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Demineralization of underground water by a nanofiltration plant coupled with a photovoltaic and wind energy system

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ABSTRACT

To face scarcity of potable water, Morocco has established wastewater and desalination plants. Morocco has also been exploiting its considerable solar and wind energies and in March 2014 launched the first decentralized nanofiltration plant using photovoltaic and wind energy to treat slightly brackish underground water and supply 1,200 students of Al Annouar High School of Sidi Taibi in Kenitra with 500 L/h (3 L/d/student). This Sidi Taibi plant was built by a European consortium of three companies located in the south of France: Belectric Co. (solar energy), Firmus Co. (membrane treatment) and Comodos Co. (wind energy). The Moroccan partners of these companies are: Ibn Tofail University (ITU), the Moroccan Membrane and Desalination Society (the MMDS) and the Regional Education Authority (REA). The aim of this article is to describe the Sidi Taibi plant and to assess its performances (recovery rate, retention rate, energy consumption and sensitivity of the membrane to the fouling, for example) for 1 year (since March 2014). During this period, the experimental results (carried out by the field work team, from March 1, 2014 to March 1, 2015) show the stability of electrical, hydraulic and retentions performances. The constancy of the hydraulic performances and the quality of the potable water produced by the plant confirm the feasibility of the coupling of the mixed renewable energies with the NF treatment for potable water production.

Keywords: Nanofiltration; Demineralization; Photovoltaic energy; Wind energy; Nitrate

1. Introduction

The availability of potable water is a worldwide issue. In arid areas potable water is very scarce, and the establishment of human settlements in these areas strongly depends on the water supply [1].

Seawater and brackish water desalination is one of the adopted processes to meet the increasing demand of potable freshwater. However, desalination is still costly despite the downward trend of the cost of reverse osmosis since the two last decades.

Desalination using renewable energy is based mostly on the reverse osmosis process followed by thermal MSF and MED processes. The main energy source is solar photovoltaic (PV), followed by solar thermal and wind energy [2]. Renewable energy powered desalination technologies are reliable processes and particularly promising for remote region where there is no access to power grid and where water is severely scarce [3].

Until today, the most important seawater desalination plant using PV energy was built in Al Khafji, Saudi Arabia with production capacity of 65,000 m^3/d. At Kwinana close to Perth (Australia), the important seawater desalination plant (2007) with a production capacity of 144,000 m^3/d works exclusively with energy from the wind farm located at 200 km north of Perth [4–9].

In Morocco, the Sidi Taibi plant (located close to Kenitra) has been operating since March 2014 and is the only renewable energy powered desalination system in service.

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The produced renewable energy is hybrid of PV and wind energy, used for desalination by the nanofiltration (NF) process. The raw water is underground water, with a slight excess in the nitrate content. The region is well known as an agricultural area, which causes a deterioration of water quality generating a risk in rural areas, where most people use the aquifer as their daily drinking water [10]. The ingested nitrate turns to nitrite, leading to child methaemoglobinaemia and old age cancer forms. The World Health Organization (WHO) fixed at 50 mg/L the maximum acceptable concentration of nitrate in drinking water [11]. The same norm is adopted in Morocco.

The Sidi Taibi plant located at Al Annouar High school (Province of Kenitra) was designed to supply 1,200 students with drinking water. Besides the slight excess of nitrates, the feed underground water presents a slight excess in salinity. NF easily brings the nitrate content and salinity to values which agree with drinking water norms.

The aim of this work is to present the Sidi Taibi decentralized desalination plant and to follow and discuss its performances (recovery rate, retention rate, energy consumption, vulnerability of the membrane to the fouling, etc.) during 1 year since the start-up.

This article includes two parts that, respectively, describe the plant and its performances. The first part focuses on water treatment (Section 2.1), renewable energy powered NF system (Section 2.2), testing protocol and determination of performances indicators (Section 2.3). The second part of this paper discusses water treatment (Section 3.1), energy storage and integration of all the system (Section 3.2).

2. Description of the plant

2.1. Water treatment

The Sidi Taibi plant project was emerged from the collaboration between Belectric and Firmus, both companies located in the Languedoc Roussillon region in the south of France. They united their skills and knowledge to set up a membrane water treatment plant that can be powered by PV and wind energy.

This desalination plant consists of four steps as described in Fig. 1.

