The Economic Analysis of Portable Photo-Voltaic Reverse Osmosis (PVRO) System

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Abstract-A reverse osmosis system was designed and powered by photovoltaic panels for the production of potable water. Elements of system design and integration were identified and optimized. These include capacity planning, standalone capabilities by providing battery storage system and economic analysis. The experimentation on the system, performed in the premises of Mechanical Department of UET Lahore-KSK Campus has proven that unit operated with successful throughput of 5.9 l/h for 5 hours with battery based and 3.8 l/h for 7 hours using battery less system. The battery-powered and direct solar operation modes were tested and in either case the system proved its worthiness. The cost comparison has been presented as well which clearly identifies that it as a cost effective energy efficient portable desalination system.

Keywords-Battery Based, Battery Less; Desalination; Photovoltaic ;PVRO.

I. INTRODUCTION

Most of the water on earth is either saline or undrinkable without extensive processing [i-iii]. Clean water supplies are not sufficient to cover the daily need of potable water for all the people in the world. The alternate solution to address this problem, is processing the sea or brackish water for excess salt content removal, so that it can be used to compensate the need [iv]. The desalination process involves excess investment on infra-structure, and high energy consumption as well. Using a desalination process in remote areas is also quite difficult and there is no viable solution which can replace it [v]. Hence there is a need to optimize the desalination set-up for use in arid areas. The economic feasibility of Photo-Voltaic Powered Reverse Osmosis (PVRO) plants has slowly proved its competitiveness and feasibility with advances in photovoltaic and Reverse Osmosis(RO) setups, each in its respective field [vi-viii]. The cost of the PVRO plants compare reasonably with the diesel fuel plants but do not compete in efficiency at some limited periods where solar radiation is either unavailable or unpredictable. Although the initial cost of the PVRO plants is high as compared to that of diesel based RO plants but in turn the maintenance and operation cost of the PVRO plants is relatively low. Moreover, skilled man-power at remote areas is also a problem. Operating a PVRO is ease as compared to diesel RO plants [ix].The energy consumption directly affects the cost-effectiveness and feasibility of using desalination technologies for drinking water production [x]. Bilton and Wiseman have described the feasibility of the PVRO plant in comparison to RO plants that work on diesel. The economic evaluation is done by comparing the cost of water used for PVRO plant and the cost of the water used for RO plants working on diesel as a fuel. It was found out after the analysis of a typical site that if the solar energy is abundant, the PVRO is appropriate to use while working with either sea water or under-ground water [xi]. Small scale PVRO plants can provide water in remote areas where drinking water is a problem and supply of drinking water is either costly or difficult due to some restrictions. Variation in solar resource, local government policies, water type can affect the feasibility of plants installed. Natural resource of water could be a problem [xii]. The economic feasibility of PVRO plants is a function of location. The efficiency of such plants differs from location to location. Geographical location of areas does matter a lot. Also increasing the feasibility of the PVRO plants can extend their feasibility to currently marginal or unfeasible locations. To date no general method of feasibility of PVRO plants have been introduced. This paper introduces this method to generalize the feasibility and effects of locations and solar resource on plants. For different conditions analyzed it was concluded that PVRO plants are more feasible than Diesel powered RO systems due to high fuel cost which in turn results in high water cost for many locations [xiii]. By using innovative methodologies and intelligent system control it is possible to reduce the cost of PVRO plants. Moreover the configuration of the PV panel is an important aspect. Natural conditions like ambient temperatures, solar resource of the area and the time since the last rainfall also contribute to the evaluations of the locations and the feasibility of the systems. Every single parameter should be examined to utmost care and should be satisfied for the operations of such plants whether it is related to operation or the basic control. It should be mentioned that the feasibility of the RO systems degrade with time because with the passage of time, some organic or in-organic material deposit themselves on the membrane module and at time, it becomes very difficult to remove them completely. A keen control and continuous inspection of deposition of such particles is very important, especially in remote areas where skilled man power is minor in numbers. All such aspects should be taken into consideration while designing a PVRO plant [xiv]. Mohamed and Papadakis compares the Photovoltaic SWRO (Sea Water Reverse Osmosis) in their paper which is directly coupled to that which uses battery powered by solar systems. Photovoltaic brackish water RO desalination plants have proved more efficient to supply water to remote areas and isolated communities. Whereas Sea-Water PVRO plants cost too much, this is due to the high energy demand of the plant. This in turn increases the maintenance and operating cost which is due