PERFORMANCE STUDY OF SMALL SCALE SOLAR PV POWERED RO DESALINATION SYSTEM

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1. Introduction

At present time, the fresh water shortage is a significant problem in many areas of the world, such as the Middle East and North African countries (MENA), the Southern European Mediterranean Islands (SEMI) and isolated communities in desert or arid areas of Central Asian countries. Main point is, that available water resources are strongly mineralized and contaminated, which is not suitable for drinking and daily usage. Another difficulty is that the part of the population lives in small villages or settlements without infrastructure, and is not connected to centralized system of electrification and drinking water supply. This condition of the life calls to consider RE utilization as a promising option. Developing of autonomous system of drinking water supply or desalination systems working on RE is one of the real solutions, particularly using solar energy, which is very attractive where the potential is usually quite high in most rural arid areas. In addition, the cost of primary fuel is getting up while the need to maintain clean environment is becoming an important issue worldwide [1-2].

Different types of desalination technologies are available in the market, which are based on various desalination methods proposed, by scientific and production organizations. Among them, Reverse Osmosis (RO) is quite suitable from small to medium capacity systems, and has good perspectives for cost reduction and improvement in efficiency in the near future [3]. Reverse Osmosis (RO) is an electrically driven technology characterized by significantly low specific power requirements. In view of these facts, it is seen that a small-scale RO desalination system powered by solar energy presents an ideal solution to provide freshwater to small communities isolated at remote areas.

According to [4] among RE powered desalination processes, estimated for 2007, RO system the leading process, with 62%, MED-14%, MSF-10%, ED-5%, VC-5% and others -4%, . The energy resources using to run the systems was estimated as 43% - Solar PV, 27%- Solar Thermal, 20%- Wind, 10%- Hybrid (solar PV and wind or solar thermal and wind power).

2. RE Powered RO Desalination

There is a number of research reports on solar powered RO systems, which the size of those systems varies from laboratory to industrial scale. According to literatures the main types of solar powered desalination systems has been classified into three groups, which described in Fig.1.

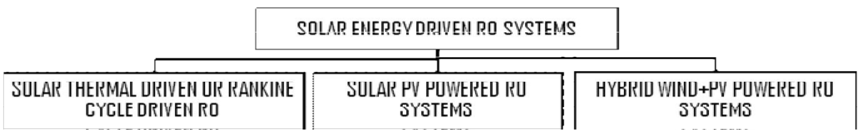

Fig.1. The main groups of solar powered RO desalination.

Choosing one of the stand-alone Solar powered RO desalination systems, actually depends on the location, geographical conditions, topography of the site, capacity and size of the plant. The main selection criteria may include such parameters as simplicity of operation, low maintenance, compact size and easy transportation.

2.1. Solar Thermal driven or Rankine cycle driven RO desalination systems:

The most common thermodynamic cycle used in energy production is the Rankine cycle with a single working fluid (water or an organic compound) or a binary cycle with water as the heat transfer fluid in the upper cycle and an organic compound in the lower cycle. The general principle scheme of Solar Rankine cycle driven RO desalination systems is given on Fig.2.

Several types of Solar Rankine cycle powered RO desalination systems have recently developed with different combination of energy supply subsystems (solar field) and heat transfer fluids in low and high thermodynamic cycles. As an example the works by Bowman et al., [5], Delgado-Torres, Garcia-Rodriguez et al.[6-11], where developed and presented several types of Solar Organic Rankine cycle powered RO desalination systems with different compositions of working fluids and mainly powered by Parabolic trough collectors (PTC). The system presented by Manolakos et al. [12,13], was projected to obtain fresh water from both brackish water and seawater, uses evacuated tube collectors.

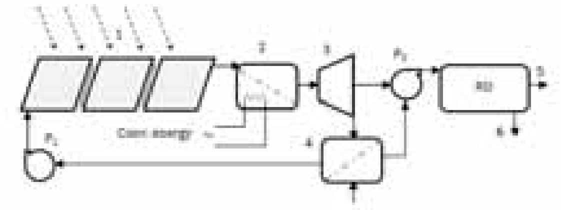

Fig.2.The principle scheme of Solar Rankine cycle powered RO desalination systems:
1- Solar collector field; 2- Superheating stage; 3- Turbine (energy generating); 4-Condenser; P-pump; RO- Reverse Osmosis system; 5-Product; 6- Brine.

