Techno-Economic Optimization of Water Pumping System Using PV/WT/Battery for Feeding Isolated Farm

Djamel Belatrache[1,2,*], Chouaib Ammari[1], Chalabia Benoudjit[3], and Yahia Ammari[4]

A R T I C L E I N F O

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A B S T R A C T

In this paper, techno-economic optimization to electrify an isolated farm in a way that covers water consumption for more than 600 trees, the system proposed is based on wind turbine and solar photovoltaic due to renewable energy potential available in the location selected (high wind speed and solar horizontal irradiation), and the results obtained show the wind turbine can cover 40% of annual farm consumption and 1% for solar photovoltaic, the integration of storage system optimizes the performance of both system when wind turbine cover all consumption without unmet load, the solar photovoltaic with storage system covers 27% of farm consumption and failed to guaranties electrification of load profile. In the economic part, the wind turbine with storage system is characterized by low investment cost (11800 $) compared to photovoltaic system (13320$) and grid connection (15588$) and eliminates electric invoice by generating free energy and minimize the dioxide carbon emissions that generated from fossil energy.

1. INTRODUCTION

In the previous 50 years, the amount of electricity utilized on a global scale has increased fast and will continue to do so in the next 50. Due to climatic change, this rise in demand may soon deplete oil supplies. [1] Positively, Environmental concerns, such as reducing carbon emissions and ensuring long-term energy sustainability, have elevated power generation strategies to a critical global priority [2]. Annually, global energy consumption exceeds 24,000 terawatts (TW), with fossil fuels dominating at over 66% of the total, while renewable sources supply roughly 23%. Additionally, 42% of the electricity generated globally is used in industry, while only 6.6% is used for agriculture [3].

The water consumption problem is a critical global issue that affects billions of people (2.2 billion people lack access to safe water). Between two and three billion people experience water shortages for at least one month per year.

The crisis is multifaceted, impacting health, education, and economics. It’s crucial to address this through sustainable management and international cooperation to prevent further escalation of the crisis [4]

One of the solutions proposed for rural and isolated farms to cover essential electrical consumption or water consumption is solar photovoltaic water pumping (SPWP)or wind turbine water pumping (WTWP).

In past years, researchers have focused on the control, optimization, and energy management of water pumping using solar photovoltaic or wind turbines [5]

Mustapha Errouha et al. use indirect field-oriented control to optimize flux and minimize power losses of induction motor, also, authors used maximum power point tracking (MPPT) based on perturb and observation to maximize energy extracted from solar panels, and the results show evolution in performance of motor between 5% to 12% according to global irradiation profile [6].

Over the past five decades, the global demand for electricity has surged significantly and is projected to keep increasing. Climate change exacerbates the issue, potentially exhausting oil reserves in the near future. As a result, producing electricity from renewable sources has become essential to reduce carbon emissions and ensure long-term energy sustainability.

Currently, the world consumes more than 24,000 terawatts annually, with fossil fuels accounting for over 66% and renewables contributing about 23%. Industry uses about 42% of the produced electricity, while agriculture accounts for a mere 6.6%.

A global concern affecting billions is the issue of water consumption. Around 2.2 billion individuals lack access to safe water, and between two to three billion experience water shortages at least once a year. This problem impacts

[1]*Department of Renewable Energy, Faculty of Hydrocarbons, Renewable Energy, Science, Earth and Universe, University Kasdi Merbah-Ouargla, BP 511 Ouargla 30000, Algeria.*
[2]*VPRS Laboratory, Kasdi Merbah University of Ouargla, BP 511, 30000, Ouargla, Algeria*.
[3]*Laboratory of Electric Traction Systems, Electrical Engineering Department, University of Batna*.
[4]*Department of Agricultural Sciences, Faculty of Nature and Life Sciences, University Kasdi Merbah-Ouargla.*
**Corresponding author:* Djamel Belatrache; Email: DjamelBelatrache@outlook.com.

various sectors such as health, education, and the economy, emphasizing the need for sustainable water resource management and global collaboration.

Solar and wind-based water pumping systems are increasingly proposed to support rural and remote farms in meeting essential energy and water demands. Recent studies have emphasized control techniques and energy optimization for such systems to enhance their reliability and performance.

In the wind power pumping system (WPPS), Zakariya Dalala et al. propose to use MPPT based on perturb and observe (P&O) mode and prediction mode, the results show enhanced stability and fast-tracking of wind speed under high and low rates [12]. Many methods proposed for optimizing the control of wind turbine like Power signal feedback control [13], bang-bang control with three separate hysteresis controllers [14], analytical method [15], and point of common coupling (PCC) [16].

