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Uninterrupted eight-year operation of the autonomous solar photovoltaic reverse osmosis system in Ksar Ghilène (Tunisia)

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ABSTRACT

Ksar Ghilène is a 300 inhabitant isolated village located in the Sahara desert at the South of Tunisia and belonging to the region of Kébili. Due to the particular location of this site, there was no local fresh water source before 2006 and this community had been depending on the external water supply, transported by trucks. The 10.5 kWp PV-powered RO desalination system (based on the international patent DESSOL®) with a nominal water capacity of 50 m^3/d was commissioned in June 2006 and currently in operation. The whole project was developed by Instituto Tecnológico de Canarias within the framework of the Spanish–Tunisian cooperation, thanks to the economic support of the Spanish cooperation and the Canary Islands cooperation. This paper presents and assesses the operation data and lessons learnt with the whole system for the period 2006–2013.

Keywords: Autonomous desalination; Solar photovoltaic energy; Isolated village; Operation data assessment

1. Introduction

Ksar Ghilène is a 300 inhabitant isolated village located in the Sahara desert, at the South of Tunisia and belonging to the region of Kèbili. The public buildings include a school, a mosque, a National Guard office and a health centre; on the other hand, the local people are accommodated in two dozens of houses. The main economic activities of the village are the agriculture (on the oasis), cattle farming and tourism. A hybrid electrification solar photovoltaic–wind energy system was installed for housework and public buildings in the framework of Hyress project in 2010 [1].

Four years before that a 50 m/d brackish water reverse osmosis (RO) desalination plant driven by 10.5 kWp stand-alone solar photovoltaic (PV) field (international patent DESSOL®) [2,3] had been installed by the Instituto Tecnológico de Canarias (ITC) within the framework of the Spanish–Tunisian cooperation (Fig. 1). Before this installation, the drinking water supply was done door-to-door by tanks from a well located 60 km away. The aim of this cooperation project was to produce off-grid freshwater

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Fig. 1. Ksar Ghilène village desalination plant and PV field facility.

from a brackish water well located in the near oasis, at 2 km, by the exclusive use of solar energy.

Different research initiatives and pilot systems related to desalination plants driven by renewable energies have been undertaken, [4–9] but none had been designed to solve a water supply real problem of hundreds of inhabitants. The Ksar Ghilène installation was the first 100% solar PV-powered desalination system with remarkable capacity (more than 2 m^3/h) to meet this goal around the world. After eight years of uninterrupted operation, the feasibility, robustness and high potential of using photovoltaic solar energy to produce freshwater in isolated locations have been reinforced. Previous analysis has identified that decision-makers and other stakeholders are not familiar with RE-powered desalination systems; so the more operative units there are, the more institutional support there will be. The roadmap developed within the ProDes project included conclusions like that [10].

Within this context, in the following sections, a data operation assessment and a technical–social description for the whole system are presented. Although the total operation period is almost eight years (commissioning in June 2006), the present paper includes information until 2013.

