

Technical and Economic Feasibility of Solar Pump Irrigation in the North-Niayes Region in Senegal

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Abstract

Northern Niayes is an area where agriculture is the main activity. Water used for irrigation in this area comes exclusively from groundwater. Farmers do not have access to electricity, thus fuel is the main source of energy used, which is very expensive. The objective of this study was to assess the techno-economic feasibility of solar irrigation pumps. Regarding technical feasibility, pump sizing was carried out on the basis of irrigation management, irrigation techniques, and water distribution. Also, the economic feasibility was studied on the basis of the Net Present Value, Benefit-Cost Ratio, Internal Rate of Return and Payback Period. Results showed for cultivated area ranging from 0.05 ha to 1.91 ha, pumps' flow rate does not vary greatly from one irrigation technique to another. It varies between 2.5 m³/h and 31 m³/h. However, pressure and power are higher when using drip and sprinkler irrigation techniques, ranging from 27.8 m to 39.9 m for drip and 40.1 m to 58.5 m for sprinkler irrigation. The power varies between 0.05 kW and 1.6 kW for manual, between 0.05 kW and 2.5 kW for drip and between 0.1 kW and 4.75 kW for sprinkler irrigation. The investment cost is variable (669 euros to 21,400 euros), depending on the cultivated area, pump brands and characteristics, and irrigation techniques. Results show that the investment cost ranges from 669 euros (438,500 CFA) to 4090 euros (2,683,000 CFA) when using the manual irrigation technique, from 1281 euros to 20,600 euros when using the drip irrigation technique and from 819 euros to 21,403 euros when using sprinkler irrigation technique for individual pumps. The investment cost is higher when using reservoirs. In this case, the investment cost varied

between €722 and €6062 for manual irrigation, €1532 and €25,882 for drip irrigation and €900 and €28,000 for sprinkling. However, the total investment cost at the entire lowland scale is higher when farmers use the pumps individually and lower when farmers use the pumps in groups when using manual and drip irrigation techniques. NPV varies between 15,993€ (0.75 ha) and 103,139€ (1.41 ha) and between 13,064€ and 86,139€ when using sprinkler irrigation techniques with PVC pipes and when using the drip irrigation technique, respectively. BCR is estimated to average 2.2, 2, and 2 respectively when using manual, drip, and sprinkler irrigation techniques. In addition, PBP is reached more rapidly when using the manual irrigation technique.

Keywords

Irrigation, Solar, Feasibility, Techno-Economic, Niayes

1. Introduction

Globally, the population is increasing at significant rate resulting in an increase in food insecurity [1]. Demographic growth and food insecurity must be tackled with an expansion of agriculture and irrigation. Production should be increased taking into account environmental concerns. Moreover, the impact on poorer nations facing food scarcity is far more critical because more land and energy resources are required to provide future demands. In fact, water is one of the world's most important resources used in irrigation purposes for food production. Moreover, climate change is exerting negative effects on the earth's water resources which are crucial for sustainable development [2]. Crop diversification as well as yield increase is possible through irrigation [3]. Irrigation is the most extensive water consumption sector. About 70% of the world's freshwater extraction and 90% of the total water use is for irrigation. Additionally, groundwater remains the most important source of freshwater for many agricultural areas when surface water resources are limited. In fact, underground water is a major drought solution for agricultural production [4].

However, irrigation consumes considerable groundwater resources and requires large amounts of energy. The main sources of energy used for irrigation are fuel and electricity which cost high, are not always accessible, and are not sustainable [5]. The cost of this energy source is very high, particularly in Africa, more especially among smallholder farmers, and is associated with a negative environmental impact. The environmental damages mitigation is possible thanks to renewable resources such as solar energy. In fact, solar powered pumping in irrigation provides a green and cost-effective alternative for irrigated agriculture. Solar energy is the world's largest available energy source [3]. Thus, solar power for irrigation water pumping is a promising alternative [5]. The use photovoltaic solar energy in irrigation in 1977 in Nebraska was among the earliest experimental uses of PV solar cells. Within the last decennium, the use of solar irriga-

tion pumps has expanded in both China and India [6]. More lately, it is observed an increase in the use of solar pumps in Africa [6]. However, any study on the technical feasibility of solar irrigation pumps in the Niayes area has not yet been conducted in the Niayes area in Senegal, to the best of our knowledge.

In North Niayes, farmers use groundwater for irrigation and do not have access to electricity and, consequently, use fuel as energy source. Therefore, solar irrigation pump may be a good alternative.