- Pretreatment step: It is composed of two prefilters connected in series. A first filter allows the removal of sludge which may be present in the wellbore. It identifies the size of particles less than 25 µm. A second prefilter allows the removal of fine particles greater than 5 µm.
- NF step: It is composed of two membranes (NF90 40×40), type: polyamide, Filmtec Dow, connected in series. The prefiltered water is collected in the modules with the aid of a high-pressure pump. The permeate is sent to a storage tank for use after a disinfection operation. 70% of the water rejected by the membrane (concentrate) is returned upstream of the high-pressure pump for recycling, while the rest, 30%, is evacuated for vegetables irrigation.
- Disinfection step (without additives): Sunpure is a compact electrochemical disinfection system which does not request any additives for the local production of drinking water. It requires electrical energy. The nanofiltered water is prepared to be disinfected and it is led into the electrolytic cell for the in situ generation of chlorine.
- Storage and distribution: After a disinfection step, the produced water was stored in a storage tank and distributed by a dispensing pump, managed by the system controller.

2.1.1. Characteristics of the water to be treated

The analysis of the raw water (underground water) gives the results shown in Table 1.

The quality of Sidi Taibi's underground water (Table 1) is not in conformity with sanitary standards because of the high concentrations of nitrate which exceeds the standards required by WHO (50 mg/L) [11]. These results could be explained by the prevailing sandy nature of the soil in the area, the frequency of fertilizer usage and the closeness of the water table [12].

2.2. Renewable energy powered nanofiltration system (PV-wind/NF system)

2.2.1. PV conversion of solar energy

PV technologies involve the direct conversion of solar energy to electricity. As the PV technology is maturing and cost of PV systems is decreasing, the demand of this renewable energy technology in developing countries is increasing exponentially [13].

Two types of PV technology are currently available in the market: (1) crystalline silicon-based PV cells and (2) thin-film

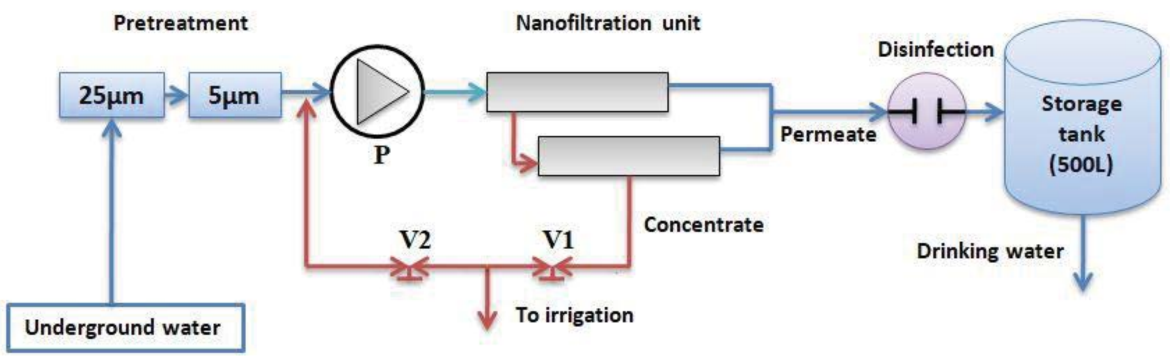

Fig. 1. Nanofiltration unit architecture. V1: pressure regulation valve; V2: concentrate recirculation valve; P: high pressure pump.

Table 1
Characteristics of the raw underground water and the WHO standards for drinking water

	Underground water	WHO standards [11]
pH	6.79	6.5–8.5
Conductivity (µs/cm)	753	–
COD (mg/L)	88	–
Sodium (mg/L)	40	<200
Ammonium (mg/L)	<0.1	–
Potassium (mg/L)	11	–
Magnesium (mg/L)	7.8	<50
Calcium (mg/L)	128	<270
Fluoride (mg/L)	0.043	<1.5
Chloride (mg/L)	57	<250
Bromide (mg/L)	<0.1	–
Nitrate (mg/L)	68	<50
Phosphate (mg/L)	<0.1	–
Sulphate (mg/L)	10	<500
Turbidity (NTU)	0.39	<5

technologies made out of a range of different semiconductor materials, including amorphous silicon cadmium–telluride and copper indium gallium diselenide [14].

Morocco is characterized by intensive solar radiation with an average of 5.3 kWh/m^2 annual sunshine varying from 2,700 h in the north to approximately 3,500 h in the south (Fig. 2 [15]).

2.2.2. Wind energy

Wind energy is emerging as one of the most promising alternative sources of energy due to its potential to meet rising demands for electricity [16]. Wind energy for electricity production nowadays is a mature, competitive and virtually pollution-free technology widely used in many regions of the world [17]. Using special turbines, the power of wind is converted into electricity. The power ratings of the most common wind turbines vary from 1.5 to 5 MW [18].