Nafey [14] presented the results of thermo-economic analysis and compared the different configurations of reverse osmosis energy recovery units powered by solar organic Rankine cycle. Three main configurations of recovery unit (Basic, Pelton Wheel Turbine, and the Pressure Exchanger) with Sharm El-Shiekh RO desalination plant for a total productivity about $146m^3/h$ (40.5 L/s).

Water is commonly used as working fluid in Rankine cycles, although other types of inorganic (e.g. ammonia, ammonia/water) and organic fluids (e.g. hydrocarbons, fluorocarbons, siloxanes) can be used. The main advantage of organic working fluids in Rankine cycles is that they can be driven at lower temperatures than similar cycles using water, and in many cases superheating is not necessary [15].

2.2. Solar PV driven RO Systems

PV is considered as a proper solution for small applications in rural areas with high solar irradiance. There is a number of R&D works reported by researchers that also proposed several types of PV powered RO systems from small size to industrial scale, which can be found from the Literature [16-23]. The general principle scheme of PV powered RO desalination systems are shown on Fig.3. and Fig.4.

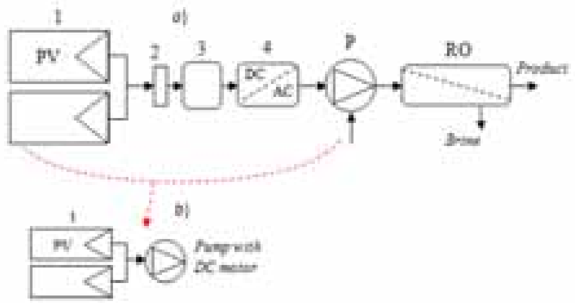

Fig.3. The general Principle scheme of PV powered RO desalination system: *a*) with battery bank; *b*) without battery bank: *1- PV panel; 2- Battery charge controller; 3-Battery bank; 4-DC/AC-Converter; P-pump; RO-Reverse Osmosis module.*

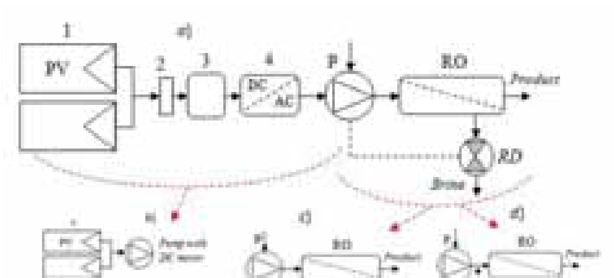

Fig.4. Principle scheme of PV powered RO desalination system with RD (energy recovery device): *a*) and *b*) with and without battery bank; *c*) and *d*) with two types of RD, respectively: *1-PV; 2- Battery charge controller; 3-Battery bank; 4-DC/AC-Converter; P-pump; RO- Reverse Osmosis module; RD- Recovery device.*

In general there is several experimental installations, were suggested, where the PV is directly connected to RO system with DC motor as the pumping subunit of the system. Where, the works of Mohamed [16], Abdallah et al. [17] and Helal et al. [18] devoted to study of such kind of systems. At the same time there is an RO desalination systems powered by Solar PV with battery bank, which are reported by Hrayshat [19] and Ahmad et al. [20]. And also Solar PV powered RO desalination systems with Energy Recovery devices, which are studied and presented by Richards [21] and Manolakos et al. [22].

From a technical point of view, PV as well as RO is mature and commercially available technology at present time. RO currently represents 42% of world-wide desalination capacity [21]. The feasibility of PV-powered RO systems, as valid options for desalination at remote sites, has also been proven. Indeed, there are commercially available standalone, PV powered desalination systems [23]. The main problem of these technologies is the high cost and, for the time being, the availability of PV cells. Currently, the RO constitutes a more realistic choice for both brackish and seawater desalination. Considering the energy supply, RO presents lower energy consumption comparing to other methods of desalination. Several RO desalination systems driven by PV have been installed throughout the world in the last decades, most of them being built as experimental or demonstration plants.