The energy management of WPPS can be using a neuro-fuzzy controller [17], HOGA (Hybrid Optimization by Genetic Algorithm) program [18], or many algorithms to achieve objectives like in [19] when using three algorithms; TOR, fuzzy, and genetic algorithm.

The objective of this study is to size and find the optimum renewable energy system to cover the water consumption of an isolated farm in southeast Algeria, the farm was equipped with an immersed pump of 10 HP and needed more than 160 m3 per day to feed more than 600 trees.

This research presents a cost-effective and sustainable alternative for persons living in remote places to cover their water usage using two distinct renewable energy sources. This study is organized into three sections. The first component contains the mathematical models for each system. The second part describes the load profile and size of solar photovoltaic and wind turbines, and the last section presents the simulation and techno-economic analysis of the data acquired via a full comparison of the proposed systems.

2. MATHEMATICS MODEL

2.1. Solar photovoltaic

Khatib and Elmenreich established a novel approach in 2014 to estimate the power output of solar photovoltaic systems. [20,21]:

$$P_{pv}(t) = \left[P_{peak}\left(\frac{G_t}{G_{stander}}\right) - \alpha_t[T_c(t) - T_{stander}]\right] \times \eta_{inv} \times \eta_{wire} \quad (1)$$

$$T(t) = T_{amb}(t) + \left(\left(\frac{NOCT-20}{800}\right) \times G_t\right) \quad (2)$$

with

P_peak : photovoltaic pic power

η_inv : inverter cc

η_wire : connecter cables efficiency

α_t : Temperature coefficient

Gt : Global irradiation

Tamb : Ambient temperature

Tstandard : Standard temperature (25° C)

Gstandard : Standard solar irradiation (1000 W/m2)

NOCT : Nominal operating cell temperature (irradiance on cell surface = 800 W/m2, air temperature = 20°C, wind velocity = 1m/s, mounting open back side)

2.2 Wind turbine

This model is mostly dependent on the meteorological threshold for wind turbine output power (P) when determining interval, as shown below [21]:

$$P = \begin{cases} 0 & (W_S < W_{in}, W_S > W_{out}) \\ \xi(W_S - W_{in})W_n & (W_{in} < W_S < W_{out}) \\ W_{rp}W_n & (W_{rs} < W_S < W_{out}) \end{cases} \quad (3)$$

with:

Ws: Current wind velocity at the turbine site.

Win: Threshold wind velocity required to begin power generation.

Wout: Safety cutoff velocity where operations stop to prevent damage.

Wrs: Velocity at which the turbine achieves its designed maximum power output.

Wrp: Peak power capacity the turbine produces under ideal wind conditions.

Wn: Total count of turbines integrated into the system.

ξ: Gradient representing the power increase from activation (Win) to peak performance (Wrs).

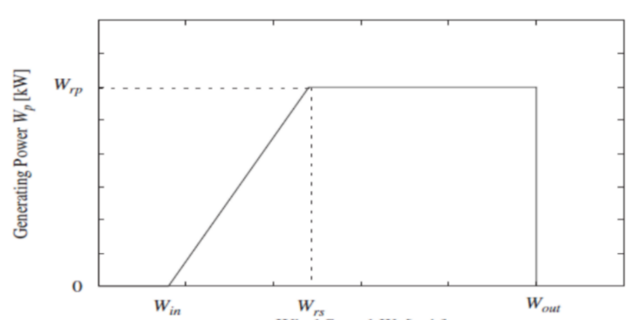


Fig. 1. Characteristics of wind turbine.

2.3 Motor pomp [22]

The motor used in pump is a cage induction motor characterize by the next four electrical equations:

$$V_{s\alpha} = R_s i_{s\alpha} + L_{s\alpha}\frac{di_{s\alpha}}{dt} + M\frac{di_{r\alpha}}{dt} \quad (4)$$

$$V_{s\beta} = R_s i_{s\beta} + L_{s\beta}\frac{di_{s\beta}}{dt} + M\frac{di_{r\beta}}{dt} \quad (5)$$

$$0 = R_r i_{r\beta} + L_r \frac{di_{r\beta}}{dt} + M \frac{di_{s\beta}}{dt} - \omega_r (L_r i_{r\alpha} + M i_{s\alpha}) \quad (6)$$

$$0 = R_r i_{r\alpha} + L_r \frac{di_{r\alpha}}{dt} + M \frac{di_{s\alpha}}{dt} + \omega_r (L_r i_{r\beta} + M i_{s\beta}) \quad (7)$$

Also, the induction motor is based on two mechanical equations below:

$$C_e - C_r = J \frac{d\Omega}{dt} + f\Omega \quad (8)$$

$$C_e = \frac{3}{2} pM (i_{r\alpha} . i_{s\beta} - i_{r\beta} . i_{s\alpha}) \quad (9)$$