to the fact that many SW-PVRO plants do not have energy recovery devices. Also, the solar batteries cost a lot and their use is required for maintaining constant pressure &flow rate through the membranes [xv]. After the test and analysis it was observed that direct coupled Sea water RO was more efficient than a small Solar Battery powered SW-PVRO plant. However large battery bank (>1500Ah) can improve the battery based system behavior but this would in turn be harmful for environment. This would also increase the operating and maintenance cost which would prove to be much costly in remote areas [xvi]. Al Sulemani & Niar describe the study of experimentation done by the Ministry of Water Resource at a particular site 900km south from Muscat, Oman's capital in their research work. The water pumped out of the well is treated first, dosing of water to balance the pH and reject water evaporation pond. The studies done over the years demonstrate that Photovoltaic RO plants are a good option for remote areas where fuel, power or portable water is a problem. The cost of the PVRO plants compare reasonably with the diesel fuel plants but do not compete in efficiency at some limited periods. Although the initial cost of the PVRO plants is high as compared to that of diesel based RO plants but in turn the maintenance and operation cost of the PVRO plants is relatively low. Moreover, skilled man-power at remote areas is also a problem. Operating a PVRO is an ease as compared to diesel RO plants [xvii]. According to them, for remote areas where power as in form of electricity is not an option, difficult access by road is also an issue or where the ground water is brackish such Solar operated RO plants can turn out to be a useful way to solve the water problems for the related community [xviii].Tamim and Kimberly's research work deals with the desalination techniques through different means and processes. According to them, there are three basic technologies used for the desalination of water namely, Chemical Processes, Membrane Technology and Distillation Processes [xix]. There are some plants which use a combination of these technologies to perform operations. Many future technologies are also discussed which can be more efficient in terms of maintenance and operation cost. The paper also states that energy consumption directly affects the cost-effectiveness and feasibility of using desalination technologies for drinking water production. They concluded that the major disadvantage of renewable energies is the lack of continuity and consistence in the supply [xx].Lee & Glater's discuss the desalination of agricultural water drained out of the system while using the membrane system. This drained water can contain a lot of mixed chemicals and micro-organisms. SO the operations require a lot of considerations like feed water supply, membrane quality and operating conditions [xxi].Two different RO plants were installed which were having the capacity of feed water of about 38,999 gpd. It was explained by them that during the selection of membrane, one has to carefully compromise between the decrease in bio-fouling potential and the performance of membrane. Also the permeate flux and the salt rejection capacity of membrane go hand in hand [xxii].Kang & Cao says that with the development about RO membranes resistant to fouling. As RO is the widely and most popular method to produce fresh water from saline water, so the membranes used in RO process should be more efficient as they are at present. The major challenge faced by this technology at present is the membrane fouling. Therefore, research was initiated to produce membranes for RO process which can run for a longer period of times as compared to the present membranes in operation. Researchers are working on antifouling RO membranes, including the selection of new starting monomers, improvement of interfacial polymerization process, surface modification of conventional RO membrane by physical and chemical methods as well as the hybrid organic/inorganic RO membrane [xxiii].Many new techniques have been discussed and considered in the paper. To start with the modification of the surface of RO membranes currently in operation is a way to go. If the surface of the current RO membranes can be modified, it can result in more efficient and fouling resistant membranes. But the use of this method either physical or chemical results in a decline of water flux. Other than that improvement in the polymerization process of membrane manufacturing is also a gate way towards producing fouling resistant membranes. Addition of polymers during the process can produce membranes much resistant to fouling [xxiv]. Another way is the addition of some inorganic compound during the process in polymeric RO membranes in a new direction to think about. The hybrid organic or inorganic membranes show a promising permeability properties and anti-fouling nature. This can be extensively used on commercial scale for the time to come. In fact, Nano composites membranes have already been introduced and can be used for commercial purposes in near future. But in getting all this to commercial market is also a challenge that should be taken over [xxv]. Many new ideas and innovative technologies are currently under research for the producing anti-fouling membranes and are only limited for the purpose due to high operation cost. Researching on such innovative ideas is the need of the hour. Sooner or later we have to fight these challenges in order to survive and thrive on this planet. This planet has not much too offer in coming years if we talk about fresh drinking water, basic necessity of life [xxvi].

