JFET 22(2) (2015) 69-79

Journal of Faculty of Engineering & Technology

journal homepage: www.pu.edu.pk/journals/index.php/jfet/index

Solar Pond Technology for Brine Management and Heat Extraction: A Critical Review

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Abstract

Heat is one of the basic constituents of energy which can be stored as well as extracted from solar ponds. Different types of solar ponds are available but main focus in this paper is on salinity gradient solar pond which is one of the emerging technologies. It can recover energy from brine water sources present in Pakistan with minimum land utilization and capturing maximum solar radiations. Numerous renewable technological sources are currently under use all across the world. However, inadequate research has been done upon salinity gradient solar ponds, which are cheaper and easy to operate and maintain. The salinity gradient solar ponds constitutes of three layers or zones: lower convective zone with maximum brine concentration, the non-convective zone with highest salinity gradient and upper convective zone which has minimum concentration of brine. The brine water can be sourced from post reverse osmosis or through any other saline water source. Solar pond technologies may have numerous feasible applications including brine management, electricity production and providing heat for different industrial processes. The paper reviews different ways to optimize the efficiency of solar ponds while making it cost effective at the same time. Most of the research on salinity gradient solar ponds has experimented on external heat exchangers in which the heat is usually extracted from lower convective zone. Heat extracted is studied on independent variables such as brine load, height of solar pond, conductivity of heat exchanger, temperature and pH of the water. The heat extracted was further considered for steam generation. The steam could be utilized as a driving force for electricity generation and workability of industrial power plants. The economic feasibility based on the current conditions of Pakistan is also discussed.

Keywords: Salinity gradient solar pond, brine management, sustainable energy, heat extraction.

1. Introduction

Despite resources present in Pakistan, the country is suffering from great setbacks in terms of energy production. It meets the energy demand by importing oil for energy production.

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Most important sources of energy production in Pakistan are oil, gas, hydropower and coal, contributing up to 43.5%, 41.5%, 9.2%, and 4.5% respectively. In terms of electricity production, the primary source is thermal energy that contributes 71.9% of electricity production followed by hydel and then nuclear [1]. However, Pakistan has great potential of switching to renewable energy technologies which have not been properly explored yet. These renewable energy sources comprise of solar, wind, biomass, biogas and also energy from solid waste. However out of these sources the most promising technologies are the one based on solar energy. Being in the Sunbelt, Pakistan receives vast amount of annual solar insolation ranging up to 200-250 W/m^2 with total sunshine hours of 1500-3000 per year [2]. This solar energy can be harvested to fulfill energy requirements of remote areas especially the desert and mountainous areas of Pakistan. Their conditions are ideal for the use of solar technologies such as photovoltaics and solar water heaters.

The most matured of all solar technologies are the photovoltaics that are being used from residential, commercial to industrial scale. It has been adopted on governmental scale from Qaid e Azam Solar power plant to more than 20 solar water pumps being installed in desert areas of Baluchistan. Other than photovoltaic, solar water heaters are very common on residential scale with passive solar heating system. However, due to higher capital cost, these heaters and geysers have not yet commercialized as much as photovoltaics. More research and work is being done on solar cooker by the organizations in Pakistan [3]. Other than these, many other solar technologies are being researched in the institutes of Pakistan to harness the maximum amount of solar energy with minimum capital cost e.g. Salinity Gradient Solar Pond (SGSP).

The government of Pakistan has initiated a program popularly known as the Saaf Paani Project. The project is of vital importance to the people throughout the country. Arrangements are to be made regarding the operations of water filtration plants with the help of solar energy. The main objective of the Saaf Paani is to install around 1324 water treatment plants. These plants are to be installed in six various districts of Punjab. The total of Reverse Osmosis (RO) Plants in this project are 765 [4]. The RO plants treat brackish underground water which can further be treated. However, one thing the government has not taken into account is the fate of the rejected brine from the RO plants. Consequently, the installation of salinity gradient solar ponds can supplement the need of brine management and energy required to operate RO plants with zero waste production.

The districts of Punjab have high annual temperatures and long hours of sunlight, therefore stability of the salinity gradient solar ponds is not difficult to achieve. Thus, by installation of salinity gradient solar ponds, the government of Punjab can meet up the energy deficit and perform brine management without adversely affecting the underground water and the agricultural soil.