Vsα : voltage vector in α axe [V]
Vsβ : voltage vector in β axe [V]
Rs : stator resistor [Ω]
Rr : rotor resistor [Ω]
Ls : stator induction [H]
Lr : rotor induction [H]
isα : current vector in α axe [A]
isβ : current vector in β axe [A]
M : mutual
Cr : resistant couple [N.m]

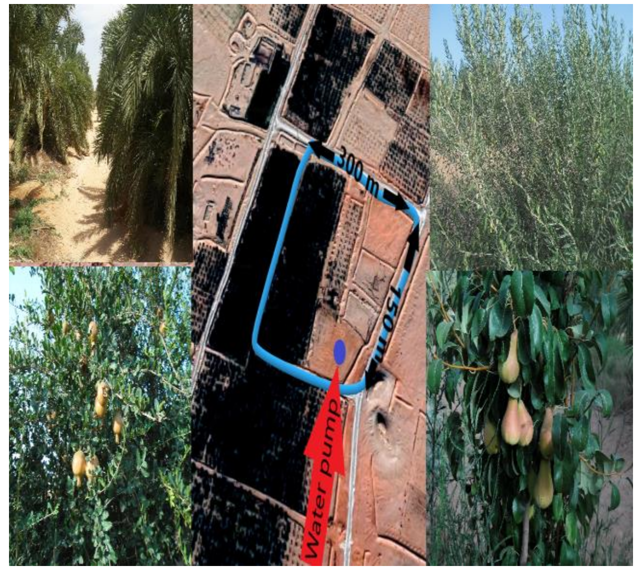
3. SIZING RENEWABLE PUMPING WATER SYSTEM

3.1. Load profile

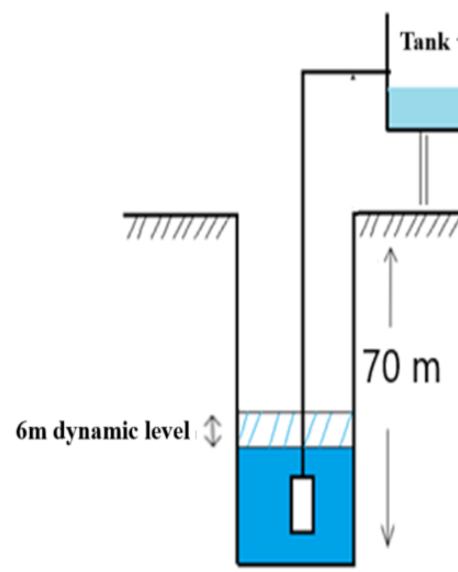
In this study, the load profile is an isolated farm situated in the Sahara of Algeria in Wilaya Ouargla, this arid zone is characterized by dry winter, high temperature in summer, and low wind speed. The surface of this farm is 4.5 ha, and contains 520 palm and more than 100 fruity trees (pomegranate, olive, plum, grapes, figs…etc.) as shown in figure 2.a. All these trees are feeding it using one water well with more than 70m deep and 6m drawdown (fig 2.b).

The borehole is equipped with an immersed pump with 10 HP (between 8 m3/h to 16 m3/h water flow), every palm consumes 300 L/day and 55 L/day for a fruity tree, this makes farm consumes more than 161 m3 every day (Table 1). The water pump needs a minimum work 7 hours every day in summer (between March to October and between 4 Am to 11 Am) and just 4 hours in winter (between November to February and between 9 Am to13 Am) to cover farm consumption.

The analysis of real consumption shows the farm consumes 30 MWyr with a 2557 kWh monthly average, the low energy consumption record in begin of the year between January to April, and the lowest consumption was recorded in March with 1385 kWh. According to the high temperature in summer, the electric consumption of the farm grows between May to October with a 3198 kWh monthly average, the highest consumption was recorded at 3899 kWh (Fig.3)



(a)



(b)

Fig. 2. (a) satellite view of the isolated farm with water pump emplacement (b) characterize of water well installed in the farm.