Morocco has an excellent wind potential [19] in the North and in the South with an annual mean wind speed between 8 and 11 m/s in the North, especially on the Atlantic coastal regions and between 7 and 8.5 m/s in the South (Fig. 3 [20]).

2.2.3. The renewable energy platform

As is shown by Fig. 4, the renewable energy platform is composed of two PV fields, one of them is connected to a wind turbine. The total power of the two fields is 23.22 kWc for an estimated annual production of 40 MWh/year. The characteristics of the two fields are as follows:

- Field 1: 96 thin-film modules, CIS technology, of 145 Wp unit power.

It is connected to a 2.2 kW vertical axis wind turbine and to the grid for a total self-consumption. The wind turbine allows the production of 2,000–4,000 kWh/year.

- Field 2: 62 thin-film modules, CIS technology, of 150 Wp unit power.

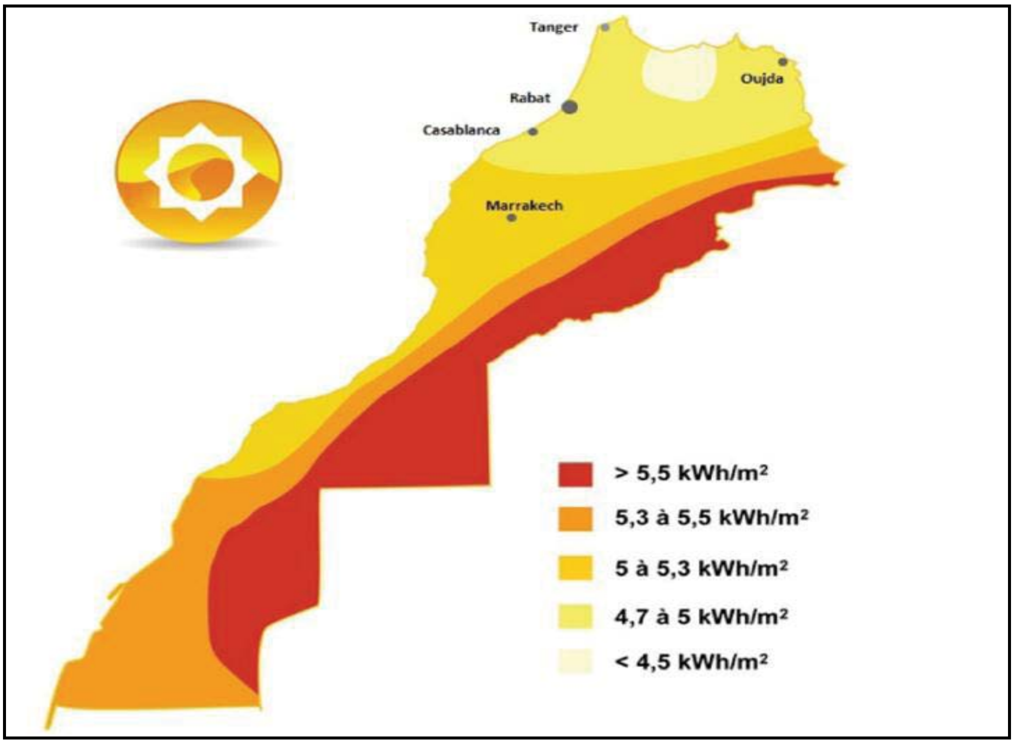

Fig. 2. Moroccan solar potential [15].