Many researchers have contributed for the high capacity water production using the photovoltaic system but almost never, a system is being prepared for the smaller capacities like l/h. This is really a challenge when it comes to size and portability. To deal with this problem, a renewable energy based set-up for the desalination system has been designed and analyzed for its performance in remote locations. The results taken through this experimental set-up has been evaluated and examined for future recommendation and modifications [xxvii].

The objective of this research is to evaluate the performance of a compact water desalination system, powered by solar energy. In cases of energy abundance and low demand on water, excess energy is to be stored in battery backup systems. The distillation technique used for this work is a RO system, powered by photovoltaic (PV) modules. RO requires less input energy than thermal desalination processes and is ideal for small water throughput requirements.

II. Material and Methods

A. Materials

A brief analysis for the type of membrane through this chart.

TABLE I
TYPE OF MEMBRANE [xiv]

Parameter	Plate & Frame Module	Hollow Fiber Modules	Tubular Module	Spiral Wound Module
Cost ($/m2)	50-200	2-10	50-200	5-50
Pressure drop across permeate	Low	High	Low	Moderate
Suitability for High Pressure	Marginal	Yes	Yes	Marginal
Membrane specific type material restriction	No	Yes	No	No
Concentration Polarization Fouling Control	Good	Poor	Very Good	Moderate

The above table clearly indicates that the choice of Spiral-Wound module is the feasible choice with respect to all the aspects. Although Hollow fibre is also a good choice with respect to cost but due to high pressure drop across permeate and poor control against polarization fouling make it less appropriate against Spiral Wound module. Hence the module selected for RO membrane is Spiral –Wound.

Before proceeding to select the type of filtration needed before the RO system, the analysis of the sample water is required. After the sample water analysis, it becomes easy to predict about the pre-treatments and filtration stages.

The RO unit for the system is a spiral wound membrane of 3" diameter, 0.0005 micron pore size with Pre filter#1 of 5 micron pore size, GAC-Granular Activated Carbon as filter #2 and micro filtration of 1 micron pore size as filter #3.The temperature of raw water was 35-40^{o}C. Two PV modules of 75W & 120W were used. To help circulate water within the system, a 24V and 1.7A DC pump was used. The designed system is shown in Fig. 1.

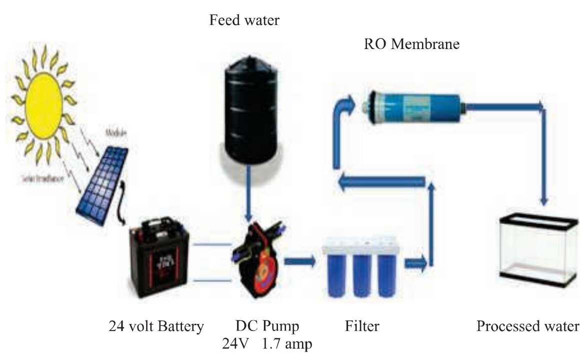

Fig. 1. Schematic of Portable Photovoltaic Desalination Unit

B. Measurement of design parameters

The solar irradiance was measured by the control console incorporated with solar panel. The output flow rate measurement would be simple by taking the volume in measuring cylinder and counting the time. Desalination unit has a DC Diaphragm pump, for which the load requirement was measured and then a factor of safety is taken into account. The included equations are as follows;

$$\text{Volume flow rate}=Q^{\cdot}=\frac{Volume of output water\ (V)}{Time(t)}$$