Table 1. Daily water consumption

Tree type	Water consumption (L/day)	Total trees installed on the farm	Total water consumption (L)
Palm	300	520	156000
Fruity tree	55	100	5500
Total	355	620	161500

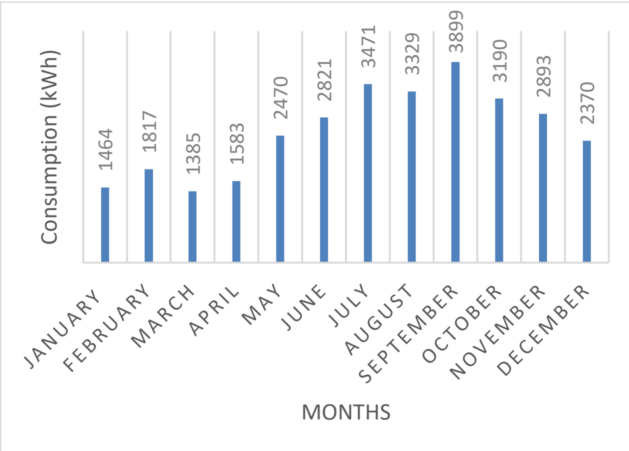


Fig. 3. Monthly consumption of the farm in 2019.

The solar potential is characterized by high solar radiation in the middle of the year (between March to September), the maximum value is recorded in June with more than 7,5 kWh/m2/day, and the lowest value is recorded in March with 5,22 kWh/m2/day, the irradiation decrease in the winter season (between November to February) and the highest value are recorded in October with 4 kWh/m2/day and lowest value are obtained in December with 2,25 kWh/m2/day (Fig.4).

The farm is characterized by high wind speed between March to June, taking a value between 3,6 m/s to 4,1 m/s and reaching the pic value in May with 4,1 m/s, in the rest of year, the wind speed takes a value between 2,5 m/s to 3,2 m/s (Fig.5). Under this wind speed value, the best wind turbine can be installed in the farm is who can work in low wind speed and extract maximum energy with height between 20m to 40m to capture good wind speed.

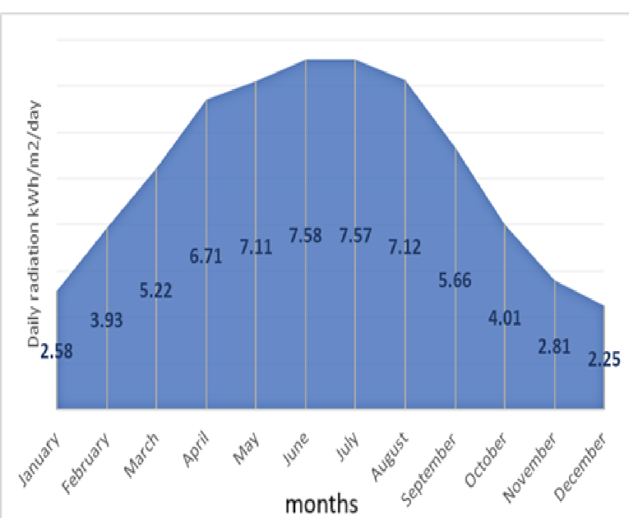


Fig. 4. Monthly average solar global horizontal irradiance.

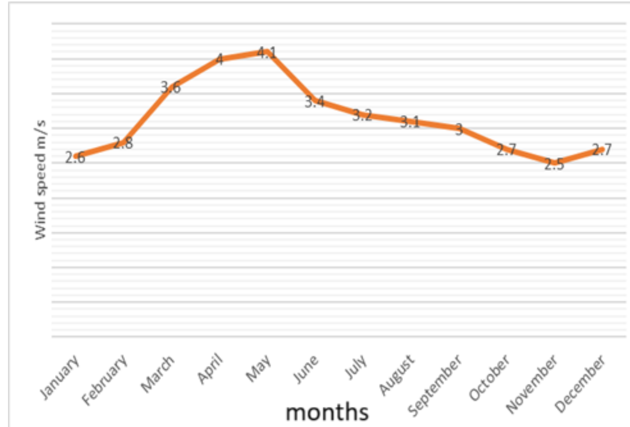


Fig. 5. Monthly average wind speed.

3.2 Wind turbine pumping system

To cover farm water consumption, two methods were used, wind turbine mechanical water pumping when this system needs significant wind speed to pump water from the borehole (70 m deep), and that is not available in this location. The second method and the most used is the size of the wind turbine can cover the essential consumption of this farm (in this case is just a water pump). The table2 summarizes the characteristics of the water pump used on this farm.

Table 2. Characterize of water pump

Mark	Eagle type E150-BS-11
Power	10 HP/ 7.5 kW
Voltage	3ph 380/415 V
Current	18,5 A
Revolution	2850 RPM
Flow	8-16 m^3/h

Sizing wind turbines using classical methods is based on next following steps:

- The first step is determining turbine power using the following equation:

$$Pt = Pu/\tau g=(7500)/0,8=9375W \quad (10)$$

with:

Pt : turbine power

Pu : useful power (minus the losses from the absorbed power)

τg : wind turbine efficiency (generally equal to 0,8)

- The second step is calculating wind speed at a specific height:

$$V(h)=V(10)*(h/10)^{\alpha}= (3,14)*(30/10)^{0,23}=4,05m/s \quad (11)$$

V(h) : wind speed at (h) height

V(10) : Wind velocity recorded at a standardized 10-

meter elevation above ground level.