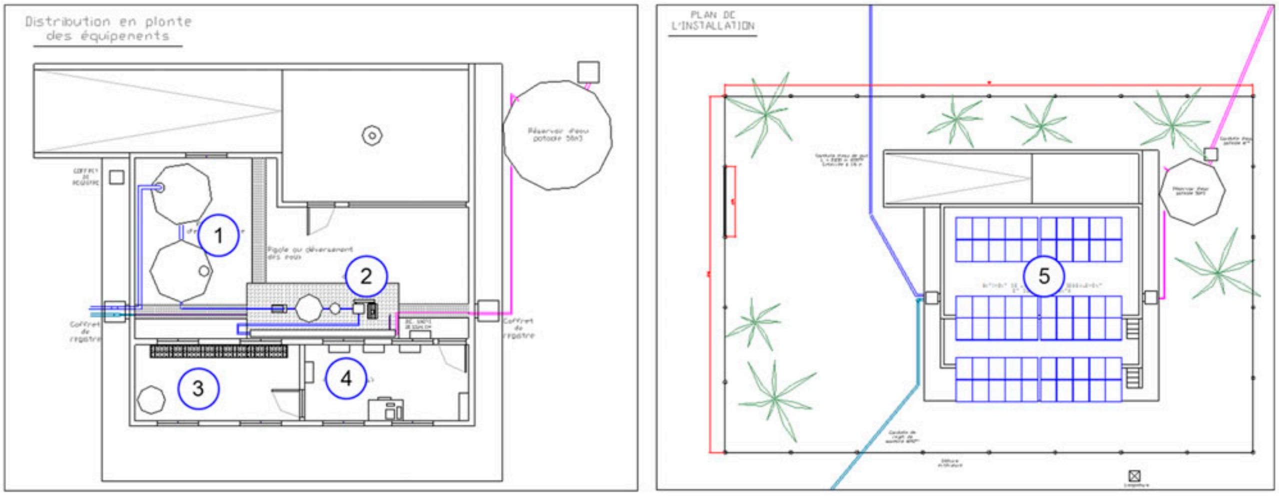
2. System description

The PVRO (photovoltaic-powered reverse osmosis) system consists of a 50 m/d brackish water RO desalination plant, a 10.5 kW peak stand-alone solar PV field, a battery bank (660 Ah) and a charger/inverter equipment with a nominal power of 10 kW. The PVRO design and the control system concept are patented by ITC (DESSOL®). All the technologies involved in the DESSOL® system were designed with the aim of operating exclusively with solar energy, instead of using conventional electrical grid or backup generators.

DESSOL® therefore combines RO and solar PV technologies by means of a control system that optimizes the production of desalinated water depending on the amount of solar radiation at the target site, the characteristics of the water to be treated and paying attention to the service life of its components, especially the RO membranes. A noteworthy aspect of the system is the use of batteries; this guarantees the production of freshwater even in days when there is less solar radiation and maximizes the production of desalinated water [11]. A complementary description of the system and its components can be consulted in previous publications [12,13].

Fig. 2 marks the main components related in the case of Ksar Ghilène installation and the Figs. 3 and 4 show the RO-PV hydraulic and electric diagrams, respectively.

The brackish water to be treated (4.0–4.5 g/L; pH 8.6) comes from an artesian well located inside the oasis. The raw water temperature is very fluctuant along the year, from 34 °C in summer to 13 °C in winter time. The raw water required (3 m^3/h) is stored with chlorine dosing in a 30 m^3 regulation tank located inside the desalination building, allowing a slow natural cooling; it is small but enough to meet with the maximum inlet temperature to the membranes.



1. Feed water regulation tanks; 2. RO desalination plant; 3. Batteries; 4. Electric panels and converters; 5. PV field, on the roof

Fig. 2. Main components of the RO-PV system.