2.3. Hybrid Wind + PV powered RO Systems

As shown in previous works, each systems has own advantages and disadvantages, respectively, which strongly dependent on technical and economic feasibility of the system, and also on natural meteorological conditions of the regions to be used. PV is considered a proper solution for small-scale desalination units in regions with high solar radiation as proposed by number of researchers. Nevertheless, in some areas with different natural conditions, wind energy may be more attractive for larger quantities of water. This may be used on some islands where a good wind regime is available.

The electrical or mechanical power generated by a wind turbine can be used to drive desalination plants. Like PV, wind turbines represent a mature, commercially available technology for power production. Wind power is one of important options for seawater desalination, especially for coastal areas that present a high availability of wind energy resources. According to some authors, wind powered RO plants appear to be one of the most promising alternatives of RO desalination [24]. The general principle scheme of hybrid Wind-PV powered RO desalination systems presented on Fig.5.

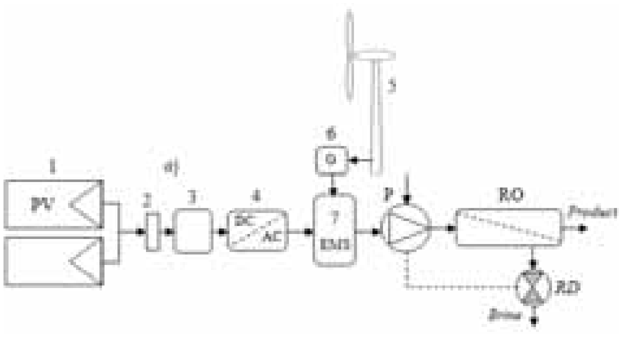

Fig.5.The general principle scheme of hybrid Wind-PV powered RO desalination systems:
1-PV; 2-Battery charge controller; 3-Battery bank; 4-DC/AC-Converter; 5-Wind turbine; 6-Generator; 7-Energy management system; P-pump; RO-Reverse Osmosis module; RD- Recovery device.

According to literature there is a number of works, which are focused to simulation and experimental investigations on development, optimization and choosing of technical and economical effective designs of hybrid wind-PV system to power a RO desalination unit based on a techno-economic analysis and also taking into account of meteorological data [25-29]. As the results of several scientific works the technical feasibility of using wind as the power source for desalination has been confirmed.

3. RE Potential of Uzbekistan

3.1. Solar Energy:

Territory of Uzbekistan belongs to the category of countries with high intensity of solar radiation. Uzbekistan has therefore favorable climate conditions for using solar energy. Technical potential of solar energy exceeds the annual requirements of Uzbekistan for power resources as much as about 4 times (65-70 mln.t.o.e/year). Fig.6. presents solar map of Uzbekistan.

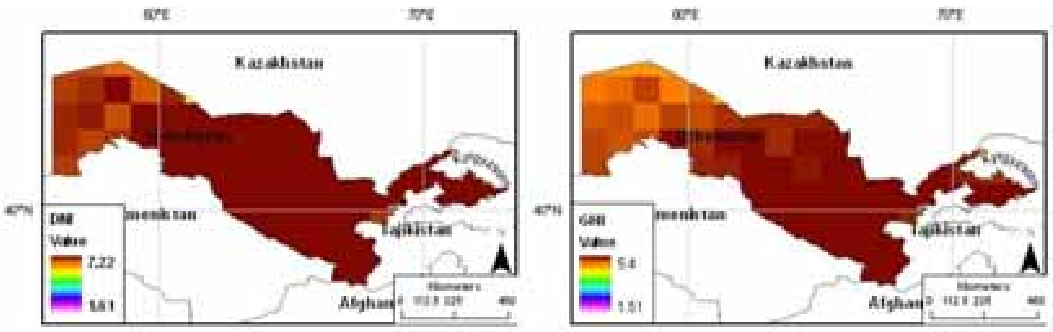

Fig.6. Direct Normal Solar Insolation and Global Horizontal Sola Irradiance in territory of Uzbekistan. [http://www.ebrdrenewables.com/sites/renew/countries/Uzbekistan/profile]

Gross potential of solar energy is $51*10^9$(t.o.e.). Technically usable potential is $175*10^6$(t.o.e.). Another important indicator is duration of sunshine in the North is averaged to about 2800 hours/year, and in the most South (Termez city) reaches 3050 hours/year, where the capacity of solar radiation for 1 m^2 is about 1 kW. So during of year it will reach about 1650-1750kWh/m^2 which equals the heat from burning of 140-150 кg of oil fuel [30].