α : A terrain interaction factor representing surface roughness and its impact on wind speed's vertical gradient. This coefficient varies between 0.1 and 0.4, depending on landscape characteristics (e.g., flat terrain, vegetation density), as detailed in Table 3.

Table 3. Variation of coefficient roughness according to site location [23]

Location nature	α
Plate	0,08 to 0,12
Little rugged	0,13 to 0,16
Rugged	0,20 to 0,23
Very rugged	0,25 to 0,40

- The third and last step to follow is to define the technical characteristics of the wind turbine (brushed surface by blades and radius of the surface) using the equation below:

S =Pt/(1/2*ρ*Cp*V3)=(9375)/(1/2×1,225×0,48×(4.05)3)

= 480,03m2 (12)

with:

S : The surface brushed by the blades

ρ : The density of air

Cp : Constant of the maximum power

The following equation determines the length of the blades (or the radius of the surface brushed by them):

R = √(S/π)=√(480,03/3,14)=12,36 m (13)

The wind turbine used in this system was based on Permanent magnet synchronous generator (PMSG) because this generator is the best in standalone profile, work with low speed and low cost of maintenance.

The figure 6 summarize all the last step in the next flowchart.

3.3 Solar photovoltaic pumping system

Sizing of a solar photovoltaic system is based on calculating the number of photovoltaic panels (series and parallel) and the surface cover by the photovoltaic system:

- Calculation of total photovoltaic panel

Npanels=Pt/Ppanel =7500/285≈26,31=27 (14)

with:

Pt : The total power of solar photovoltaic field should produce

Ppanel : the power of one panel (equal to 285 W)

The Table 4 summarizes the technical and electrical characteristics of photovoltaic panels.

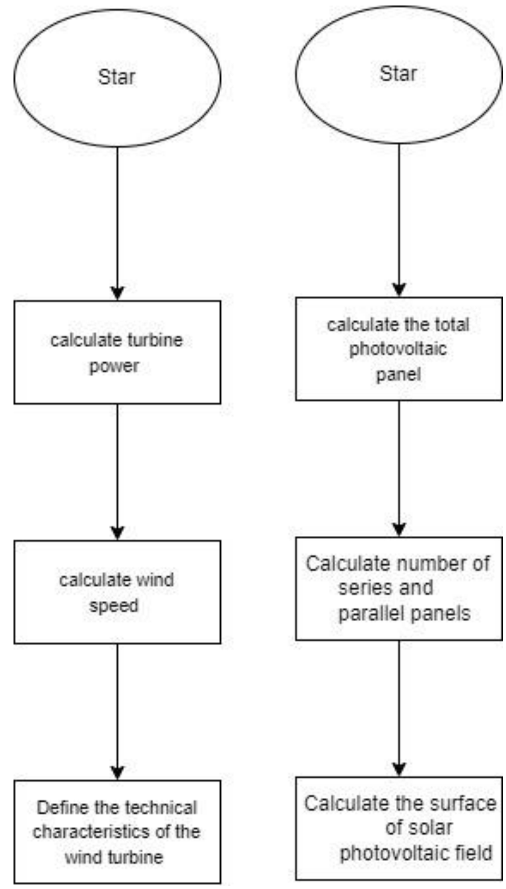


Fig. 6. Flowchart of wind turbine and solar photovoltaic system.

Table 4. Characterize of solar photovoltaic panel

Mark	Condor type 72 cell
Type	Polycrystalline
Nominal power	285 W
Voltage mpp (Vmpp)	36 V
Court circuit currant	7,92
Efficiency (%)	13
Lifetime (years)	25
Dimension (m)	1,9×0,9×0,05

- Calculation number of series and parallel panels

The output voltage and current of the system are determined by the number of panels in series and parallel, respectively. When there are several panels connected in a series, a chopper is needed to boost the output current.

When there are several parallel panels, a transformer needs to be built to raise the output voltage. (Fig.6).

Ns = Vwp/Voc=380/36=10,5≈11 (15)

where Vwp is voltage of water pump.

NP=Nt/Ns=27/11=2,45≈3 (16)

Nt : total number of panels

Ns : number of series panels

- The surface of solar photovoltaic field

Polycrystalline panels are noted for their excellent efficiency and dependability at high temperatures. The solar system's covered area is computed as follows:

$$S = (1,9*0,9)*27=46,17 \text{ m2} \quad (17)$$

The polycrystalline panel was used due to effectiveness cost, durability and more environmentally friendly.