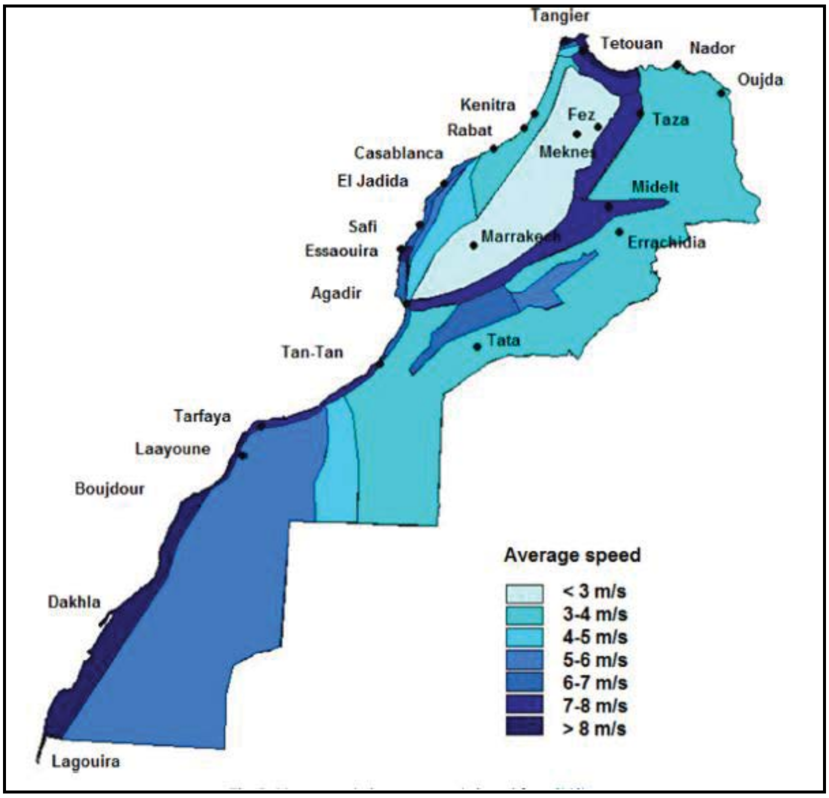

Fig. 3. Moroccan wind energy map (adapted from Ref. [20]).

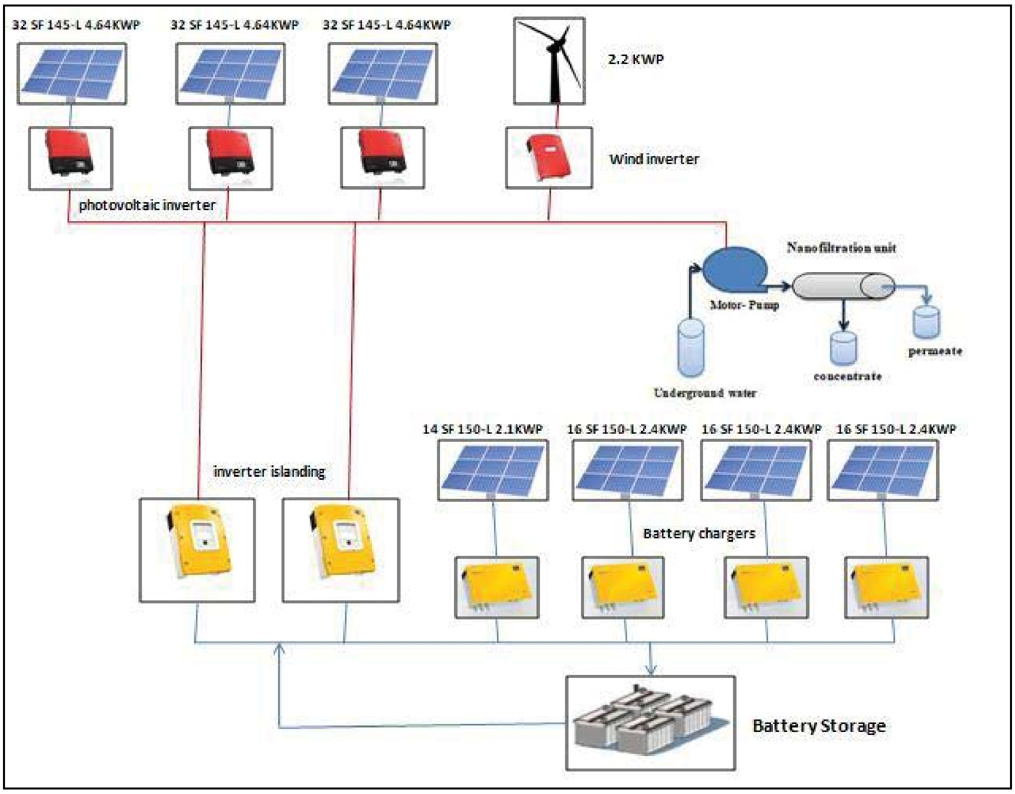

Fig. 4. Nanofiltration desalination unit architecture powered by a stand-alone PV-wind hybrid system. ▬▬ : Alternating current (AC), ▬▬ : Direct current (DC).

It is connected, via chargers, to a battery bank with a C100 capacity of 1,200 Ah and a nominal voltage of 48 V. Composed of 24 lead gel (OPzV) cells, 8 V 1,200 Ah each wired in 4 parallel chains of 6 elements in series each.

The stored energy can be used during peak consumption periods or for night use.

Fig. 5 presents the monthly irradiation data of the site.

