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Nitrate removal by nanofiltration powered by a hybrid system of renewable energies (solar and wind): technico-economic assessment

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ABSTRACT

Population growth is accompanied by an increase in food demand. In Morocco, the application of large amounts of fertilizer to meet this demand has increased nitrate concentrations in groundwater. However, it is estimated that 6% of these resources exceed the nitrate content recommended by the World Health Organization (50 mg/L) for drinking water. This study focuses on nitrate removal from groundwater by nanofiltration powered with renewable energy mix (solar and wind) in Sidi Taibi in the province of Kenitra (Morocco), which is characterized by intensive solar radiation (5.3 kWh/m^2) and has an excellent wind potential (5 m/s). The plant is installed at Al Anouar high school. This plant provides drinking water to 2,000 pupils. The raw water is a groundwater, which is slightly brackish and with a nitrate content of around 70 mg/L. The purpose of this study is to carry out a technico-economic study on nitrate removal from groundwater operating with a renewable energy mix to assess the cost of the water produced by this system. The hydraulic production capacity of the plant is (12 m^3/d) with a recovery rate of (75%) and the nitrate content is lowered up to 18 mg/L. The total energy produced in 1 y is 43 MWh. Finally, the cost of the drinking water produced is estimated to 0.8820US $/m^3.

Keywords: Groundwater; Nitrate removal; Nanofiltration; Wind turbine; Photovoltaic panels; Technico-economic

1. Introduction

UNESCO reports that more than two billion people worldwide still lack access to safe water in 2019 [1]. Fresh water represents only 2.5% of 70% of planetary water and only 0.7% is accessible to humans. This meager global resource is very unevenly distributed geologically: 85% of the world's population lives in the most arid part of the planet. Population growth, accelerated urbanization and economic development have dramatically increased water needs in a context of water scarcity. To deal with this situation in the short and medium term, the strategies developed by the states revolve, first, around appealing to unconventional resources, in particular the desalination of water and the reuse of purified wastewater.

Nitrates are very abundant in the environment and consequently cause ecological imbalances such as eutrophication of lakes and red tides [2,3], in addition, high concentrations of nitrate in drinking water pose a serious

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threat to human health [4] and causes diseases like methemoglobinemia, blue baby syndrome and forms of cancer of aging [5–7]. In Morocco, in irrigated regions, diffuse nitric pollution in groundwater increases the risk of deterioration of water resources and poses health risks for the rural population. African countries and those in the Middle East, which are characterized by many dry months with insufficient rainfall which do not have access to fresh water resources, are bypassed towards desalination technologies that were developed ago several years because most of the cities in these countries are located along the coast [8]. Desalination is an energy intensive process; it uses fossil fuels as an energy source which will be exhausted within 50 y if consumption is at the current rate [9]. The International Desalination Association (IDA) reports that currently around 18,500 desalination plants operating in 150 countries with a maximum contractual capacity of around 99.8 million cubic meters of water per day as of 2017 [10]. According to IDA, Saudi Arabia, United Arab Emirates, Spain, Kuwait and Algeria are the largest producers of desalinated water [11]. Recent estimates indicate that around 53% of the world's desalination potential is installed in the Middle East and North Africa (MENA) region, followed by North America and Asia [12]. In the United States, 325 desalination plants are operational. According to the Texas Water Development Board [13], Florida is the first region using desalination technology in the states with 150 operational desalination plants and their capacity will be increased by a further 25% by 2025, or 33 million m^3/d [14]. Texas has 46 desalination plants with a total capacity of 465,605 m^3/d [13]. Around 1,000 desalination plants are operational in India with a capacity of 291,820 m^3/d [15]. China is also one of the main countries with 57 desalination plants of varying capacity. The largest is the Tianjin seawater desalination plant developed by International Desalination Association (IDE) with a capacity of 200,000 m^3/d [16]. New alternative energy sources must be exploited for future energy security. Solar and wind are the most abundant, clean and sustainable energies that build a qualitative and reliable hybrid system superior to those of single resources [17–19]. Storage batteries for this kind of system are essential; they increase stability and efficiency when wind speed and radiation are not sufficient [20,21].