4. SIMULATION AND RESULTS

4.1 Simulation of wind turbine water pumping system

After simulation of wind turbine water pump using Matlab Simulink, the results show that the wind turbine produces more than 20 MW every year, the water pump used just 12 MW because the control system ignores any power lower than nominal power of water pump (fig.8). Total excess energy is 8 MWh with 21 kWh average, the maximum value record in August with more than 190 kWh (fig.9), that make integrating of the storage system is necessary. The water pump works 1478 hours/year when the load profile (the farm) needs 3650 hours, this difference can be decreased by integrating the storage system.

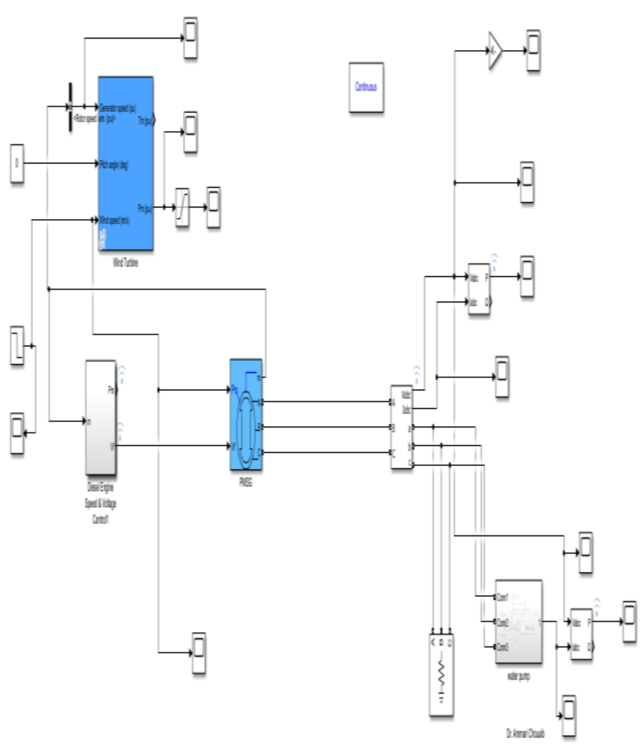


Fig. 7. Simulink model of the proposed system.

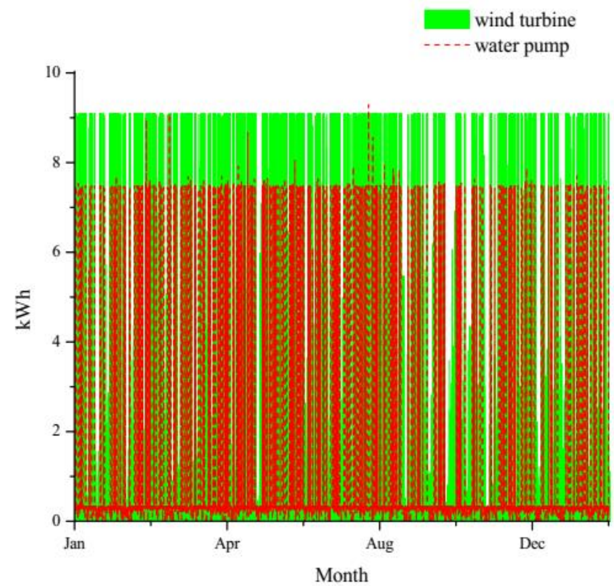


Fig. 8. the power of the wind turbine and water pump.

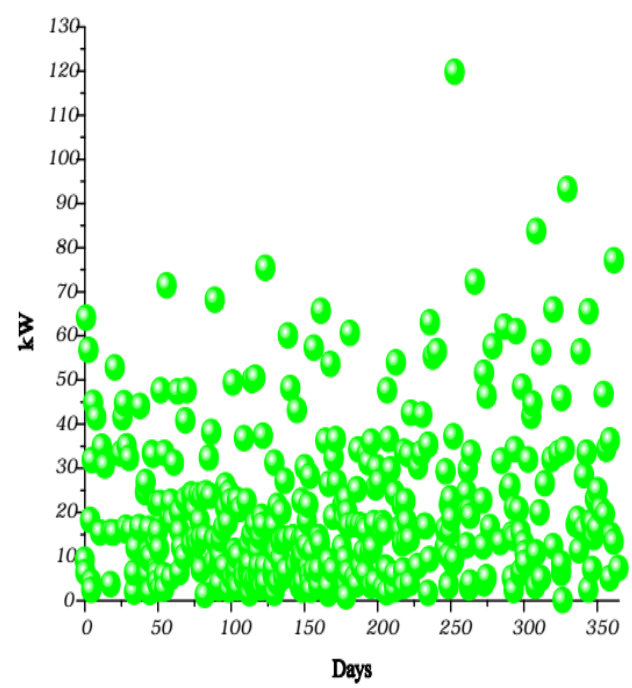


Fig.9. excess power of wind turbine water pumping system.