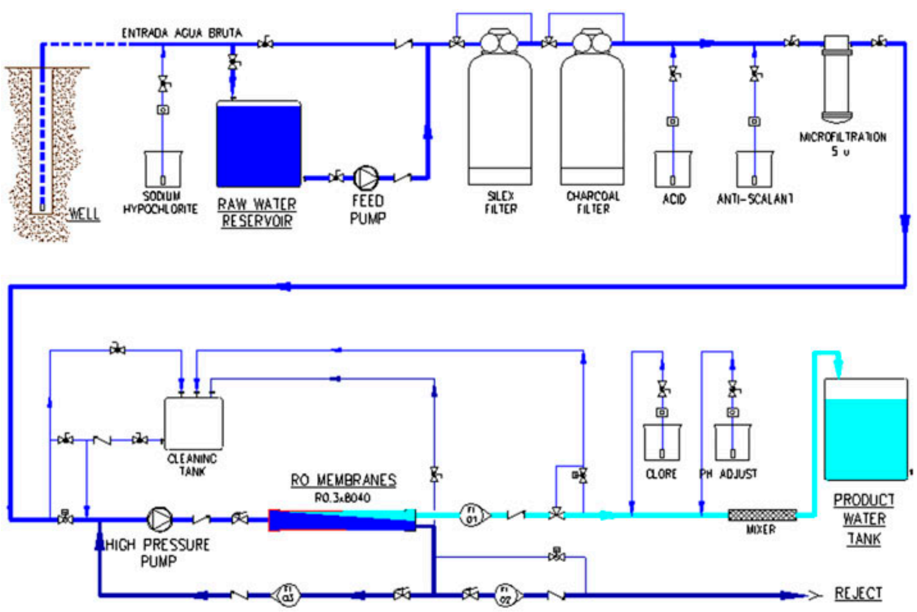


Fig. 3. Desalination plant hydraulic schematic diagram.

The RO pre-treatment consists of a sand filter, a chemical dosing (to reduce pH and inhibit scaling), an activated carbon filter to eliminate free chlorine and a cartridge filter. After the pre-treatment stage, the raw water is blended with part of the brine. The RO rack (1 × 3–8″ elements) was designed for a 70% recovery rate (11 bar operation pressure). Before being stored in a 25 m^3 elevated freshwater tank outside the building, the product water is post-treated by stabilizing pH and adding chlorine as a preservative. The system is completed with the brine discharge (0.9 m^3/h) and the chemical cleaning devices. The brine reject is mixed with raw water using a by-pass valve system. This mix allows the use of the rejected water for the irrigation purposes of the oasis forest side.

The energy system is composed of 7 solar PV generators in parallel coming up to 10.5 kW peak power (40° PV panels fixed inclination). The solar PV field supplies energy to the isolated electric grid. It is composed by a stationary lead-acid battery bank (660 Ah) and a 10 kW charger/inverter equipment. This converter is one of the most important parts of the

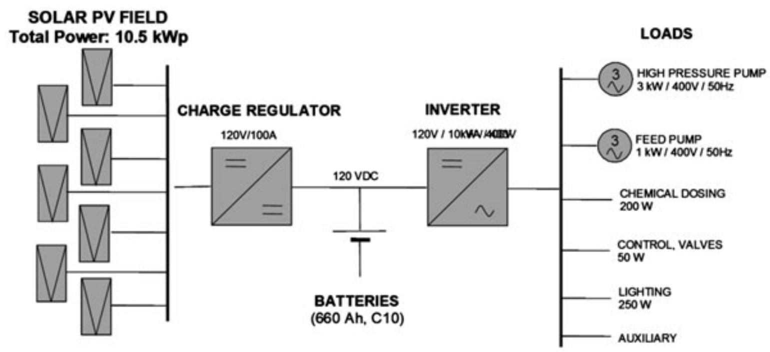


Fig. 4. General electric diagram of the isolated energy system.

energy system as it has the mission of controlling the battery charge as well as supply the AC current to the RO plant. This equipment makes that the PV field operates at the maximum power point and it allows modulating the output AC signal in order to keep it constant to 230 V.

The load system management is carried out by the charger/inverter following the DESSOL® operation criteria. Therefore, the control system always keeps the batteries above their minimum capacity, assuring a long life and maximizing the operation hours; in other words, the control system allows an optimal daily operation of the desalination plant.

3. Seven-year operation data assessment

The main operation data have been periodically collected by the local staff. During the uninterrupted eight-year operation period, the main data have been collected in different sample times, depending on the parameter importance (i.e. some key data were collected each hour). Although the operation time is eight years (May 2006–May 2014), the period of data available and further analysis is for the first seven years.

A comparison of the main operation data in the commissioning (June 2006) and seven years later is illustrated in Table 1. It is necessary to mention that the maximum water demand for the village was estimated in 15 m^3/d (summer 2006 scenario).

The desalination plant has successfully produced more than 15 million litres of freshwater in more than 8,000 h of operation during the last seven-year operation. Table 2 shows the annual freshwater production and hours of operation evolution.