Membrane-based technologies are expensive processes and especially nanofiltration (NF) and reverse osmosis (RO). Others factors affect the cost of NF and RO treatment process such as the plant production capacity of m^3, the produced water quality, the raw water quality, recovery rate and energy. In this context, PV-based desalination systems are available in various sizes ranging from 0.8 to 60,000 m^3/d with an approximate cost of US $ 34.21 to 0.825/m^3 [10]. In addition, desalination plants powered by wind power are available in sizes ranging from 1 to 250,000 m^3/d with an approximate cost of 15.75 US $/$m^3$ to 0.66/m^3 [10]. Desalination systems based on hybrid wind-PV energy have been implemented in many countries with a size ranging from 3 to 83,000 m^3/d and the cost of water for these systems ranges from US$ 6.12 to 1.4/m^3.

In this study, the performance of the Sidi Taibi treatment plant based on NF powered by a renewable energy mix (solar panels and wind turbine) in the reduction on nitrate is carried out for drinking water production. The annual electrical capacity is of the order of 43 MWh/y. The main objective of this work is to calculate the cost of m^3 of treated water and the kWh produced by this electrical installation in this station.

2. Materials and methods

2.1. Description of the plant

The energy management system is widely used for renewable energy generators, especially for photovoltaic panels and wind turbines, due to the unpredictable nature of solar irradiation and wind. The Sidi Taibi plant is equipped with 400 m^2 of photovoltaic (PV) panels and a wind turbine, which produce the electricity that powers the treatment system and other equipment in the plant. Fig. 1 summarizes the different elements of the Sidi Taibi desalination plant.

2.2. Energy part

The Wind Turbine (WT) is UrWind 2.2, with a vertical axis of the Darrieus and Savonius type. This technology promotes its rotation in all directions of the wind. The power of the wind turbine is 2.2 kW and allows a production of 2,000 to 4,000 kWh/y. This turbine is connected to the PV panels, which are thin-film type with efficiency up to 12%. PV panels involve the direct conversion of solar light radiation into electricity. The capacity of the plant is ensured by: 62 panels of (150 W) stored in the batteries and 96 panels of (145 W) feed the system. The electricity for this facility is managed by three components: the first one is the Converter DC/AC (Sunny Boy): The inverter converts the direct current of the photovoltaic modules into alternating current identical to that of the grid. The second one is the energy management Sunny Island (SI) who ensures an economical and secure energy supply at all times. It balances peaks in load and consumption and supports the energy supply in the event of a network failure. The last one is the Charge Controller Sunny Island (SI), which is a solar charge controller with maximum power point monitoring. A large part of the electricity produced is sent to the storage batteries, which are in the order of 24 units of 2 V each of lead gel type (OPzV). The storage capacity is 48 kWh [22]. The Sidi Taibi station produces a total energy of about 25.43 kWh of which 15 kWh (Table 1) is self-consumed and the rest is injected into the school network.

2.3. Water part

The water treatment unit consists of a pump emerged in a well 30 m deep which supplies the NF unit with groundwater. At the inlet of the pilot plant there are two prefilters that serve to physically pretreat groundwater. The aim of this step is to protect the membranes and increase their lifetime. The first pre-filter allows the elimination of any sludge present in the wellbore. It removes particles larger than 25 μm. The second pre-filter removes particles larger than 5 μm. Then, the pretreated water is directed into the NF, which is composed of two membranes (NF90) modules, connected in series. Prefiltered water is sent to