- Tables 2 and 3 summarize the estimated PV production of the fields:
- Location: 34°11′15″ North, 6°41′25″ West, Elevation: 13 m a.s.l.,
- Field 1:
  - o Nominal power of the PV system: 13.9 kW (CIS)
  - o Estimated losses due to temperature and low irradiance: 9.4% (using local ambient temperature)
  - o Estimated loss due to angular reflectance effects: 2.8%
  - o Other losses (cables, inverter, etc.): 14.0%
  - o Combined PV system losses: 24.2%
- Field 2:
  - o Nominal power of the PV system: 9,300 Wp
  - o Inclination of modules: 20°
  - o Battery size: 48 V, 1,200 Ah
  - o Discharge cut-off limit: 80%
  - o Percentage of days with fully charged battery: 100%
  - o Releasable energy/10 h: 37,248 Wh
  - o Estimated losses due to temperature and low irradiance: 9.5% (using local ambient temperature)
  - o Estimated loss to angular reflectance effects: 2.7%
  - o Other losses (cables, inverter, etc.): 14.0%
  - o Combined PV system losses: 24.2%

2.2.4. PV-wind coupled NF system

The technical container is equipped with filtration system (NF unit) but of the entire power electronics complemented by storage batteries. Battery technology chosen is lead gel (OPzV). The storage capacity is 48 kWh.

These batteries are suitable for loads produced by a PV generator. Battery charge is controlled by an inverter provided to remote sites, the stored energy which is managed in real time by an intelligent system. Indeed, it will be able to

Table 2
The estimated photovoltaic production of the field 1

Inclination=16°, Orientation=0°				
Month	E_d	E_m	H_d	H_m
January	43.20	1,340	3.96	123
February	53.50	1,500	4.91	137
March	66.20	2,050	6.26	194
April	72.40	2,170	6.86	206
May	75.60	2,340	7.29	226
June	78.80	2,360	7.62	229
July	80.20	2,490	7.75	240
August	76.70	2,380	7.45	231
September	67.50	2,020	6.49	195
October	58.00	1,800	5.51	171
November	45.80	1,370	4.26	128
December	40.70	1,260	3.76	117
Yearly average	63.3	1,920	6.02	183
Total for year	23,100		2,200	

E_d: Average daily electricity production from the given system (kWh).
E_m: Average monthly electricity production from the given system (kWh).
H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2).
H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2).

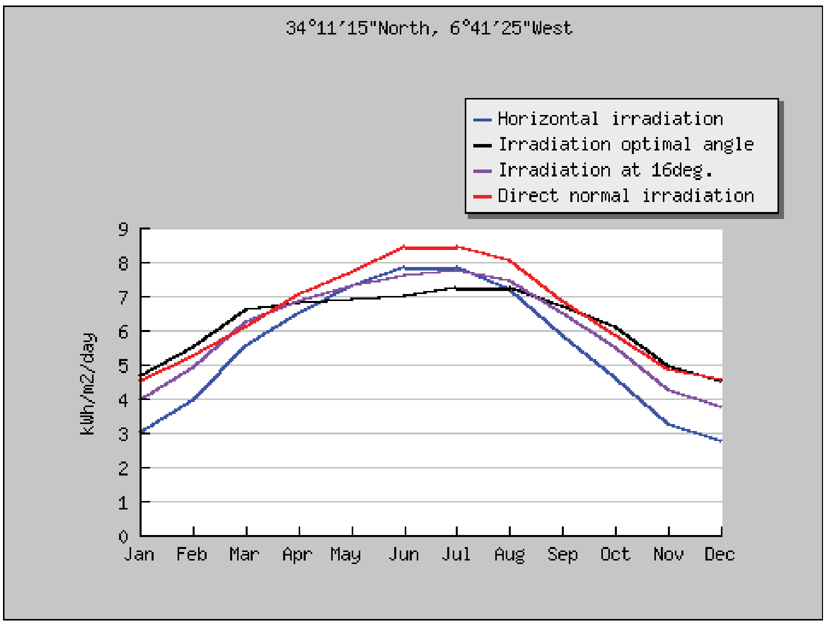

Fig. 5. Monthly irradiation diagram – Sidi Taibi.

Table 3
The estimated photovoltaic production of the field 2

Inclination=20°, Orientation=0°				
Month	E_d	E_m	H_d	H_m
January	30.40	944	4.17	129
February	37.10	1,040	5.10	143
March	45.10	1,400	6.38	198
April	48.50	1,460	6.88	207
May	50.00	1,550	7.22	224
June	51.70	1,550	7.49	225
July	52.80	1,640	7.65	237
August	51.10	1,580	7.44	231
September	45.70	1,370	6.59	198
October	40.00	1,240	5.70	177
November	32.20	965	4.48	134
December	28.90	895	3.99	124
Yearly average	42.8	1,300	6.10	185
Total for year	15,600		2,230	

E_d: Average daily electricity production from the given system (kWh).
E_m: Average monthly electricity production from the given system (kWh).
H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2).
H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2).

couple the solar and/or wind turbine with the energy stored in the batteries according to the consumption of the filtration system and the PV production. Fig. 6 shows a schematic diagram of a PV-wind coupled with NF system.