The integration of a storage system with a 20 kW capacity helps the system to cover water consumption without unmet load during the year, which means 161 m3/day of necessary water is covered. Also, the battery offers more than 2769 hours/year of work for the water pump and this is more what the farm needs (photovoltaic field and battery offer more than 4100 hours/year when the farm needs just 3650 hours/year) (Fig.10), the battery are protected by integrating manager system to keep it work in the first half of state of charge (between 100% to 50%).

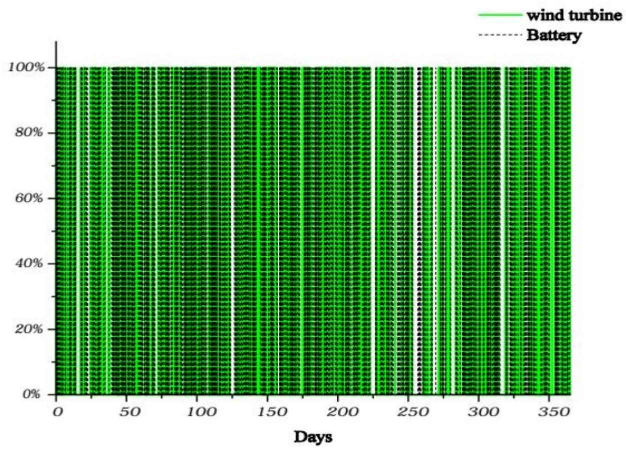


Fig. 10. Participation of wind turbine and battery power output.

4.2 Simulation of photovoltaic water pumping system

The simulation results show that the solar photovoltaic field produces more than 11 MWh every year water pump works just 68 hours/year. The production of photovoltaic generators takes the same shape as solar irradiation, with the maximum value record in March and April with more than 7,3 kWh (Fig.11). the participation of excess energy and uncovered consumption make integration of the storage system an obligation to use more than 10 MWyr (Fig.12), the storage system will take the value of average excess power (31,7 kW).

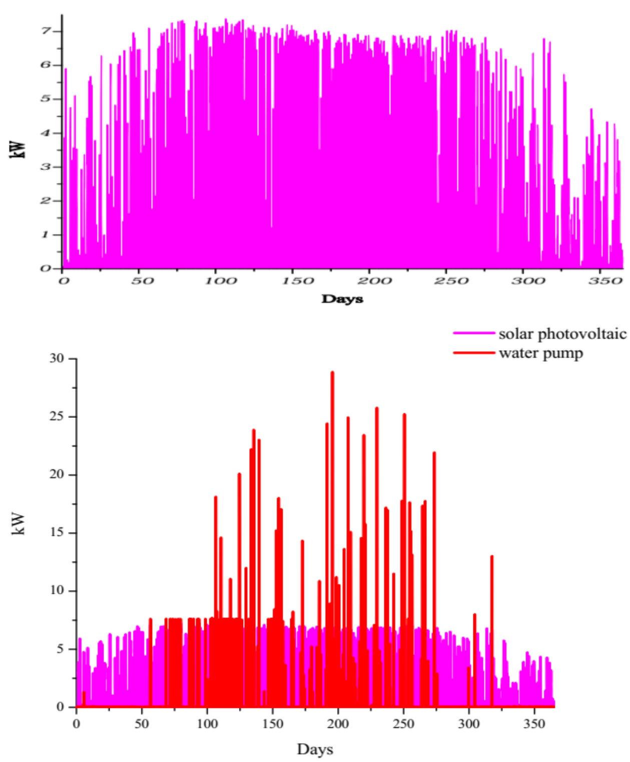


Fig. 10. (a) production of solar photovoltaic and comparison, (b) comparison between PV production and water pump consumption.

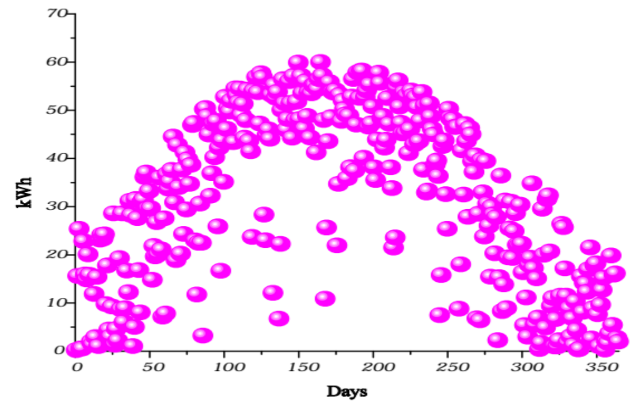


Fig. 12. excess power of solar photovoltaic water pumping system.