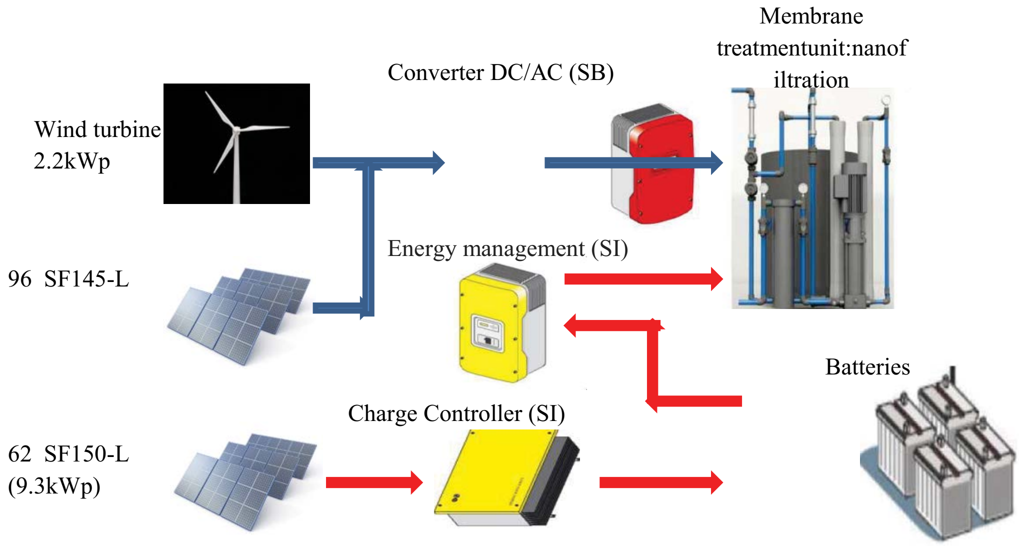

Fig. 1. General diagram of the different components of the Sidi Taibi plant.

Table 1
Whole electricity consumption of Sidi Taibi plant

Equipments	Power (W)
Filtration system	3,500
Air conditioner	5,000
2 Light fixtures	100
WebBox	10
Fan	250
Immersed pump	1,500
SUNPUR (electrochemical disinfection)	100–700
Supply of buildings	4,500

the modules using a high-pressure pump. The nanofiltered water is routed to be disinfected by an electrochemical disinfection system based on the in-situ generation of chlorine (Table 2). After disinfection, the nanofiltered water is stored in a 500 L tank and then distributed to supply the high school with drinking water [22] (Fig. 2).

3. Results and discussion

3.1. Performance of the Sidi Taibi plant

3.1.1. Water treatment

Raw water and treated water after the disinfection step are sampled and analyzed for monitoring throughout the period from March 2015 to February 2016. The performance of NF and the quality of the produced water (permeate), which is almost constant 460 L/h (Fig. 3), depends generally on the quality of the feed water. Table 3 shows the various parameters carried out on the raw water and permeate. From these results, it is noted that almost the majority of the parameters are in standard required by the WHO except the content of nitrates, which exceeds slightly WHO recommendation (70 mg/L). This exceed is due to human activities such as excessive application of fertilizers [23], random discharge of manure from domestic sewage and livestock [24] and water irrigation worn [25]. Nitrates are very stable and soluble in water, hence the stability of its concentration in groundwater during the study period (Fig. 4). NF with recovery rate of approximately 75% (Fig. 5), lowers nitrate content from 70 mg/L in the input of the unit to 18 mg/L in the permeate at the output of the unit. The produced water meets the standard required by WHO for drinking water. The electric conductivity of groundwater is around 750 µS/cm, the NF process brings this value less than 88 µS/cm, which confirms the efficiency of salt rejection (Fig. 6). These results show that the NF process has a high efficiency in retaining nitrate and salts present in groundwater.

3.1.2. Energy platform

3.1.2.1. Photovoltaic panels

Firstly, the energy produced under real conditions is generally less than that which would have been produced under standard conditions. This is due to the daily global radiation, the position of the solar panels (orientation and inclination) and the temperature. The power, generated by a PV, depends on the temperature of the cell and the solar radiation. The electricity production of a photovoltaic generator is indicated by (1) [26].

$$P_{\text{PV}} = P_{\text{PV nominal}} \times \left(\frac{G}{1000}\right) \times \eta_{\text{mppt}} \tag{1}$$

where G is the solar radiation at the surface PV (W/m^2), $P_{\text{PV nominal}}$, is the nominal power PV for G = 1,000 (W/m^2) and η_{mppt} is the efficiency of the module.

