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Design, construction, and operation of the first industrial salinity-gradient solar pond in Europe: An efficiency analysis perspective

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ABSTRACT

A 500 m^2 industrial salinity-gradient solar pond (SGSP) was constructed in a mineral processing plant (Solvay Minerales) in Granada (Spain). This renewable energy technology was designed to supply a low-temperature heat (up to 60 °C) to achieve the temperature requirements of the flotation mineral purification stage. The low-temperature source was integrated to partially replace the fuel oil boiler used to heat the water used in the flotation stage. Theoretical calculations based on solar radiation indicated that the use of the SGSP would reduce the annual fuel consumption by more than 50%, thus providing a significant improvement at both economic and environmental levels. Two months after the SGSP was established, in August 2014, the temperature in the storage zone of the SGSP reached approximately 90 °C. The overall performance was evaluated in two periods (2014 and 2015) in terms of the retrofitting of mining facility with a solar pond and a new method to assess the thermal efficiency of the solar pond in a long-term perspective has been proposed. The overall efficiencies obtained after the first and second operation periods were 10 and 12%, respectively, with maximum values of 28 and 24% obtained during the first operation months. Regarding the economic savings, the fuel oil cost of the flotation unit was reduced by a higher percentage than the fuel oil consumption, due to the decreasing tendency of fuel oil prices during 2014 and 2015. Reductions of 52 and 68% were obtained in the first and second periods of operation, respectively, when compared to 2013. In addition, not only does the SGSP have considerably reduced operating costs but also the environmental costs are clearly reduced when considering the reduction of CO_2 emissions.

1. Introduction

The emission of greenhouse gases and their impact on climate change are of major concern nowadays. Solar energy is promoted as one of the most promising substitutes for traditional energy resources; however, its intermittent and unstable nature is a major drawback, which leads to a disparity between supply and demand (Valderrama et al., 2016; Yu et al., 2013).

Solar ponds are classified into the category of a solar thermal system, functioning as both a collector and a storage facility of solar energy for future use. Solar ponds have been investigated extensively over the past decades. The characteristics that make them attractive are, first, the capacity for long-term storage, which can supply sufficient heat for the entire year, and second, the annual collection efficiency in the range of 15–25% for all locations and the capacity to supply adequate heat even at higher latitudes. A solar pond consists of three distinct zones. The first is located at the top of the pond and contains the less dense salt/water mixture; this is the upper convective zone (UCZ), which has the function of protecting the salinity-gradient layer. In the second zone, the salt/water density varies, increasing with depth; this is the gradient zone or non-convective zone (NCZ), also called the salinity-gradient layer. The main purpose of this zone is to act as an insulator to prevent heat from escaping to the UCZ, thus maintaining higher temperatures in the deeper zones. The third zone is the lower convective zone (LCZ), also called the energy storage zone, which consists of saturated brine with almost homogeneous salinity and density. The heat stored in the LCZ can be used as a heat source for the heating of buildings, power production, and industrial processing or

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Table 1
Successful experimental solar ponds reported in the literature during the last 5 decades.

		Name/site	Construction year	Area (m^2)	Maximum temperature (LCZ)	Applications	References
Israel	Eilat	Ein Boqek solar pond	1977	6250	85–90	Electrical production	Tabor and Doron (1986)
		Beith Ha'rava solar pond	1982	25,000		Electrical production	Tabor and Doron (1990)
USA	Ohio	Ohio State University		200	62–69	Pilot Plant (research)	Rabl and Nielsen (1975)
		Ohio State University		400		Pilot Plant (research)	Nielsen (1980)
		Ohio Agricultural Research and Development Centre	1977	156	46	Heating building (Greenhouse)	Fynn (1981)
		Miamisburg	1978	2020	51.1	Heating building (Swimming pool and recreational building)	Shah et al. (1981), Bryant et al. (1979)
	New Mexico	University of New Mexico (Albuquerque)	1975	175	93	Heating building (House)	Wilkins et al. (1986), Zangrando (1991)
	Texas	University of Texas (El Paso)	1983	3355	72	Industrial process heat (food canning factory); Desalination, electrical power production	Reid et al. (1985), Swift et al. (1987), Liao et al. (1988), Hull and Nielsen (1988)
	Illinois	University of Illinois	1987	2000	70	Heating building (swine research facility)	Newell et al. (1990)
India	Bhavnagar	Central Salt and Marine Chemicals Research Inst.	1970	1200		Pilot Plant (research)	Srinivasan (1993)
		Institute's experimental salt farm	1980	1600	75	Pilot Plant (research)	Mehta et al. (1988)
	Bangalore	Institute of science in Bangalore (Pondicherry)		100	70	Pilot Plant (research)	Patel and Gupta (1981)
		Indian Institute of Science	1984	240	50–70	Pilot Plant (research)	Srinivasan (1990), Akbarzadeh and Manins (1988)
	Karnataka	Masur		400		Heating building (Rural community)	Srinivasan (1993)
		Hubli		300		Heating building (To supply hot water for college)	
	Gujerat	Khuj Dairy (Bhuj)	1987–1991	6000	99.8	Industrial process heat (Milk processing dairy plant)	Kumar and Kishore (1999)
Australia	Aspendale (Victoria)	Commonwealth Scientific and Industrial Res. Org.	1964	44	63	Pilot Plant (research)	Davey (1968)
	Laverton (Victoria)	Cheetham Salt Works	1981	900		Pilot Plant (research)	Golding et al. (1982)
	Alice Spring	Northern Territory	1980	2000	80	Electrical power production	Collins (1984)
			1984	1600	80–85	Electrical power production	Sherman and Imberger (1991)
	Pyramid Hill (Victoria)	Pyramid Salt Ltd facility/RMTI University	2000	3000	62	Industrial process heat	Leblanc et al. (2011)
Other countries	Argentina	Puna	1981	400		Chemical production	Lesino et al. (1990), Lesino and Saravia (1991)
	Italy	Margherita Di Savoia		25,000		Desalination	Folchitto (1997)
	China	Zabuya Lake (Qinghai Tibet Plateau)		2500	39	Chemical production	Nie et al. (2011)
	Spain	Solvay Martorell (Catalonia)	2009	50	63	Pilot Plant (research)	Valderrama et al. (2011), Bernad et al. (2013), Alcaraz et al. (2016)