The desalination plant operated correctly since the commissioning. No relevant fouling or scaling problems were detected. Due to the water demand in the village is lower than the design nominal capacity (15 m^3/d—summer 2006), the unit has not required to be connected more than 5 h per day as a general norm. Few significant breakdowns have occurred; just only some short failure events in the water quality sensors.

Initially, data were analysed monthly every year. For the RO plant, monitored information included the following parameters: volume of product water per month, operation hours per month and monthly average product conductivity; the chart of Fig. 5 shows the monthly operation hours during three years.

Table 1
Desalination plant operation data comparison (June 2006 vs. June 2013)

Desalination plant operation data	(June 2006)	(June 2013)
Raw water flow (m^3/h)	3.00	2.80
RO rack feed flow (m^3/h)	5.20	5.50
Raw water conductivity (uS/cm)	5.760	5.630
Raw water temperature (℃)	33	26.8
Raw water SDI	<3	<3
Operation high pressure (bar)	12.0	12.9
Product flow (m^3/h)	2.10	1.90
Product water conductivity (uS/cm)	170	210
Total recovery (%)	70	67.9%
Specific energy consumption (kWh/m^3)	1.70	1.91

Table 2
Annual freshwater production evolution (July 2006–2013)

Data	2006#	2007	2008	2009	2010	2011	2012##	2013
Freshwater volume (m^3)	1.299	2.508	2.693	2,127	1.741	1,731	1.185	1,780
Operation time (%)*	20.1	20.8	20.8	22	15.5	15.7	17.4	N/A
Average water production (August) (m^3/d)	12.3	12.8	12.3	6.76	10.01	6.65	6.67	N/A
Average water production (February)** (m^3/d)	5.7	6.5	8.3	4.89	8.3	3.26	3.56	N/A

#Six months of operation.
##Values for 10 months.
*Ratio "Operation hours during water production days/(24 × operation days)".
**For the case of year 2006, values are for December.

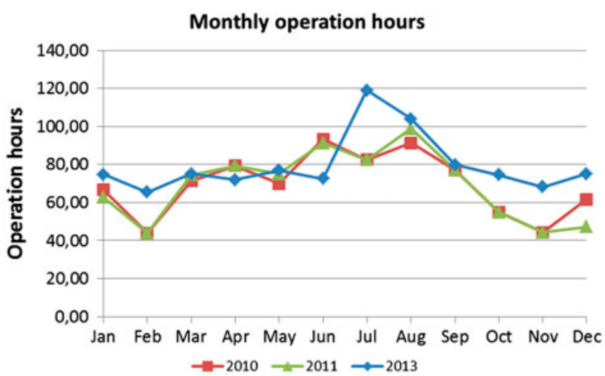


Fig. 5. RO desalination plant operation data: monthly operation hours.

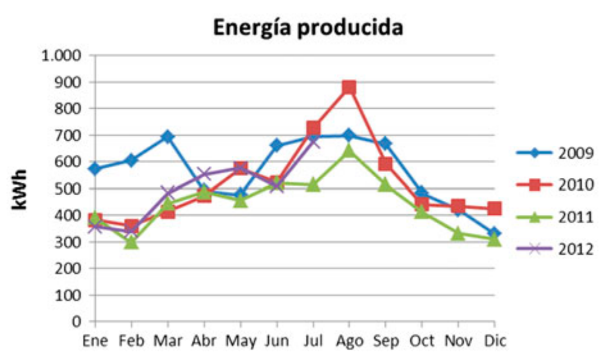


Fig. 6. Chart of generated solar energy (monthly values).

The charts presented in Figs. 5–7, indicate that the higher levels of both water and energy production took place during summer time. As days are longer, the number of sunshine hours is higher.

Concerning the PV system, data analysed were energy produced and consumed (See monthly values in Figs. 6 and 7).