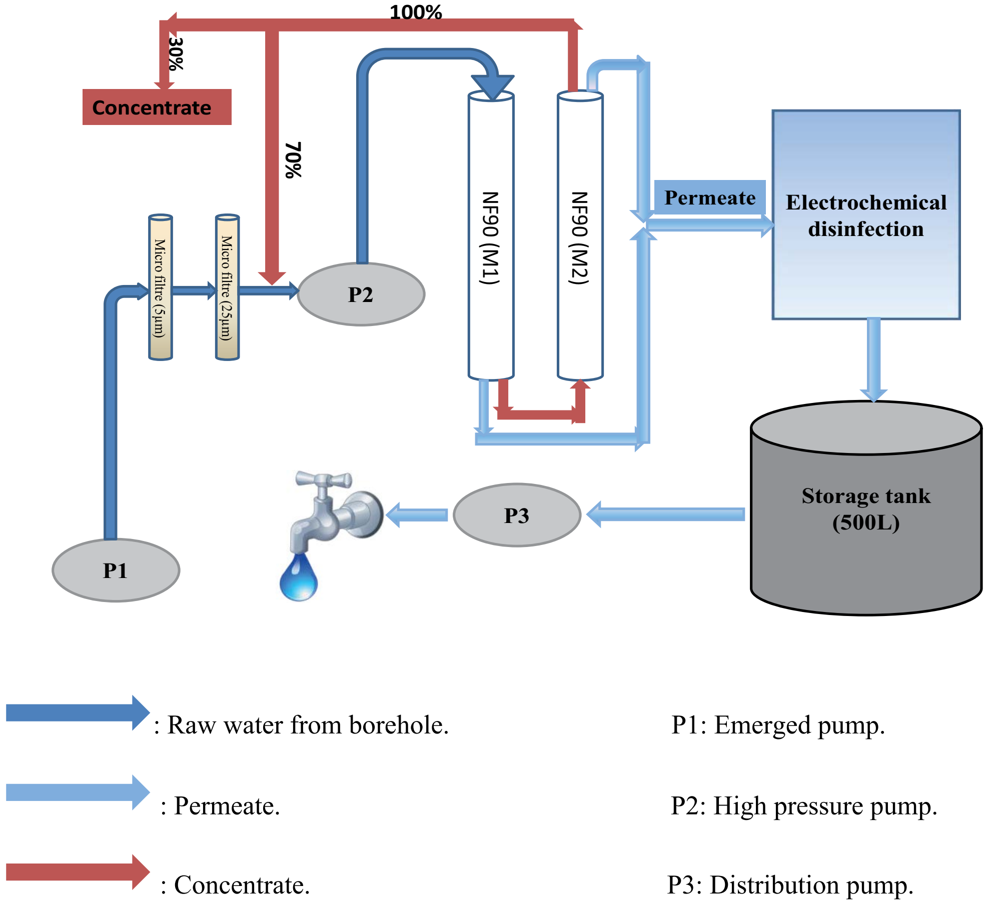

Fig. 2. Diagram NF unit.

Table 2
Operating characteristics of the electrochemical disinfection system of the plant

Electrochemical disinfection system (SUNPUR)	Recommended values	Data sources (BELECTRIC)
Power input	220V AC	Manufacturer
Required chloride of low water	10–250 mg/L	Manufacturer
Minimum flow rate	400 L/h	Manufacturer
Maximum flow rate	Depend on current supply	Manufacturer
Power consumption	100–700 W	Manufacturer
Water temperature	4°C–25°C	Manufacturer
Ambient temperature	Maximum 50°C	Manufacturer

The Sidi Taibi plant is made up of two structures, the first of which is above the container with an orientation of 0° South and 20° of inclination and the second has an orientation of 0° South and 16° of inclination. The plant includes 158 thin-film type PV panels, with a power of 145 Wp for (96 panels) and 150 Wp (62 other panels) with a total capacity of 23.23 kWp, for an estimated annual production of 40 MWh.

As shown in Fig. 7, the energy curve produced and stored in the batteries varies between 65% and 97% throughout the year, which ensures a stable power supply to the water treatment unit and other components that require electricity and guarantees a constant production of drinking water.

3.1.2.2. Wind turbine installation

The wind turbine generates energy when the wind speed is within the cut-off speed, and this is depends on the wind speed, air density and the area of the wind turbine. The

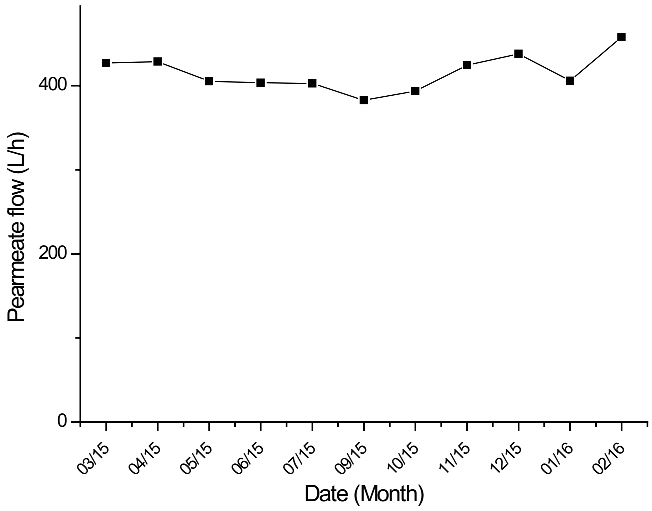

Fig. 3. Evolution of the permeate flow rate over 1 y.