3.2. Wind Energy:

Wind energy resources potential of Uzbekistan: Total (average during of the year) $2200*10^3$ (t.o.e.); Technical Potential $425*10^3$ (t.o.e.). Average yearly wind speed on the whole territory of Uzbekistan is 2-2.5m/sec. This circumstance eliminates the prospective of wind power engineering in the country, especially for wind turbines of middle and high power. On the other hand, monthly average, seasonal average and yearly average wind speeds on the territory of Uzbekistan are different; it is 4m/s in July (summer) and 8m/s in January (winter).

The analysis of wind speeds in Uzbekistan and their instability during a day and year shows, that the creation of autonomous wind power stations in Uzbekistan is ineffective. It is reasonable to create combined installations like wind power generator with photovoltaic station. The Region with most high potential of Wind Energy is Becobod-Kokand Line in Tashkent Province. The average speed of wind in this territory is 6m/s. As shown on wind map, the yearly average distribution of wind speed on the territory of Uzbekistan is in Aral Sea basin, Kyzylkum desert territory and foothill zones of Tashkent region (Charvaq and Bekabad) yearly average wind speed is 4-5 m/sec and more. Taking into account that these territories are remote to considerable distance from grid and on hard-to-reach desert, mountain and foothill regions, utilization of wind energy in such regions looks economically expedient. In the most part of the territory of Uzbekistan specific wind capacity is 50-150 W/m^2. On the north, in Aral Sea basin and foothill zone of Tashkent region, it exceeds 150 W/m^2, and in Fergana valley – less than 30 W/m^2 [30-32].

4. Drinking water shortage in the region

Uzbekistan State Program on Provision of Rural Population With Drinking Water for the period 2000-2010 envisages construction of water-supply networks and improvement of the level of drinking water supply for the population up to 85%, provision of remote rural settlements with alternative sources of water and energy supply; in 2002-2005 it is intended to provide 1.2 thousand settlements with water of drinking quality, while in 2006-2010 it is intended to provide that for 1.3 thousand settlements. More than half of these settlements are located in Bukhara, Navoiy regions and in Karakalpakstan Republic [33]. National strategy of regional and local initiatives for transition to sustainable development is based on the principle of provision of overall socio-economic development of local and regional zones, contributing to achievement of sustainability of settlements. 62.8% of the population resides in 11,844 rural settlements. The issue of social construction in rural areas is in the focus of attention of the state, which inherited a system with low coverage of social needs of the population and significant disparities in the levels of development of infrastructure between towns and villages, as well as territorial disparities between regions of the Republic.

Drinking water supply in rural areas has been developed on the basis of special programs being consistently implemented. Within the years of independence 21,210 km of water supply lines have been built in rural areas. There remains, however, a problem of water supply for remote and hard-to-reach rural settlements. More than 1,183 settlements (of which about 900 are located in desert and semi-desert areas) cannot access water (or energy) through traditional methods [33].

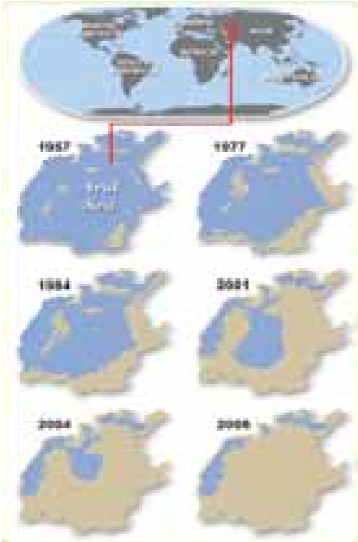

Fig.7. Situation of Aral Sea
(www.bracsystems.com/environment.html)

Fig.7. shows the history and present situation of Aral Sea. Last years the region around the Aral Sea turned to be a large salt desert. It is continue to grow with increased temperatures and also affecting more populated regions. Salinity level of water resources and soil is growing rapidly. The quality of drinking water currently in the territory of Karakalpakstan, Provinces of Bukhara and Khorezm is critical, which means that its quality is below proper usage. The ground water resources, which are main resource of drinking water in these areas, are contaminated and salinity degree is very high.