2.3. *Testing protocol and determination of performance indicators*

A number of key parameters of the installation were measured (permeate flow rate (L/h), concentrate flow rate (L/h), transmembrane pressure (bar)) and performance indicators calculated as specified in Eqs. (1)–(4). The parameters taken into account are as follows:

- The recovery rate is calculated using the following equation:

$$Y(\%) = \frac{Q_p}{Q_f} \times 100 \tag{1}$$

where Q_f and Q_p are the feed and the permeate flow rate, respectively.

- The retention (R) is defined as follows:

$$R(\%) = \frac{(C_f - C_p)}{C_f} \times 100 \tag{2}$$

where C_p and C_f are, respectively, the permeate and initial concentration.

- The salt retention is defined as follows:

$$R(\%) = \frac{(\text{Cond}_f - \text{Cond}_p)}{\text{Cond}_f} \times 100 \tag{3}$$

where Cond_p and Cond_f are, respectively, the conductivity of permeate and feed water.

- The specific energy consumption is proportional to the transmembrane pressure. It is calculated by the following relation:

$$E(\text{kWh / m}^3) = \frac{\Delta P \times 100}{\eta \times Y \times 36} \tag{4}$$

where ΔP is the transmembrane pressure in bar, η is the global pumping system efficiency, Y (%) is the recovery rate.

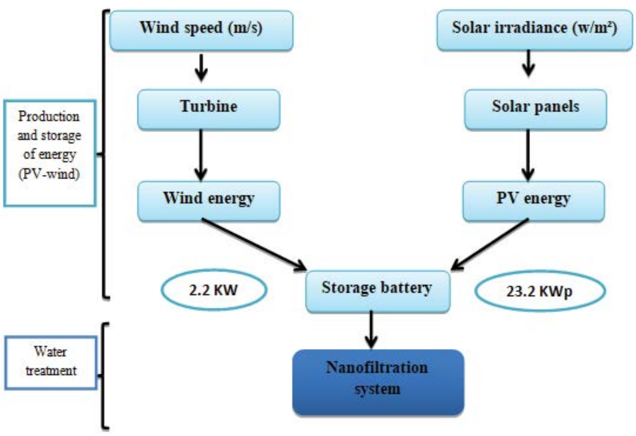

Fig. 6. Schematic diagram of a PV-wind coupled with nanofiltration system.

3. Performances of the plant

3.1. *Water treatment*

3.1.1. *Retention performance*

During the experimental period, extends from March 2014 to March 2015, the underground water and the permeate were regularly sampled for analysis.

The monitoring of the quality of the underground water makes it possible to evaluate the effects of the various quality parameters on the NF treatment. In particular, the fouling depends on the quality of the feed water. This phenomenon has a direct impact on the quality of the permeate and the daily production of the drinking water.

At the same time, the monitoring of the permeate quality not only enables the evaluation of the overall performance of the NF treatment, but also allows the calculation of the retention rates for various water constituents by using Eq. (2). The analysis parameters of the feed water and the permeate are presented in Table 4.

According to these results, one can say that the quality of the Sidi Taibi's underground water is characterized by a

Table 4
Characteristics of the underground water, permeate and retention of ions by nanofiltration membrane

	Underground water	Permeate	Retention (%)
pH	6.79	6.33	–
Conductivity (µs/cm)	753	350	53
COD (mg/L)	88	<15	–
Sodium (mg/L)	40	10	75
Ammonium (mg/L)	<0.1	<0.1	–
Potassium (mg/L)	11	7.5	31
Magnesium (mg/L)	7.8	0.2	97.4
Calcium (mg/L)	128	4.2	96.7
Fluoride (mg/L)	0.043	0.001	97
Chloride (mg/L)	57	3.4	94
Bromide (mg/L)	<0.1	<0.1	–
Nitrate (mg/L)	68	18	73.5
Phosphate (mg/L)	<0.1	<0.1	–
Sulphate (mg/L)	10	4.9	51
Turbidity (NTU)	0.39	0.2	–

slight excess in nitrate content, which exceeds the standards required by the WHO. This nitrate content can be explained by the penetration of the two main nutrient components, nitrogen and phosphorus [21]. Indeed, nitrates have certain characteristics which account for the evolution of their current levels in the water table: they are very stable and very soluble in water, and their penetration in soils is slow (their migration speed would be about 1 m/year) [22]. As a result, the nitrate concentration in underground water is stable during 1 year of study (Fig. 7). Therefore, to achieve acceptable quality for drinking water, the application of NF technology could be useful to treat water with such high nitrate concentration [23,24].