Where Q is in liter/sec.
Load requirement of pump=L=Current (I) ×Voltage (V)
Load requirement of pump=L=1.7x24 =41W
Power of Photovoltaic Panel chosen:
$P = FS \times L$=1.75x40.8≈75 W
(Where 1.75 is Factor of Safety (FS))

C. Experimental procedure for PVRO Desalination System

The data was collected in June-2012, at Coordinates: 31°45′N74°14′, for solar irradiance in the specific location. A reference PV module was used as a reference to compare the enhancements that a second system would gain with an added battery storage system. The solar irradiance was measured to have the estimate of the input energy was analyzed with respect to the output water flow rate and the quality and then output of water.

During the first five days, the system was run by using the battery as the energy storage source. In the chart, there is no output seen in the first couple of hours because of not enough sunlight. Meanwhile, the battery was charging and once it got charged and ample sunlight was there, the system started to work with good output till about five hours. The flow rate is in Litre/hour. The results are shown below.

III. Results and Discussion

The experiments were conducted for 10 days as it is quite enough for any variations in the weather conditions. In the summer season, it is the maximum output that can be achieved and this time duration provides good statistical evidence to prove our results. Following is the data collected for the solar irradiance (W/m^2) during the operational timings. Wp of the panel is 75W for battery based system and 120W for battery less system. Results are evaluated quantitatively, qualitatively and economically. Output power and solar irradiance of the battery based system has been explained in Fig. 2. It can be observed from the graph that the maximum power output is around noon times where as it is minimum during morning and evening times. The corresponding values of the solar irradiance are indicated on the right side of the graph. For the battery based system the solar irradiance is least in the morning & evening times.

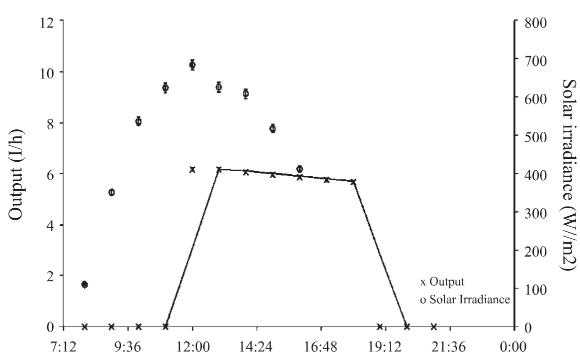

Fig. 2. Battery-BasedSystem with 75W PV Panel

The RO unit produces 6.6 l/h using electricity whereas using the battery-based PV panel of 75W, the output flow rate of the desalination unit was approximately 5.9 l/h for 5 hours.This implies that one day output of battery-based PV panel would be 29.5 l/day. However by using the battery-less PV panel of 75W, the desalination unit has maximum output flow rate ≈ 3 l/h for peak hours only.

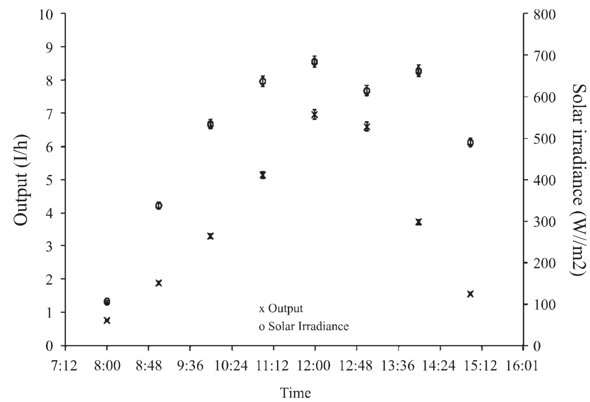

Fig. 3. Battery-Less System with 120W PV Panel

That is why instead of using 75W panel, 120W panel was used for direct connection, which gave us the output flow rate of 3.8 l/h for 7 hours. So one day output of battery-less PV panel is approximately 26.6 l/day.