According to the seasonal operating mode of the system, a maximum consumption of 19.3 kWh/d for summer months (6.65 m^3/d of water production in 3.42

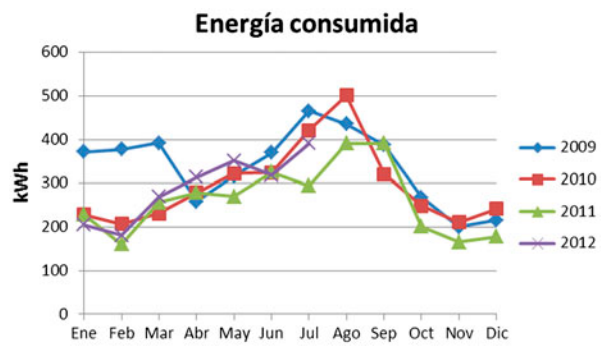


Fig. 7. Chart of consumed energy (monthly values).

operating hours) and a minimum consumption of 13.9 kWh/d for winter months (4.26 m^3/d of freshwater production) is obtained.

An increase of the conductivity of the water product during summer months is detected, which is caused by the increase in the temperature of the feed water and the consequent dilatation of the membrane pores, allowing a higher pass of dissolved salts.

Subsequently, a deeper analysis was done. Once the mayor and minor water production days and energy consumption days were identified, (see Table 3).

An hourly analysis was done for those days, making a comparison between maximum and minimum water production days of each year. Several parameters were analysed, such as fresh water flow,

Table 3
Maximum and minimum values in different years of the whole period

Parameter	Maximum value (day)	Minimum value (day)
Volume of water produced (m^3)	12.60 (16 August 2011)	1.22 (5 November 2011)
Energy produced (kWh)	24.15 (27 August 2010)	3.47 (18 March 2011)

operating pressure, product conductivity, recovery and specific consumption.

According to this analysis, differences between the maximum and minimum values of product water flow are about 17% (1.73–2.08 m^3/h)

On the other hand, power and energy balances were analysed (see Figs. 8 and 9).

There are a relevant number of days in which the plant stays off although there is available power from the PV field. This is due to the demand of water which is under the RO plant production; as soon as the product water tank becomes full, the plant stops automatically, losing the energy that could be generated by the solar field after batteries get charged.

Furthermore, a comparison between the parameters of measurement and the design values was also done in order to know their deviation. The results are shown in Table 4. Over the years, water production starts to decrease, reducing as well the per cent recovery; the pressure values are always higher than the design values, increasing as years go by. This is caused by the membrane degradation due to the fact of continuously stopping and starting the plant.

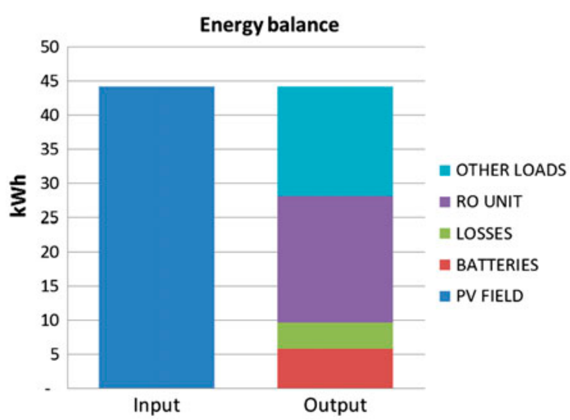


Fig. 8. Energy balance for the day 27.08.10 (energy balance example).

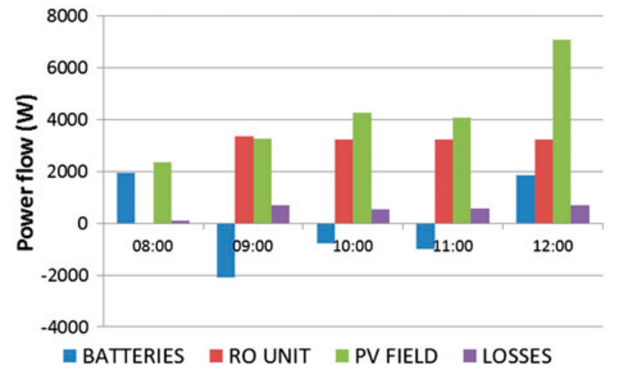


Fig. 9. Hourly power balance for the day 25.01.12.