There is also an opportunity in desert and semi-desert zones for utilization of alternative sources of energy, energy saving and water pumping, including the use of Photovoltaic systems (PVC), manufacturing of such systems is being currently arranged by industrial plants in the Republic. Extent of sustainability of any settlement is determined by the condition of ecology, availability of consistent sources of decent income, provision with housing, available set and quality of social services, as well as by the extent to which the functioning systems of health care cover major needs of the population in drinking water, healthy food and sanitation [33].

As mentioned above, small scale solar powered RO desalination systems could be reliable solution for rural usage in most arid areas of Central Asian countries. In the current work, some aspects of possible solutions of this problem are given for the case of Uzbekistan.

5. Solar powered RO desalination as a solution in arid areas of Uzbekistan

Because of economical, technical restrictions and also natural and meteorological difficulties, it is impossible to build traditional water treatment systems in each small village. In some cases it is difficult even to build water pipe lines to connect them to central water supply systems because of natural conditions, mostly in mountain and desert areas. One of the promising solutions for this problem is developing of autonomous water desalination systems working on RO, particularly solar energy [1-2].

During of last years, several projects have been developed by The Government of Uzbekistan and by International Organizations. Also number of research works is going on by Uzbek scientists, where we can refer to works of Khaydarov et al. [34], which devoted to development of novel solar powered water desalination based on direct osmosis process. The pilot unit with productivity of 1 m^3/h has been constructed. It consists of solar batteries with capacity of 500 W for pumping various fluids (feed, brine, product, working solution) of the device, solar thermal exchangers for recovery of working solution, water pretreatment unit on the base of fibroid sorbents and water disinfection devise with energy consumption of 0.1W. With the support of UNESCO in 2005 the device was installed in a village of Aral Sea Region to remove salts with total concentration of about 17g/L. The product salinity after the treatment was about 50 mg/L

Based on National and International Research teams practice and also taking into account of natural or meteorological factors and also need and requirements of consumers developed a preliminary design of small scale PV powered RO desalination system with expected daily productivity about 100L. The principle scheme of the system is described on Fig.8.

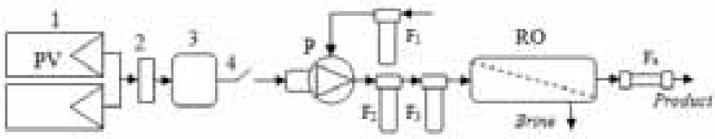

Fig.8. Principle scheme of PV powered RO desalination system:
1- PV panel; 2-Battery charge controller; 3-Battery bank; 4-switch; P- Booster Pump with DC motor; F_1- Sedimentation pre-filter; F_2 and F_3 – Polypropylene and granulated carbon filters; RO-Reverse Osmosis membrane module; F_4- Active carbon post-filter.

The proposed system is expected to be a promising option by its compactness, its transportability, and its technical and economic feasibility.

5.1. Parametrical study:

The final parametrical characteristics of the proposed system could be obtained by determination of technical parameters of each subunit [34].

The efficiency of electrical power operation subsystem:

$$\eta_{PV} = \eta_{max}\eta_l = \frac{P_{PV}}{\eta_b A_{PV} Q_s \tau} \quad (1)$$

where, P_{PV} - operating electrical power; Q_s -average daily solar irradiation; A_{PV} - total surface area of PV array; η_b - efficiency of battery bank; τ - average sunny hours; η_l - losses due to connections and η_{max} - the maximum power point efficiency of PV modules.

The maximum power point efficiency of PV modules decreases with increasing cell temperature, which can be expressed as follows:

$$\eta_{max} = \eta_s + \mu_t (T_c - T_s) \quad (2)$$

$$\eta_s = \frac{I_s V_s}{A_{PV} Q_{ss}} \quad (3)$$

$$\mu_t = \eta_s \frac{\mu_V}{V_s} \quad (4)$$

where, η_s - module efficiency under standard operation conditions; T_c and T_s are the actual cell temperature and temperature under standard operating conditions (25 °C), respectively; μ_t - temperature coefficient of efficiency at the maximum power point that can be found by the approximation [19]; μ_V - voltage temperature coefficient; V_s - module's voltage at the maximum power point under standard operation condition.