1.1 Salinity Gradient Solar Pond Principle

Figure 1 depicts the working principle of salinity gradient solar pond. Brine water from source waste is collected in a pond. Due to settling of salts, concentration gradient is established in the pond which results in three zones based on temperature and concentration difference.

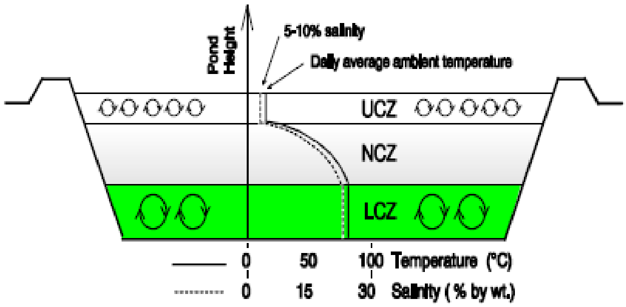


Figure 1. Schematic of Salinity Gradient Solar Pond. Adopted from [5].

The upper convective zone (UCZ) has lowest concentration of salts while the lower convective zone (LCZ) has highest concentration of salts. Salts from the incoming brine water absorb solar radiation and settles down due to which temperature difference is created between the two layers. The absorbed solar energy is stored in the LCZ which is also known as storage zone. Since the thermal conductivity of water is very low, increasing width of non-convective zone (NCZ) acts as a thermally insulating layer. The NCZ keeps the heat trapped in LCZ from where heat exchangers extracts the heat for power generation.

2. Types of Salinity Gradient Solar Ponds

There are mainly four types:

2.1 Salt Gradient Solar Ponds

The salt gradient solar pond concept was first suggested by Dr. Rudolph Bloch in 1948. Salt gradient solar ponds are also known as salinity gradient solar ponds. They are the simplest and easiest to operate from all solar ponds for brine management where solar energy is stored in salt mixtures.

The heat trapped in salt mixtures is extracted by using two methods. Heat from the heated brine can be extracted using an external heat exchanger where cold brine is returned to the pond. In the other method heat exchanger can be placed inside the lower convective zone. Placing heat exchanger inside the pond requires large pond area. Although this arrangement improves the heat exchange efficiency but it would double the repair and maintenance cost due to excessive corrosion of heat exchanger parts.

2.2 Solar Gel Pond

Solar gel pond is another type of solar pond technology, which does not require the salt concentration to be maintained. It contains a thick layer of polymer gel that floats on LCZ. This type of pond is used to avoid thermodynamic heat losses. The density of polymer gel is in between fresh and saline water which allows it to float on the salt solution. About 2–7% salt solution is used in the lower convective zone to keep the gel layer floating on top [6].

Evaporation losses are eliminated in solar gel ponds which reduces the heat losses from surface. Hence they are found to be more advantageous than salinity gradient solar ponds.

However, a limiting factor for the establishment of solar gel pond is its highly expensive gel used.

Figure 2 depicts the first experimental gel pond (18m^2 surface area, 1.22m depth). It was constructed at the University of New Mexico (UNM).

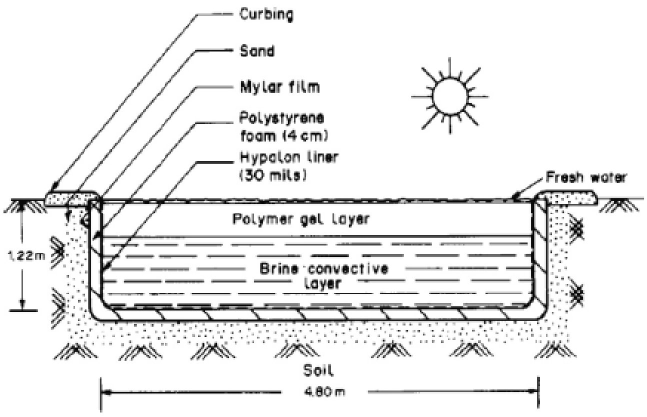


Figure 2. Solar Gel Pond. Adopted from [6]

2.3 Equilibrium Solar Ponds

Equilibrium solar ponds use salts that are highly affected by temperature as their solubility is directly dependent on temperature. The salts which can be used in an Equilibrium solar pond are $Na_2B_4O_7$ (borax), KAl $(SO_4)_2$, $CaCl_2$, $MgCl_2$, and NH_4NO_3 [6].