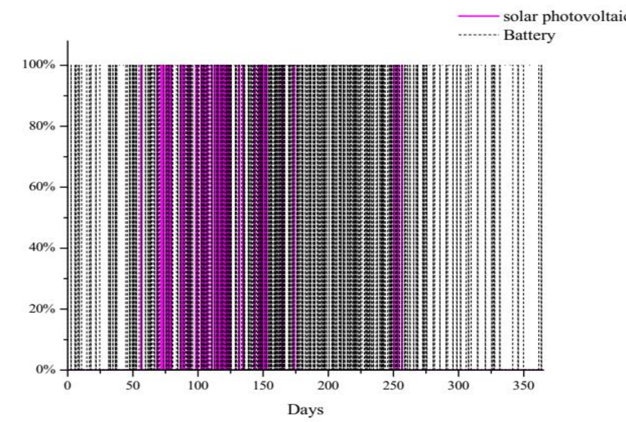


Fig. 13. participation of photovoltaic panels and battery power output.

With a 32 kW battery capacity, the photovoltaic water pumping system covers the farm consumption of 994 hours/year with 93% coming from the battery. The state of charge of the battery is protected by integrating relay control charge and discharge of the battery, the role of this relay is to make the battery run in the first half of SOC (between 100% to 50%). The system failed to cover the annual consumption of the farm and most of the system production is concentrated in the middle of the year (May, June, and September) due to most excess power of photovoltaic panels taking high value between April to September (Fig.13).

4.3 Economic analysis

This part will focus on the wind turbine pumping system with a battery and compare it with a real farm for electrical consumption because the photovoltaic pumping system failed to cover farm consumption with or without a battery.

The initial investment cost of a wind turbine pumping system with battery is 11,8 k$, and the storage system (converter and batteries) presents 76% of the global investment cost when the wind turbine is the lowest component in this system with 2700 $ (34% of investment cost). Connecting the farm to the grid is not a good economic choice due to the high investment cost of equipment (transformer with line connection) of more than 15,5 k$. the comparison shows the wind turbine pumping system with or without batteries has a lower investment cost than a grid connection. Table 5 shows details of the initial investment cost for each system.

Furthermore, the farm consumes more than 1235$ per year for the electrical invoice, this value presents 20% of gross annual income, the consumption grows by 1% every year, the wind turbine pumping system with storage system offers free energy with a good economic solution to eliminate electrical invoice.

Table 5. The initial cost of each component in the wind turbine pumping system and grid connection

Wind turbine pumping system		
Components of system	Initial cost	Operating and maintenance cost
wind turbine	2800 $	28 $
Bidirectional converter	3000 $	30 $
Battery	6000 $	60 $
Total	11800 $	118 $
Photovoltaic pumping system		
PV panel	27*160 $	10 $
Bidirectional converter	3000 $	30 $
Battery	6000 $	60 $
Total	13320 $	100 $
Grid Connection		
Transformer+ line connection	15588.46 $	

Reduced Greenhouse Gas Emissions when using renewable generator (PV or wind turbine) produce power without emitting greenhouse gasses (network connection). By replacing or lowering the usage of fossil fuels and reduce emissions like carbon dioxide (CO_2), which are key contributors to global warming and climate change. Renewable energy generator decreases reliance on nonrenewable energy sources, boosting energy independence and security for rural area.

5. CONCLUSIONS

In this study, a comparison of three systems was achieved for feeding an isolated farm in the Sahara of Algeria, the farm with more than 600 trees, which needs more than 161 m3 every day, the solution proposed uses wind turbine or solar photovoltaic system to feed water pump with 10 HP. The results show that both systems (wind turbine and solar photovoltaic) failed to cover farm consumption without a storage system when the wind turbine feeds the farm for 1478 hours and solar photovoltaic for 68 hours in time the farm needs 3650 hours, also the results obtained show an excess power with more than 20 kW for wind turbine and 32 kW for solar photovoltaic system. The integration of lead acid batteries optimizes the performance of wind turbine systems when covering consumption without unmet load with more than 4100 hours/year. Also, the photovoltaic system failed to reach the minimum energy consumption with more than 19 MW unmet load. The economic analysis shows the lowest investment cost is for a wind turbine pumping system with batteries at 11800$ compared to 15588 $ for a grid connection, also wind turbine pumping systems offer free energy and eliminate electrical invoices.

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