The use of NF technology removes the nitrate concentration of underground water up till 73% of retention rate. Hence, the drinking water (permeate) contains no more than 20 mg/L, which is almost less than the WHO standards (Fig. 7).

On the other hand, the results obtained in this research shows that NF membrane is able to reduce 96% of calcium ions and 97% of magnesium ions. This could be explained by the fact that NF membrane has a high retention of charged particles, especially bivalent ions, making this technology suitable to remove hardness and a wide range of other components in one step [25]. Concerning the anions, the retention sequence is: R (F^-) > R (Cl^-) > R (NO_3^-). This result may be explained by the fact that when an ion is strongly hydrated, it becomes more bulky and will be more rejected by NF membrane (Table 5) [26–28].

Indeed, the application of NF membrane reduces the conductivity of underground water from 753 to 350 µs/cm with a salt retention of 53% (Fig. 8). These results are explained by the fact that all ions are definitely better rejected by this operation.

Finally, NF90 shows the ability to reject both monovalent and divalent ions of Sidi Taibi's underground water with very reasonable values. Moreover, it reduced the salinity of this water to values which agree with the drinking water norms. Therefore, the produced water does not require any remineralization, it is directly distributed after a disinfection step.

Table 5
Feed composition and retention of ions by nanofiltration membrane

Ion	Feed concentration (mg/L)	Retention (NF90) (%)	Hydration energy (kJ/mol) [28,29]
Mg^{2+}	7.8	97.4	1,921
Ca^{2+}	128	96	1,584
Cl^-	57	94	376
F^-	0.043	97	505
NO_3^-	68	73.52	329

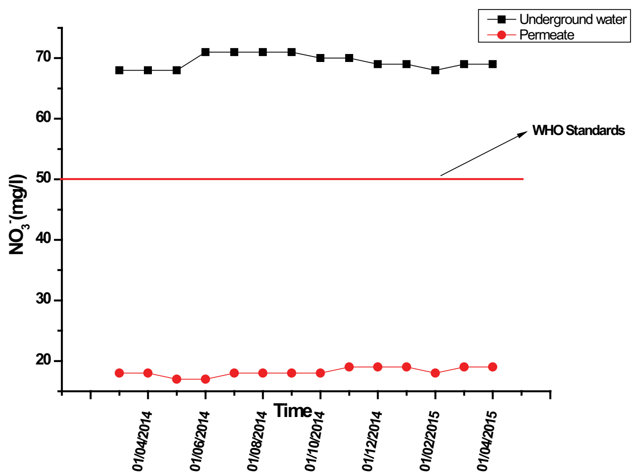

Fig. 7. Evolution of the nitrate content in the underground water and in the permeate versus time. Period: March 2014 to April 2015.

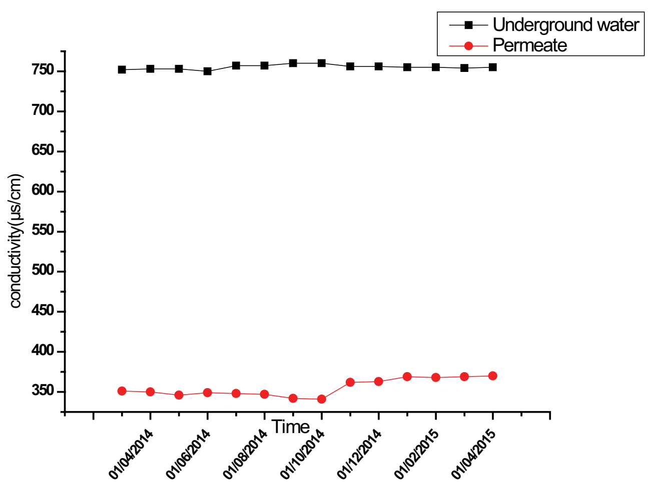

Fig. 8. Evolution of the conductivity of the underground water and the permeate versus time. Period: March 2014 to April 2015.