Equilibrium solar pond has advantage over saturated solar pond that it does not crystallize under the influence of cold temperature

2.4 Shallow Solar Ponds

Shallow solar pond is a solar energy collection system along with short energy storage capacity. It does not require salt gradient layers. It works on the principal of evaporation from brine by bringing it in contact with solar radiations and is similar in working of solar stills. Shallow solar ponds are cheap and simple to build, easier to operate and maintain continuous supply of large amount of heat.

These ponds are small and shallow and have an average depth of 0.04m-0.15m. A plastic film adjacent to the top surface of water is fixed to avoid heat loss from the system.

For industrial and commercial use, The *Solar Energy Group* at the Lawrence Livermore Laboratory (LLL), California has designed the world's first shallow solar pond, where brine water heat energy is used to heat the process water temperatures between 25^{o}C to 60^{o}C. The design is composed of simple plastic bag (5m * 60m) which is filled up to a small depth (100mm) in the water bag. Bag is then covered with insulating fiber glass [7].

Further research on shallow solar ponds suggests that for efficient working of shallow solar ponds, water must be removed from the pond daily for consumption to avoid heat loss [8].

3. Conventional Applications of a Large Scale Salinity Gradient Solar Ponds

3.1 El Paso Solar Pond Project

The project of El Paso Solar Pond was started in 1983. Main purpose of this project was operational research on salinity gradient solar ponds and its demonstration. It was operated at El Paso under the supervision of University of Texas (UT), and is in continued operation since 1985. This pond covers an area of $3000m^2$ and has a depth of 3.25m. The UCZ is 0.7m in depth, NCZ is 1.2m and LCZ is 1.35m. Aqueous solution of sodium chloride is used in the pond [5].

During its operation El Paso solar pond was used for generation of electricity, supplying industrial process heat, desalination and the management of reject brine. For desalination, salinity gradient solar ponds are economically very effective under favorable conditions like availability of saline water, land and the exposure of the land to sun rays as compared to other energy sources (Figure 3 shows the economic comparison). The direct use of reject brine from desalination units like brine concentrator and recovery system (BCRS) is an added application of solar pond technology. It is one of the most important applications of solar ponds if the environmental impacts are taken into account. It is a “zero discharge” system, because this system eliminates the disposal issues of the brine which is rejected from desalination process. The study on El Paso Solar pond demonstrates that application of salinity gradient solar ponds not only provides green energy from desalination waste but it also helps in management of waste brine. Furthermore, the surface water from the solar pond is mostly clear water can be utilized as a cooling source for the process of thermal desalination which can reduce the electricity consumption.

The desalination research at El Paso was completed in two phases. In the first phase solar pond was coupled with desalination technology to find out whether the system is feasible or not, while the second phase was focused to make the solar pond coupled desalination more effective regarding its costs and efficiency. The second phase was also focused on the identification of the important factors that affect the production of distillate and the rate at which energy is consumed [5].

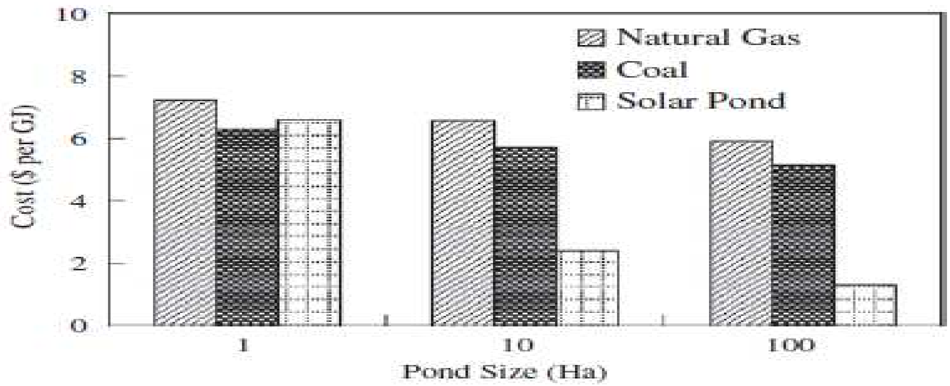


Figure 3. Industrial Heat Cost of Natural Gas, Coal and Solar Pond. Adopted from [5].

Electricity generation is another useful application of salinity gradient solar ponds but it is less cost effective than currently used electricity generation technologies. However, the cost of electricity generation by salinity gradient solar ponds can be reduced to a great level if the pond size is increased as shown in Figure 4.