Similar results were obtained for the maximum and minimum energy consumption days, which are very close to the maximum and minimum water production days.

The project has generated the following positive impacts on the village:

- Improvement of the living conditions: more social stability and high-quality water access.
- 100% of energy autonomy through the photovoltaic solar power, avoiding the use of fossil fuel and the associated polluting impacts.
- High reduction in health problems, mainly in those diseases caused by bacterial presence in water.
- Increment in the number of visits of nomad people leading to more social and economic activities in the village.

Although the capacity of producing water is 40% higher than the local demand, this over supply of water allows the continuity of the water supply, which

Table 4
Selection of data comparison between nominal point and maximum and minimum water production days

Parameter	Nominal value	% deviation (maximum production day) 2010 (16-ago)	2011 (16-ago)	2012 (30-July)	% deviation (minimum production day) 2010 (5-November)	2011 (5-November)	2012 (27-ene)
Production (m^3/h)	2.08	0.96	0.96	−1.44	−8.65	−11.06	−20.67
Work pressure (bar)	11.43	8.49	11.99	13.74	15.49	13.74	20.73
Specific consumption (kWh/m^3)	2.3	−28.49	−28.49	−27.32	18.26	26.13	35.91
Recovery (%)	70	0.00	0.00	−0.73	−3.06	−3.90	−7.56
Product Water conductivity (uS/cm)	150	60	N/A	N/A	17	N/A	N/A

is guaranteed in the case of a possible increase of the demand, like new touristic accommodations, water supply to other visitants, etc.

The creation of a local structure management that guarantees the correct working of the installation is significant. CRDA, with the support of ITC, has coordinated the operation and maintenance tasks by training local technical personnel to perform this maintenance work.

Last but not the least, institutional and local association support is absolutely necessary on projects of these characteristics, especially in developing countries. Success would not be possible without this support.

There have not been relevant or specific failures, but usual problems that appear in conventional RO plants and PV installations.

4. Conclusions

The installation of a 10.5 kWp PV-powered RO desalination system (based on the international patent DESSOL®) with a nominal water capacity of 50 m^3/d was commissioned in June 2006 in village of Ksar Ghilène (Tunisia) by ITC. A successful period of seven years of uninterrupted operation has been analysed. RO desalination plant, fed with solar photovoltaic energy, works correctly, but due to the seasonal low demand of water in the village, it is not operating in its design conditions and it produces less water than expected in certain moments of the year.

During summer time, water quality is reduced due to the high temperature of feed water, increasing the water product conductivity. But the salinity (TDS, Total Dissolved Solids) is always kept under the maximum concentration of 300 ppm.

There are some concluding points to be taken into account in the future to improve the plant operation in several ways:

- By creating new water demand:
  - Either distributing or selling the water excess to close villages.
  - Creation of new crops, as can be the hydroponic, although it is expensive, the plant will have a solution to the water excess and also the village will increase its resources.
  - Increase of touristic offer, with the creation of a new hotel.
- By adding a new load to the photovoltaic field and convert the system in a co-generation unit that produces water and electricity.
- New control adjustments to optimize the batteries operation and the RO unit start/stop sequences.
- Increase the frequency of chemical cleaning to recover the original water production and quality. As demand is low, this has not been a problem yet, but will require attention as soon as new water services are provided.

There are many other remote locations in the North of Africa, where this successful experience could be replicated, starting with the appropriate analysis: wide and deep study of the local conditions: raw water characteristics, solar resources, local water demand profile, socio-economic reality, quality, quantity and cost of current water demand supply, relevant local associations and related administrative issues [14].

The current drinking water shortage situation is becoming a more and more relevant problem in certain regions of the world [15–18]; moreover, this water deficit is expected to be aggravated due to the climate change effects along the coming years. This scenario requires coordinated and global actions; the free pollution water generation through RE-powered desalination is surely a significant contribution to drive a process towards a sustainable solution [19–23].

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