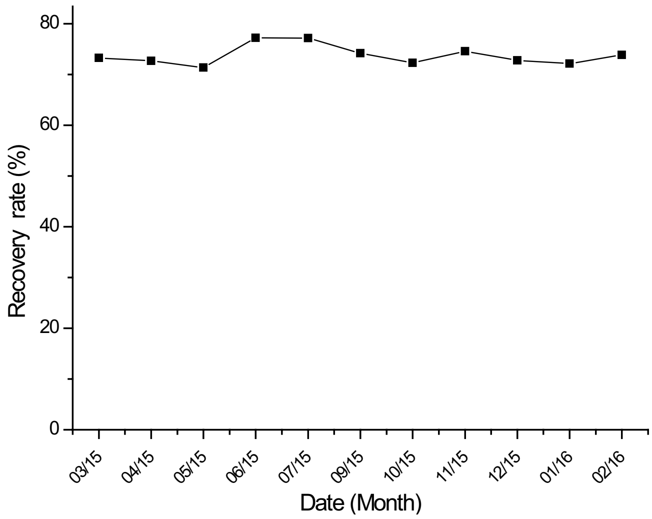

Fig. 5. Evolution of the recovery rate over 1 y.

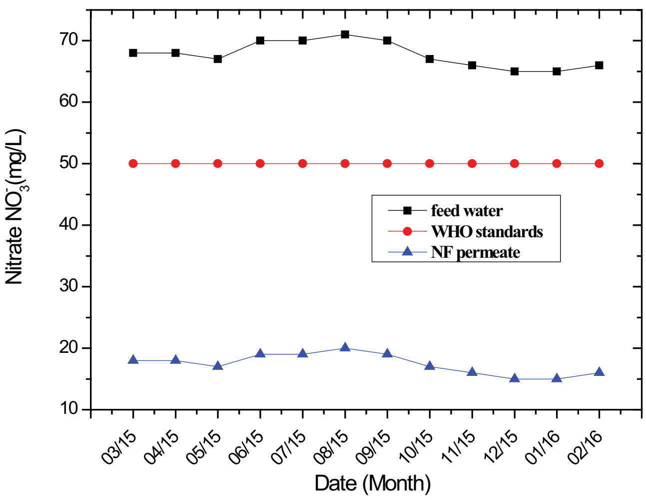

Fig. 4. Evolution of the nitrate content in groundwater and NF permeate over 1 y.

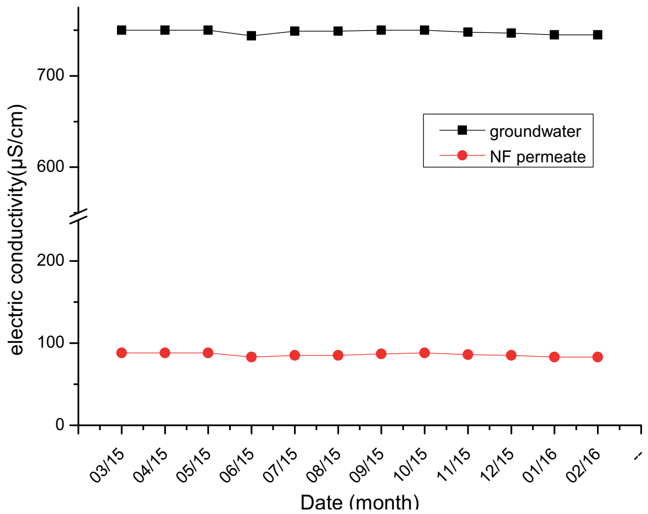

Fig. 6. Evolution of groundwater electric conductivity and NF permeate over 1 y.