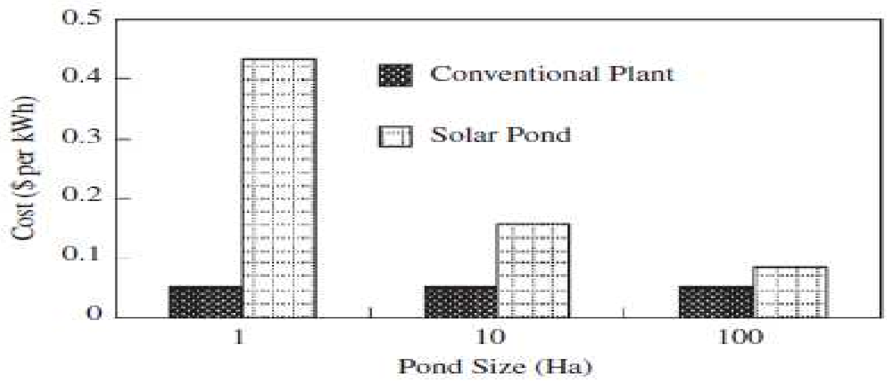
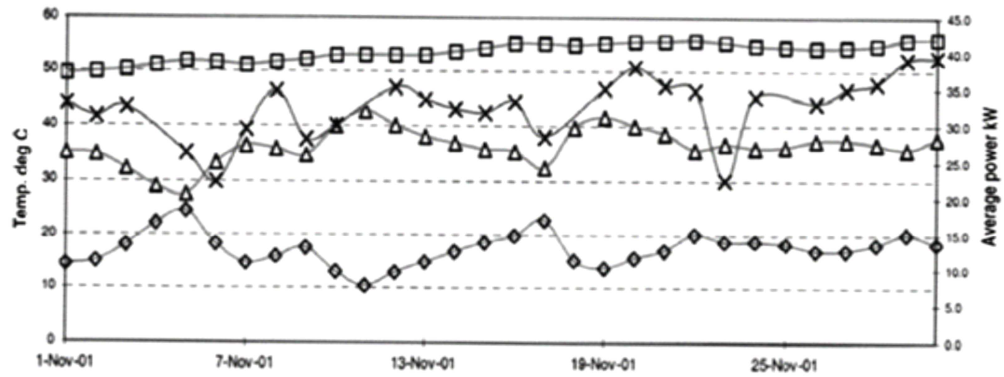


Figure 4. Comparison between Cost of Electricity of Conventional Plant and Solar Pond. Adopted from [5].

3.2 Pyramid Hill Solar Pond

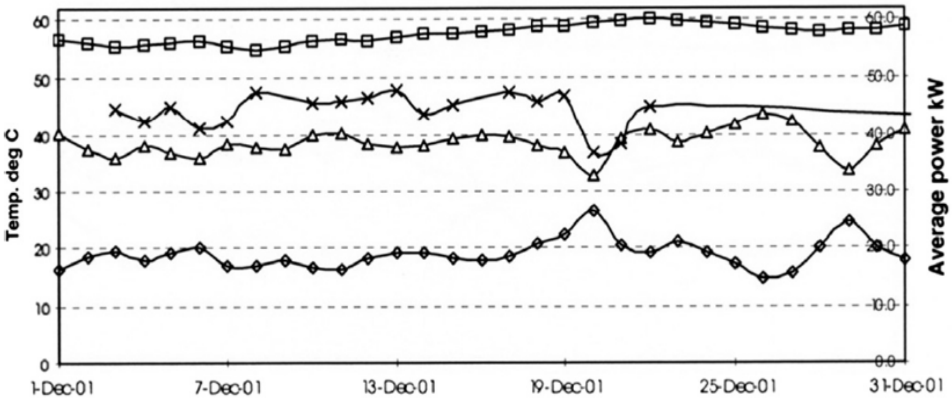
Another process efficient example of salinity gradient solar pond is of Pyramid Hill solar pond, Australia. The major applications of Pyramid Hill solar pond include; providing heat for production of salt, to grow small fairy shrimps known as brine shrimps, and thermal desalination. For salt production the heating system provides air at 45°C for use in crystallization. The average rate at which heat was delivered to the application site was different at different times. It is clear from the figure 5, 6, and 7 that the average temperature of LCZ raised from 56°C in November 2001 to 60°C in December 2001, and then dropped to 55°C in February 2002 [5]. The drop in temperature occurred probably because of extra water added to the upper layer of pond to compensate evaporation losses.