3.1.2. Hydraulic performance (NF unit productivity)

The NF module consists of two NF 90 40×40 membranes, type: Polyamide Thin-Film Composite Filmtec Dow, installed in series with a total area of 15.2 m² (7.6 m² × 2) allowing a permeate flow rate of 7.6 m^3/d with salt retention of 99.8%. This technology enables to produce a clean drinking water from brackish water sources with very important fluxes, it is also designed to operate at lower pressures (5–10 bars) than RO membranes, and the power requirements are significantly reduced [30–36].

Fig. 9 shows the yearly evolution of the permeate flow rate which is almost constant (around 460 L/h). This stability is mainly influenced by the compatible execution of the operating parameters of NF membrane (pressure: 5 bar and recovery rate: 75%), and the operating characteristics of the plant (Table 6).

Finally, the application of NF membrane enables to satisfy the daily requirement of drinking water for the high school with a specific energy consumption of 0.2 kWh/m^3. This value is still less than the specific energy required for demineralization of brackish water by reverse osmosis [25,37–39].

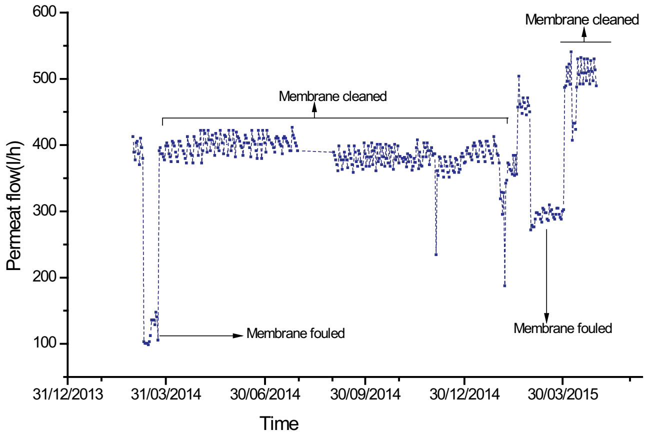

Fig. 9. Evolution of the permeate flow rate versus time. Period: March 2014 to April 2014 at TMP = 5 bar and recovery rate = 75%.

Table 6
Operating characteristics of the plant

Parameters	Recommended values	Data source
Maximum operating temperature	113°F (45°C)	Manufacturer
Maximum operating pressure	41 bar	Manufacturer
pH range, continuous operation	3–10	Manufacturer
Maximum feed flow rate	15.9 m^3/h	Manufacturer
Maximum feed silt density index (SDI)	5	Manufacturer

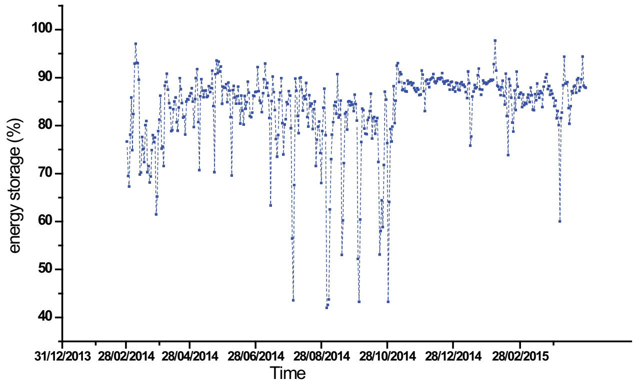

Fig. 10. Energy storage versus time. Period: March 2014–March 2015.

3.2. Energy storage and the integration of all the system (PV-wind/nanofiltration)

During 1 year since the starting-up, the energy storage curve of Sidi Taibi plant shows that the batteries has enough power (Min: 42% and Max: 97%) for the NF consumption request (Fig. 10). This also ensures a constant water flow production whatever the weather (rain, heat, wind, etc.) (Fig. 9).

4. Conclusion

This study shows the effectiveness during 1 year of a small decentralized membrane-based desalination coupled with hybrid energy system of PV and wind. The produced energy is used for the potable water production by NF and for the daily requirement of electricity for the high school. The membrane unity is fed by underground brackish water where nitrate content exceeds slightly the recommended range.

During the year of the study, the combination of photovoltaic-wind hybrid system with a nanofiltration (PV-WIND-NF) in the Sidi Taibi plant shows:

- Stability of hydraulic performance;
- Stability of retention performance;
- Stability of electricity production;
- Lower energy consumption;
- Feasibility of the coupling of the mix renewable energy and NF treatment for drinking water production.

This kind of decentralized desalination plant using NF membrane process is a promising way to provide water especially in rural areas and remote zones who are suffering of water scarcity and who do not have access to electric grid and where solar radiation and wind speed are appropriate.

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