Table 3
Water characterization before and after NF treatment

Sample	Underground water	Permeate without concentrate recycling	Permeate after 70% of concentrate recycling	Rejection (%)
pH	7.1	6.33	7.02	–
Electric conductivity (µS/cm)	750	88	92	87
Sodium (mg/L)	4.95	0.77	12.84	84.4
Potassium (mg/L)	7.04	1.5	3	78.6
Magnesium (mg/L)	36	1.3	1.47	96.3
Calcium (mg/L)	112	8	17.95	92.9
Chloride (mg/L)	57	3.4	11	94
Nitrate (mg/L)	68	18	35.13	73.5
Sulfate (mg/L)	35	1.2	1.4	96.5
Cl_2 (mg/L)	–		0.2	–
Turbidity (NTU)	0.39	0.2	0.2	–

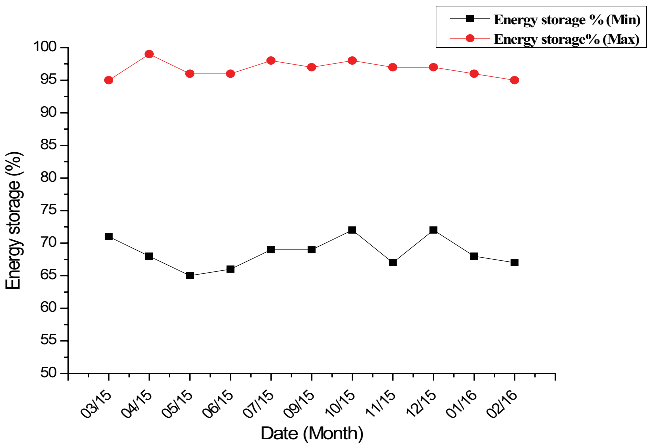

Fig. 7. Energy storage over 1 y.

power, generated by a wind turbine, is indicated by Eqs. (2) and (3) [27–29].

$$P_{\mathrm{WT}}\begin{cases} V < \mathrm{VCi}, V > \mathrm{VCo} \\ \rho\mathrm{CAV3VCi} \leq V \leq \mathrm{VCo} \end{cases} \quad (2)$$

where ρ is the density of air (kg/m³), *A*: is the area of the windmill perpendicular to the wind (m²), *C* is the power coefficient of the wind turbine, *V* is the wind speed (m/s) at the height of the turbine hub, which is calculated according to Eq. (3):

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^a \alpha \quad (3)$$

where V_1 as the wind speed at a reference height denoted by H_1 and α is the Hellman coefficient.

The estimated power of the wind turbine of Sidi Taibi plant is 2.2 kW and allows a production of 2,000 to 4,000 kWh/y.

The users of this process will thus be able to have a supply of treated water outside the daytime periods thanks to the energy stored in the batteries.

The additional electricity (energy produced: 25.43 kWh, energy self-consumed: 15 kWh, excess energy: 10.43 kWh) not used will be injected into the network of the high school for these needs, making it the first high school to be autonomous in energy.

3.2. Economic evaluation

3.2.1. Cost of kWh produced by the plant

The plant of Sidi Taibi plant includes 158 photovoltaic panels and a wind turbine. Coupling of these two renewable energies allows this plant to have a general power of 25.43 kWp for a total production of 43 MWh/y. The cost of the kWh produced by the installation is calculated according to the formulas in Table 4.

Table 4
General formulas for costs calculating

Parameters	Formula
Amortization factor (*A*)	$A = \frac{i(1+i)^n}{(1+i)^n - 1}$ [30]
Annual fixed charges (AFC)	AFC = *A* × Total cost [30]
Annual membrane replacement costs (AMR)	AMR = 0.05 × Unit price [30]
Operating and maintenance annual costs (AO&M)	AO&M = 0.2 × AFC [30]

3.2.2. Annual operating costs

The annual operating cost covers all expenditures incurred after the plant is commissioned and during actual operation. Table 5 summarizes the expenses involved in this evaluation.

According to the literature, the cost of the conventional kWh produced in Morocco is close to 0.085 US $ [31]. The cost of kWh produced by the renewable energy mix (solar and wind) in the Sidi Taibi plant is much higher compared to the cost of conventional kWh. This significant cost difference is explained by the higher cost of renewable energy equipment.

3.2.3. Total desalinated water cost

The cost of produced drinking water is calculated using the same previous equations. Except that in that case, the cost of energy consumed during the treatment must be taken into consideration. This estimate is done on the basis cost of kWh previously calculated, 0.1662 US $/kWh) (Table 6).

Generally, the quality of the incoming raw water affects the replacement rate of the membranes. This replacement rate varies between the lower limit of 5%/y which applies to low salinity brackish water and 20%/y which is the upper limit corresponding to high salinity seawater [32]. In our case, the replacement rate used is 5%.