Daily avg. ambient temp., Daily avg. pond temp., Daily avg. temp. diff. (pond and ambient)

Average Power

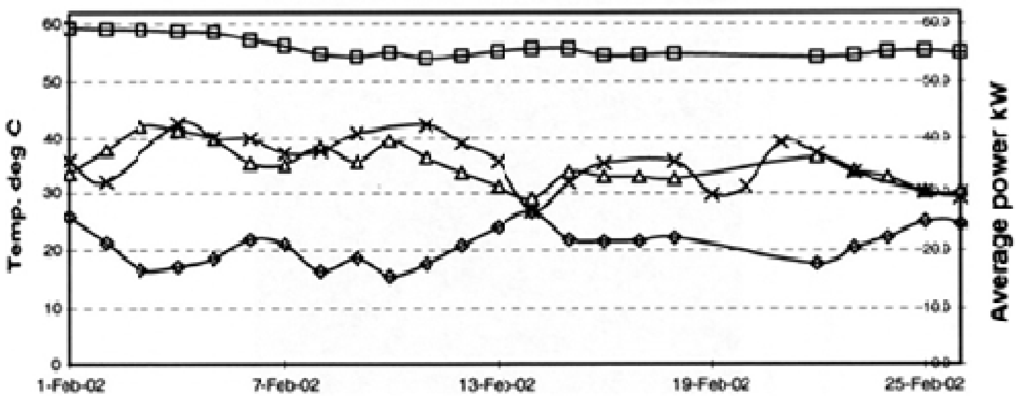
Figure 5. Daily Average temperature of Ambience, LCZ and difference between both in November. Adopted from [5].



Daily avg. ambient temp., Daily avg. pond temp., Daily avg. temp. diff. (pond and ambient)

Average Power

Figure 6. Daily Average temperature of Ambience, LCZ and difference between both in December. Adopted from [5].



Daily avg. ambient temp., Daily avg. pond temp., Daily avg. temp. diff. (pond and ambient)

Average Power

Figure 7. Daily average temperature of Ambience, LCZ and difference between both in February. Adopted from [5].

4. Important Parameters to Study Salinity Gradient Solar Ponds

Parameters like pond volume, brine concentration, pond height, air velocity on the water surface and role of liners to trap heat can impact SGSP efficiency in the local weather. These parameters can be studied by setting up a laboratory or pilot scale salinity gradient solar pond. However, in this work discussion of universal parameters are considered.

4.1 Pond Covers and Light Reflectors

The heat trapping in solar pond depends directly on the surface area exposed to sunlight. Impact of solar reflectors have been reported in detail to give an increase in solar pond efficiency. Reflectors help to trap more energy within the system, thereby facilitate to give more heat extraction. Cover is another essential component of solar pond which only traps heat but does not reflect light back into the pond as done by the reflectors. Figure 8, shows effect of heat trapping with and without the use of reflectors in the solar ponds. Considerable increase in the heat trapped is achieved when both covers and reflectors are used.

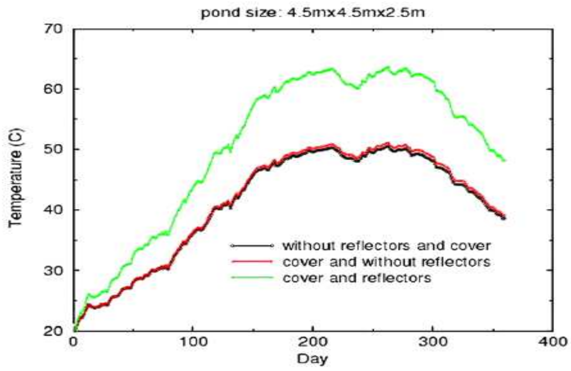


Figure 8. Relation of Temperature with Presence of Reflector and Covers. Adopted from [9].

4.2 Air Velocity

Air velocity plays an important role in keeping the gradient zone stable. The principle of maintaining stable zone is to suppress the convectional currents among all the layers. Therefore, a minimum velocity effect is desired which would otherwise induce surface currents that may lead to mixing of layers, resulting in reduction in effectiveness of heat extraction from SGSP. According to research based on heat pipe heat exchangers (HPHE), if the mean air velocity is decreased from 5 to 1m/s then a drastic increase in thermal efficiency is achieved [10]. Figure 9 illustrates the effectiveness of heat transfer with the decrease in mean air velocity. Specially designed rings can also be placed on the UCZ to reduce convection currents. Typical rings are made of high density polyethylene (HDPE) having thickness of 1.5mm and width of 35mm [5].