TABLE II
Quality of Different Types of Water [xiii]

Parameter	Raw Water KSK	RO Water KSK	Guideline WHO
PH	7.2	7.1	6.5-8.5
Chlorides (mg/L)	530	40	250
Calcium(mg/L)	24	12.8	-
Total Dissolve Solid (mg/L)	1000	14	1000
Magnesium (mg/L)	24	9.7	-
Sulfate (mg/L)	350	15	250
Total Hardness (mg/L as $CaCO_3$)	160	72	500

The designed unit is portable and can be easily operated by a layman even so there is no specific cost involved for the labor using this system as compared to other heavy duty installation required distillation systems. There is almost negligible maintenance and operational requirement for the designed system. Only the quarter yearly cost for replacing the RO membrane could be considered. The life span varies from area to area and raw water quality, but roughly it will be workable up to 20-25 years keeping the regular maintenance required for the different parts in mind.

IV. Conclusion

The successful design and testing of a water purification system operating on solar energy is presented. For remote/disaster-stricken areas having abundant solar energy and unavailability of access to pure underground drinking water, this system proves key to confront the scarcity of potable water and fulfills the needs of a small population. The photovoltaic arrays generate energy that is environmentally friendly that reduces the environmental and noise pollution of comparable diesel generators. The difference between the battery less and battery based system is only 17 - 18% excess energy which makes us consider the battery less system. For a specific available solar energy, the battery-based system produces only 9.8% more product water. Hence the battery-based or battery-less systems, both can be used, but battery –less system is more cost effective with just small decrement of output flow rate then battery-based system.

V. Recommendations

Improvements in the designed unit can be done by incorporating the photovoltaic panel with solar tracking device. In this way, the efficiency of the system will be increased. If instead of coupling a big photovoltaic panel, two small panel of equal output can be coupled in series, then the price can further be reduced because larger the photovoltaic panel, more will be the cost. To address the decreasing rate of drinkable fresh water globally, many human rights organizations are funding research on desalination to facilitate people with adequate drinkable water. Thermal desalination systems can also be employed with the collaboration of such organizations for industrial-scale water purification because their production ability is massive. For better efficiency, the filters for pretreatment of feed-water at Reverse Osmosis water treatment plants must be cleaned every few days (back washed) to clear accumulated sand and solids. In particular, the research should be conducted to reduce the process energy consumption, as well as to minimize the harmful effects of scaling and fouling on membranes and to obtain higher water flux membranes. The modified models for Desalination Plants may be applied to have the Hybrid solar desalination. The main idea is to employ the solar power in both form, PV and Thermal, or to incorporate the PVRO Designed system with some other renewable energy as well. The system was tested using brackish water, it can be modified to use for the purification of sea water. The results can be analyzed to check the feasibility of the system.

VI. Applications

The system designed is feasible for using in the areas which is vulnerable to natural disasters. In this way, the availability of electricity is impossible to be available and so the system is compatible to work within such region. Keeping in view the disaster of Earth Quake 2008 in Northern areas of Pakistan, it has been found that the cost of supplying fresh water is always greater than producing water out of PVRO System. The designed unit is portable and can be easily operated by a layman even so there is no specific cost involved for the labour using this system as compared to other heavy duty installation required distillation systems. There is almost negligible requirement for the designed system. Only the quarter yearly cost for replacing the RO membrane could be considered. The life span vary from area to area and raw water quality, but roughly it will be workable up to 20-25 years keeping the regular maintenance required for the different parts in mind.

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