3.2.4. Energy cost

To calculate the energy cost, such factors as the working pressure of the high pressure pump, power consumption of the metering pumps which is proportional to the transmembrane pressure (TMP) and inversely proportional to the recovery rate, and energy cost must be taken into account. In our case, the energy consumption for the technology is in the range of 0.2 kWh/m³, which depends on TMP (5 bar), and recovery rate (75%).

The annual production of the water by Sidi Taibi plant is: 12 m³ × 365 = 4,380 m³/y.

The energy consumed by the plant during 1 y is: 4,380 × 0.2 = 876 kWh/y.

Finally, the cost of cubic meter of produced drinking water by Sidi Taibi plant is 0.8820 US $/m³.

The cost of fresh water production around the world depends on several factors such as the size of the

Table 5
Cost of the kWh produced by the plant

Parameters	Cost/y
Amortization factor (*A*)	0.08
Annual fixed charges (AFC)	5,360$
Operating and maintenance annual costs (AO&M)	1,072$
kWh produced by the plant	0.1662$

Table 6
Cost of the m^3 of drinking water produced by Sidi Taibi plant

Parameters	Cost
Amortization factor (*A*)	0.08/y
Annual fixed charges (AFC)	2,640 $/y
Annual membrane replacement costs (AMR)	50 $/y
Operating and maintenance annual costs (AO&M)	594 $/y

desalination plant, the technology used, the location of the solar or wind profile, the quality of the feed water, the type of renewable resource used for power generation, and whether the plant operates off-grid or on-grid. Examples of desalination plants coupled with renewable energies are presented below: PV-desalination; a sizes ranging from 0.8 to 60,000 m^3/d with an approximate cost of US $ 34.21 to 0.825/m^3 [10]. Another case wind – desalination plants in sizes ranging from 1 to 250,000 m^3/d with an approximate cost of US $ 15.75 to 0.66/m^3 [10]. Desalination -wind-PV hybrid energy have been implemented in many countries with the size ranging from 3 to 83,000 m^3/d [10]. The cost of water varies from US$ 6.12 to 1.4 $/m^3 [10].

According to the hydraulic conditions of the Sidi Taibi plant, this is about 12 m^3/d, using NF-PV-Wind. The cost of drinking water produced is largely lower than that found in various similar studies [10]. The comparison in this case is under the experimental conditions of these studies. This is largely due to the conditions set; TMP (5 bar), recovery rate (75%), the sizing methodology adopted and also the production capacity.

4. Conclusion

This study is dedicates to determining the performance of Sidi Taibi station where the treatment of groundwater by NF is powered by a renewable energy mix (solar and wind). The results over 1 y show a stability of the performance from both points of view, electricity and drinking water production. The annual electricity production is 43 kWh; this quantity meets the energy needs of the NF unit and equipment's. Excess is controlled in the school circuit. The price per kWh is estimated at 0.1662 US$.

The NF unit ensures hydraulic stability, all year round, in terms of drinking water production capacity of around 12 m^3/d. Nitrate, which is in excess (70 mg/L) in the feed groundwater, is removed with a rejection of 75%. The reduction in salinity is significant, reaching 88 μS/cm with a retention rate of 87%. The NF process has a great capacity to remove the majority of monovalent and bivalent ions (K^+, Cl^-, Na^+, Ca^{2+}, NO_3^-, …) to meet the standard of drinking water. The cost of 1 m^3 of drinking water produced under these conditions is calculated to be 0.8820 $.

Currently, the cost of producing fresh water by renewable energy-desalination (RED) systems remains even higher than that of conventional desalination-energy systems. However, the selection of small RED power plants for isolated dry lands with low water demands has advantages due to the elimination of the high cost of connecting to the power grid and transporting water.

Coupling a hybrid renewable energy system (photovoltaic-wind) with NF membrane treatment technology (PV-WIND-NF) is a win-win solution, especially in rural areas that have neither access to the electricity grid nor to clean sources of drinking water, where sun and wind are abundant.

The use of renewable energy resources is encouraged to meet the growing demand for electricity and to supplement existing energy sources for fresh water production. The distributive nature of renewable energy sources is ideal for providing electricity in areas that are not connected to the grid, it will also reduce greenhouse gas emissions in the local environment. Renewable energy can be used economically for small-scale distributed fresh water production in remote areas. This approach will reduce reliance on fossil fuels for water desalination and minimize the cost and risk of transporting and distributing fresh water to remote populations.

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