The working temperature of the module (cell) could be determined by the method of Duffie and Backman, which is based on energy balance on module surface [35]:

$$T_c = T_a + I \frac{\tau\alpha}{U_l} \frac{1-\eta_c}{\tau\alpha} \quad (5)$$

where, I incident solar radiation U is the heat loss coefficient from the cell to surroundings (by convection, radiation and conduction from the surface and bottom of cell). τ and α are respectively, coefficients of transmittance of the cover over the cell, and absorption coefficient of cell surface. η_c is the efficiency of the module radiation conversion to electrical power.

The efficiency of pumping subsystem η_{PS} can be calculated as the ratio of hydraulic power of the pump and the operating electrical power E of the subsystem as follows [36]

$$\eta_{PS} = \frac{C_h G h}{E} \quad (6)$$

where, C_h - hydraulic constant; G - water flow rate; h -total height.

The total efficiency of the PV Pumping system depends on the PV array and the pumping subsystem efficiencies, which can be written as

$$\eta' = \eta_{PV} \eta_{PS} \quad (7)$$

The performance of RO system depends on recovery coefficient of RO module, which could be defined as the ratio between fresh water flow rate and brackish water flow rates:

$$R = 100 \cdot \frac{G_p}{G_f} \quad (8)$$

$$G_p = (1 - R) G_f \quad (9)$$

where, G_p and G_f - are fresh water and brackish water flow rates, respectively. Also G_p called specified recovery coefficient of the RO module. Recovery rate depends on the temperature, membrane and water properties, particularly the viscosity. Warmer water leads to an increase of the membrane permeability.

5.2. Pilot Project of proposed system:

Developed design and created pilot unit of Solar PV powered RO desalination system, which includes two main subunits: First – energy supply subunit with PV panel with peak power 30W (mono-crystalline silicon modules), battery bank (24V, 8Ah), battery charge controller and switch; Second- treatment subunit, which includes booster pump with DC motor (voltage: 24V,current: 0.6A, max flow rate: 60 L/h, Pressure: 345-550kPa), five stage RO system (sedimentation pre-filter, polypropylene and granuled carbon filters, RO membrane and active carbon post-filters), pressure controller, water inlet and outlet valves, tank for cleaned water (with 12L capacity). In Fig.9 and Fig.10 respectively, presented principal scheme and general view of proposed small scale PV powered RO desalination system with productivity 100-120 L/d.

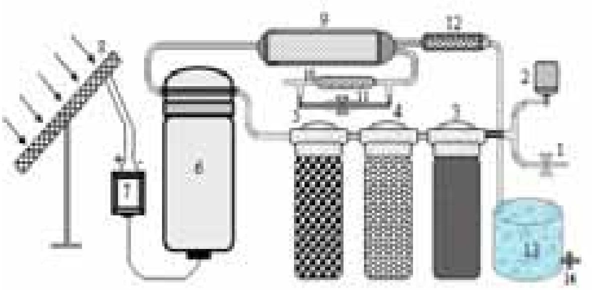

Fig.9. Principle scheme of PV powered RO desalination system:
1-Water inlet; 2-Presure controller; 3,4,5–Polypropylene, sedimentation and active carbon filters, respectively; 6- Booster Pump with DC motor; 7-Battery bank; 8-PV Array; 9-RO membrane; 10,11-Feed water control and valve; 12-Post-Active carbon filter; 13-Clean water; 14-outlet valve.

Fig.10. General view of PV powered RO desalination system

As shown on Fig.10, unit is quite compact and easy transportable. The results of indoor and outdoor experimental investigations (under natural conditions of Tashkent City, during of different months and seasons) shows, that units productivity ranges between 50L and 120L, dependently on quality of brackish water and meteorological conditions (solar radiation intensity).

5.3. Results of Preliminary experimental investigations:

In order to study of the performance of proposed solar PV powered small scale RO desalination unit, experimental investigations conducted in the Laboratory of Solar thermal systems of Physical-Technical Institute. Here presented the results of experiments on 15th of May 2010 and 22nd of March 2011.

<u>Experimental results on 15th of May 2010.</u>

In Fig.11 presented the solar radiation intensity and the temperature range during the day, and in Fig.12 presented variation output of the electrical current and voltage during the day.

