across various stills while relative efficiency is constrained within the parameters used

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and the stills used in the study.

Many researchers have used fuzzy AHP techniques in desalination systems like multi-stage desalination (MSD), reverse osmosis (RO), multi-stage flash desalination (MSF), vapor compression (VC) and multi-effect distillation (MED). Fuzzy logic was used in controlling the upper saline water temperature of MSD plants. The research also focused on controlling various parameters for implementing MSD plants in the selected location (Ismail, 1998). Various operational constraints was adopted for implementing a RO desalination plant using fuzzy logic. The proposed methodology resulted in profit for the plant by increasing the availability and decreasing the manpower requirement for RO implementation (Zilouchian and Jafar, 2001). Fuzzy logic was adopted for analyzing MSF and RO systems using various control parameters like brine salinity, pre-heating (Gambier and Badreddin, 2003). Water potential was assessed for irrigation and human consumption using fuzzy logic. It was found that the water used for irrigation is more important than for human consumption (Tsakiris et al., 2009). Major factors which affect the daily productivity of solar still was analyzed using fuzzy logic (Mamlook and Badran, 2007). The same authors (Mamlook and Al-Rawajfeh, 2008) extended the research by using fuzzy logic to analyze which of those factors affect the productivity of MED. The various factors considered in their research included top saline water temperature, pH, temperature and salinity of the sea water. The AHP was used to determine the most suitable desalination process considering seven factors. The desalination processes considered in the research include MSD, MSF, RO and VC. The factors considered were water quality, recovery ratio, consumption of energy, efficiency of instruments and total cost (Hajeeh and Al-Othman, 2005). Various water conservation policies in Kuwait was analyzed using fuzzy AHP. Reusing treated brine water, promoting water conservation were some of their recommendations (Hajeeh, 2010). It is found from the literature that researchers have used fuzzy (Gambier and Badreddin, 2003; Ismail, 1998; Mamlook and Al-Rawajfeh, 2008; Mamlook and Badran, 2007; Tsakiris et al., 2009; Zilouchian and Jafar, 2001), AHP (Hajeeh and Al-Othman, 2005), fuzzy AHP (Hajeeh, 2010) in desalination systems.

Integrated fuzzy AHP DEA approach can be used in energy related areas like solar photovoltaic, solar thermal, wind, desalination, power stations, materials and metallurgical applications to determine the weights of influencing parameters and to find the relative efficiency among a set of energy systems. Some researchers used fuzzy for finding the efficiency frontier in petrochemical industries (Taylan et al., 2016), generation sector (Mojallizadeh and Badamchizadeh, 2017; Tanha Aminloei and Ghaderi, 2010; Yu and Dexter, 2010). AHP was used for categorizing frontier energy industries in manufacturing sector (Jovanović et al., 2015) and integrated fuzzy AHP DEA approach has been used (Criswell and Thompson, 1996; Lee et al., 2013, 2011) for finding the relative efficiency of energy technology and hydrogen energy technologies.

Fuzzy logic helps in arriving at concrete estimates despite the vagueness of human thought. AHP helps in obtaining the relative weights for a set of critical attributes. The benefits of integrating fuzzy logic and AHP is to achieve precision in determining the relative importance of criteria and to develop a hierarchal structure for the multi-criteria decision making purpose. It can handle both linguistic assignment and numerical values. The benefits of applying an integrated fuzzy AHP approach to solar still is to determine the relative importance/weights of criteria that affects the performance and efficiency of solar still. DEA is a benchmarking technique employed to know the frontier in the selected area by estimating the relative efficiency of various decision making units (DMU). The benefits of integrating fuzzy AHP and DEA are to find the relative efficiency of DMU considering the weights of criteria obtained from fuzzy AHP. The advantage of implementing such an approach in solar still is to rank and prioritize the important criteria which is involved in the performance, efficiency and productivity of a solar still. Also, the relative efficiency of various solar stills by considering both technical and economic factors can be determined by giving due importance to the influencing criteria. The main objective of other techno-economic analysis (TEA) such as top-down or bottom-up cost approach is to determine the cost and technical feasibility of a particular system (here solar still) and compare the results. In this paper, the integrated approach (fuzzy AHP DEA) is a step ahead i.e., it helps to evaluate the relative efficiency of various solar stills considering several criteria simultaneously to arrive at an optimal decision. The pros of the integrated fuzzy AHP DEA are: comparative analysis of different variant of targets (here solar stills), any measurable criteria for all variant of solar still can be used in DEA, reverse coding of input and output criteria is possible, improvement criteria for the selected parameters can be identified and implemented, human preference can also be incorporated in DEA and fuzzy AHP DEA can be incorporated as a complement to other techniques. As every approaches have some cons associated with them, similarly this integrated fuzzy AHP DEA also has some cons such as: difficulty arises if there is a missing value in the dataset and weak assumption in DEA may lead to underestimation of the relative efficiency of decision making units.

It is concluded that, even though various researchers used fuzzy and AHP techniques in desalination systems, no one has used an integrated fuzzy-AHP-DEA analysis for analyzing the different solar stills. Hence this research gap is addressed in this paper in addition to analyzing the innovative nano-PCM based solar stills from a techno-economic viewpoint. Nanoparticles were incorporated with PCM to modify its thermal properties like thermal conductivity, latent heat of vaporization and decreasing its charging and discharging rate (Dsilva Winfred Rufuss et al., 2017; Kamaraj et al., 2016). Even though nanoparticles improve the thermal properties of PCM in solar still, economic feasibility of the solar still with nano-PCM is one of the essential parameter that needs to be analyzed. Three input criteria namely fabrication/installation cost, skilled labour requirement and land area requirement are considered along with four output criteria namely annual cost, commercial potential, annual productivity and technical complexity. An integrated fuzzy-AHP-DEA analysis is carried out to determine the relative efficiencies of 20 solar stills (for which the data is available for the parameters considered). Also, the relative weights of each criteria and their importance with reference to a particular still are determined.

2. Solar stills

Desalination is an essential response to the growing water scarcity problem. It has been reported in our previous paper (Dsilva Winfred Rufuss et al., 2016) that, by the year 2030 half of the world population will experience severe water crisis. There are various desalination process available to desalinate the saline water, of which solar still holds its significance owing to its enviro-economic friendly nature (Kaushal and Varun, 2010; Sathyamurthy et al., 2017; Velmurugan and Srithar, 2011). Solar stills work by the evaporation and condensation processes similar to natural rain. A detailed classification of the desalination process and solar stills are represented graphically in Figs. 1 and 2 respectively. Low productivity is a major drawback in solar stills, and hence extensive research work has been carried to improve the productivity by modifying the design and operational parameters (Ahsan et al., 2012; Arunkumar et al., 2013, 2012; Gaur and Tiwari, 2010; Murugavel et al., 2010; Rahbar et al., 2016; Sakthivel et al., 2010; Sharshir et al., 2016). The various design and operational parameters are comprehensively listed in Fig. 3.

The basic model of solar still is called a simple single slope solar still. This does not have any enhancements present for augmenting the productivity. The setup of simple single slope solar still is depicted in Fig. 4.

Researchers tried to add various components like sun tracker (Abdallah et al., 2008), photo-voltaic-thermal (PVT) (Kumar and Tiwari, 2009), collector (Badran and Al-Tahaineh, 2005), concentrator (Abdel-Rehim and Lasheen, 2007) and fin (Velmurugan et al., 2008a) to