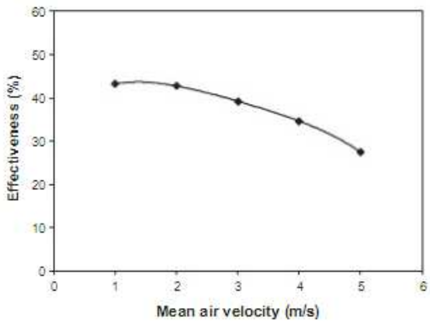


Figure 9. Effectiveness of SGSP against mean air velocity. Adopted from [10].

4.3 Brine Density against Elevation

In solar pond the concentration of brine solution is minimal in UCZ and it increases with depth in NCZ. Thus, the concentration becomes maximum and constant throughout the LCZ, so the density of the brine is also minimum at UCZ and maximum at LCZ. In NCZ the density increases with the increase in depth as shown in the figure 10. The density of UCZ becomes equal to pure water since fresh water is continuously added from top [10]. In sum, as the density gradient increases with respect to elevation, energy storage in the LCZ also increases.

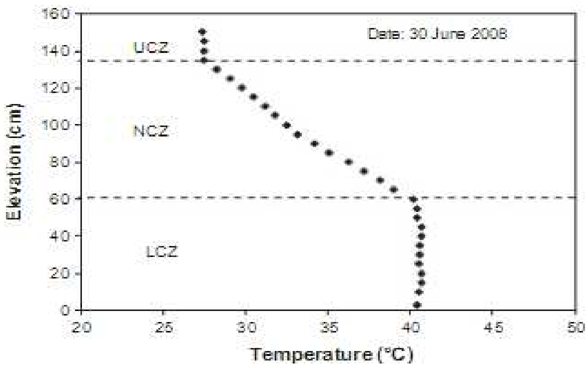


Figure 10. Temperature variation in difference parts of SGSP with respect to elevation. Adopted from [10].

5. Conclusions

Most of the study on salinity gradient solar ponds is done in European countries and United States where temperature variance is limited. Research studies in countries like Pakistan should be performed as the potential of these solar ponds is greater where sun shines for longer hours in a day and over seasons. Thus keeping in view the climate of Pakistan, salinity gradient solar pond technology has great potential in use and application all over the country. In various parts of Punjab and Sindh the distribution of global solar radiation is more than 60% at the average which shows the potential of this technology use in sub-continent [11]. Moreover, the groundwater of certain areas of Punjab and Sindh has high concentration of salts that may also be used to extract heat for electricity generation and industrial purposes. Salinity gradient solar ponds has greatest potential in desert and warm areas of Pakistan that receive the solar radiations up to 23.6MJ per day at maximum [12].

It also has application in industries where brine water is rejected from processes and needs proper disposal like reverse osmosis plants for water treatment.

Major RO plants in Pakistan	RO plant capacity - Gallons Per Day	Salt Concentration of Water-mg/ L
Site: Asia board (For Boiler) Location: Norida bad	2,50,000	---
Mianoor Industries (Pvt.) Ltd. Location: Karachi	150 000	4526
Site: Gawadar Port Authority Location: Gawadar	100000	61724
Site: British Petroleum Location: Badin, Sindh	50 000	---
Site: Engro Foods Pvt. Ltd Location: Sahiwal	63000	1800-2300

Table 1: Major RO plants in Pakistan. Adopted from [13], [14], and [15]

In sum, the potential of installing a large scale salinity gradient solar pond is immense. It can bring Pakistan to a new platform in the field of science and technology as there is a vast possibility of research in this area. Study on salinity gradient solar ponds will also provide an incentive to stakeholders of Saaf Paani Project for brine management and to fulfill their energy requirements for operating reverse osmosis plants.

The Government of Pakistan should embark on this venture by building strong relations with the people of academia. Research funding should be considered for universities so that optimized results for the progress of salinity gradient solar ponds can be considered, before wide scale reverse osmosis plant installations in the country.

Acknowledgements

The authors greatly acknowledge the financial support from Water Aid in Pakistan for this study project titled “WASH Action Research with Academia”.

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