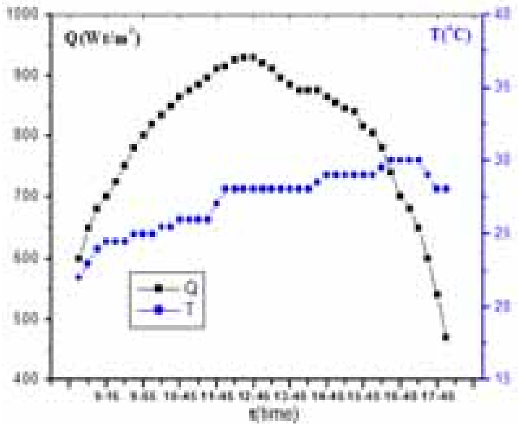

Fig.11. Solar radiation intensity (Q) and the temperature (T) range during the day.

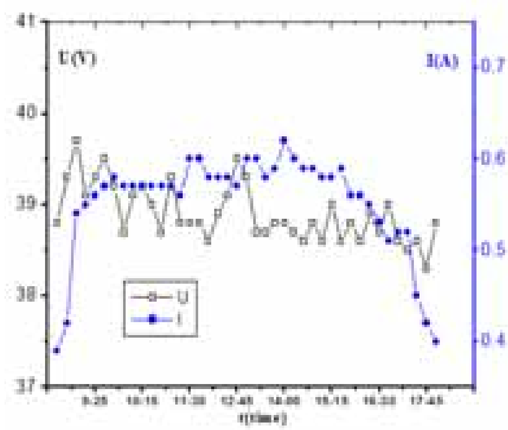

Fig.12. Variation of output electrical current and voltage during working hours of system.

Results shows, that the maximum current during the day occurred between hours 11:30 am to 15:15 pm, which was about 0.60 A. The maximum voltage occurred between 11:45 am and 12:15 pm, which achieved to 38-40V.Fig.13presents the electrical power output for operating of the motor, which runs the RO system. The flow rates of desalinated water as a function of sunny hours of the day are presented in Fig.14.

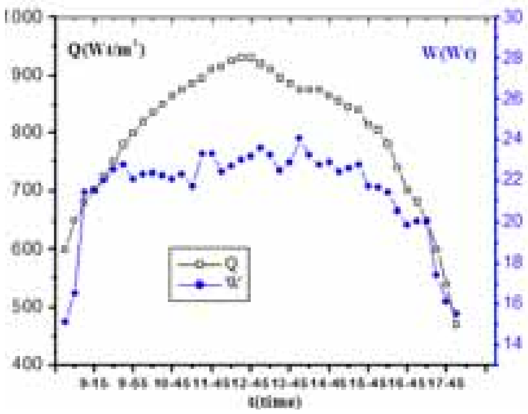

Fig.13. Solar radiation intensity (Q) and the electrical power output during the day.

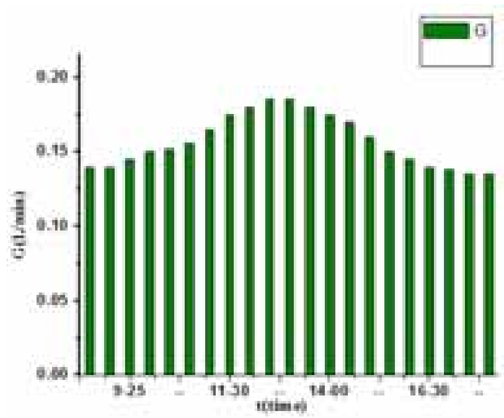

Fig.14. Desalinated water flow rate (G) as a function of the hours of the day.

The results of measurements during the day (from 8:30 am to 18:00 pm) shows, that output power ranged between 15.2 and 24 Wt, and the maximum occurred between 11:30 am and 14:30 pm. The flow rates of desalinated water, as presented on Fig.15, ranged between 0.14 and 0.19l/min. The maximum flow rates also as a function of power, achieved at the time interval between 11:30 am and 14:30, respectively, and reached to 0.19 l/min.

<u>Experimental results on 22nd of March 2011.</u>

Similar set of results was taken after almost a year of operation with the same system. Fig.15 presents the solar radiation intensity and the temperature range during the day, and in Fig.16 presented variation output of the electrical current and voltage during the day.

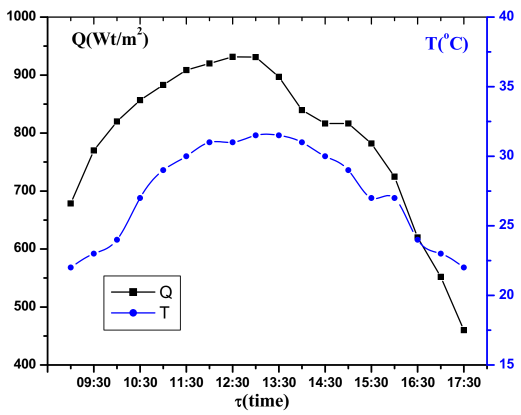

Fig.15. Solar radiation intensity (Q) and the temperature (T) range during the day

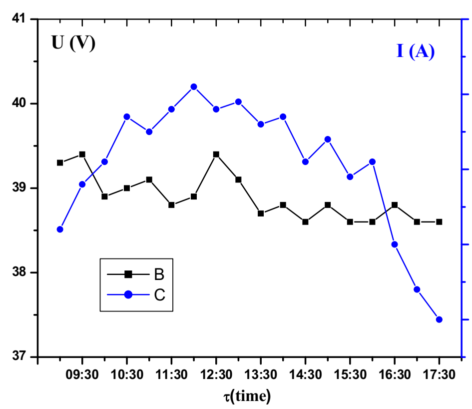

Fig.16. Variation of output electrical current and voltage during working hours of system

Results shows, that during the period between hours 11:30 am to 13:30 pm when the solar radiation intensity was abow 900 Wt/m^2, the maximum value of current occurred, which was about 0.60 A, where the voltage was more stable, which was about 39 V.Fig.17 presents the electrical power output and the flow rates of desalinated water as a function of sunny hours of the day are presented in Fig.18.

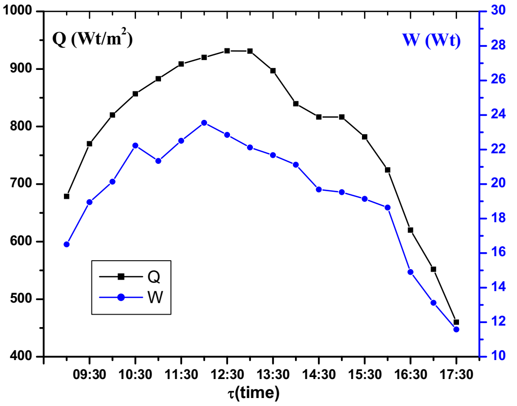

Fig.17. Solar radiation intensity (Q) and the electrical power output during the day.

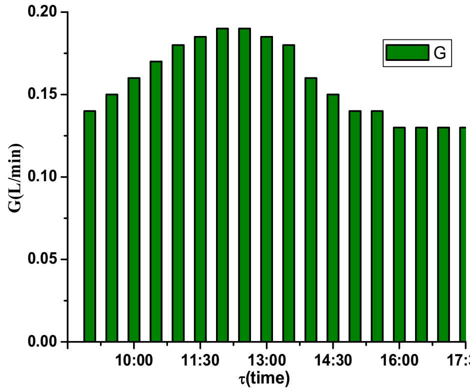

Fig.18. Desalinated water flow rate (G) as a function of the hours of the day.

The results of measurements during the day shows, that output power ranged between 12 and 24 Wt, and the maximum occurred between 11:30 am and 13:30 pm. The flow rates of desalinated water, as presented on Fig.18, ranged between 0.13 and 0.19l/min. The maximum flow rates also as a function of power, achieved at the time interval between 11:30 am and 13:30.

6. Conclusion

Choosing any type of solar powered RO desalination system, which divided into three groups as: Rankine cycle driven; PV driven and Hybrid (particularly Wind-PV) powered RO systems depends on the location, natural conditions, topography of the site, capacity and size of the plant. The main selection criteria may include such parameters as simplicity of operation, low maintenance, compact size, easy transportation etc. Taking into account of these facts, the current presentation proposes a developed small scale PV powered RO desalination system, which is a promising option for preparation drinking and cooking water by its compactness, transportability, technically and also economically feasibility. However, the proposed system needs future research and experimental investigation on optimization of technical parameter and economical feasibility based on natural conditions of local areas.

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