2. Materials and Method

2.1. Presentation of the Study Area

Nguethiouro is a lowland located in the Gandiolais region, at the southern end of the Senegal Delta. It is an integral part of the Niayes area and occupies its northern extremity. The Niayes area is a natural region located in the northwest of Senegal. Nguethiouro is geographically localized between 16°28'30" and 16°24'05" in western longitude and 15°50'20" and 15°56'10" in northern latitude (Figure 1) with altitudes ranging from 6 m to 13 m a.s.l.

This lowland is composed of 15 plots. The plots vary in size from 0.05 ha to 1.91 ha (Figure 2).

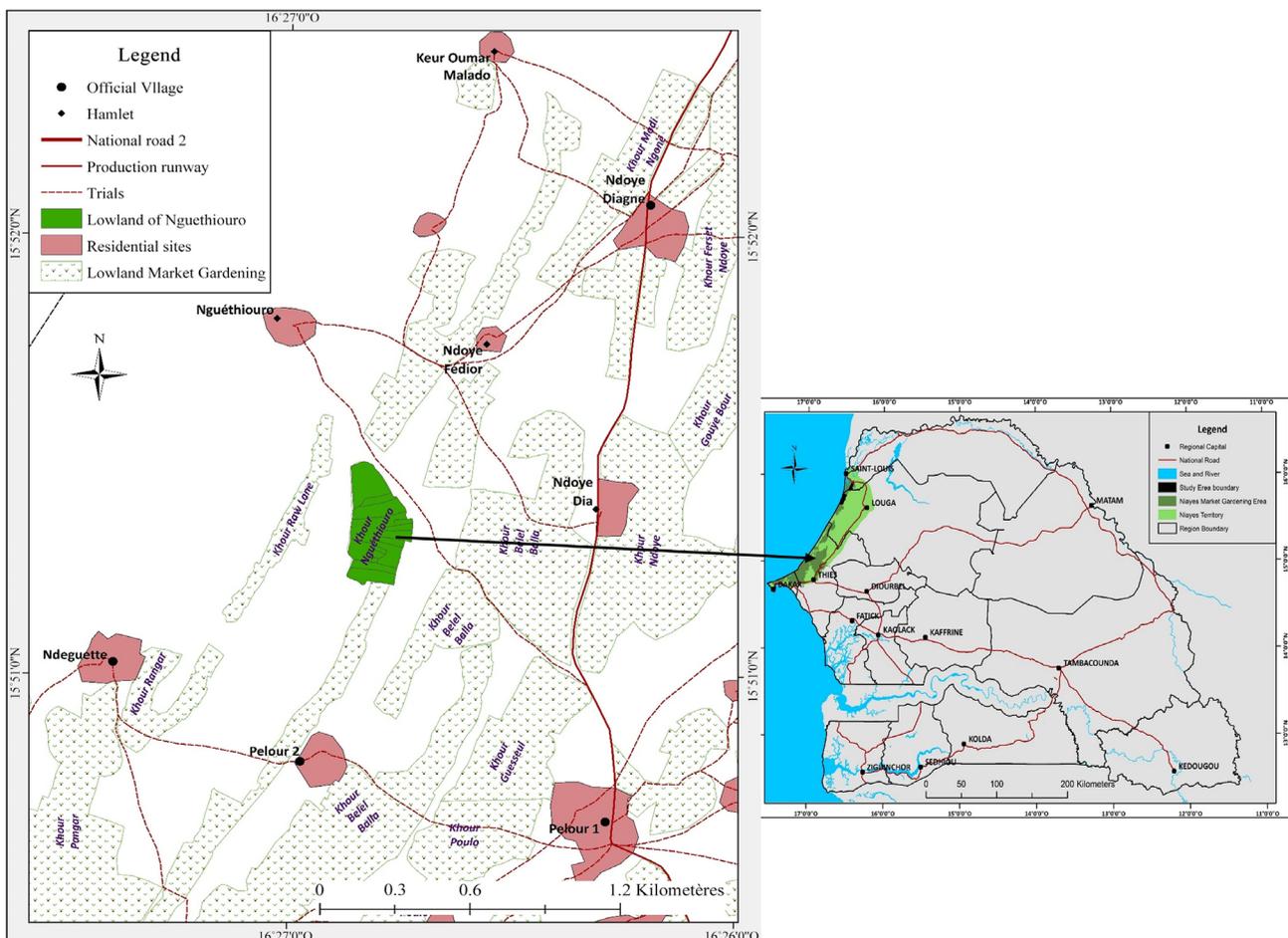


Figure 1. Localization of the study area.

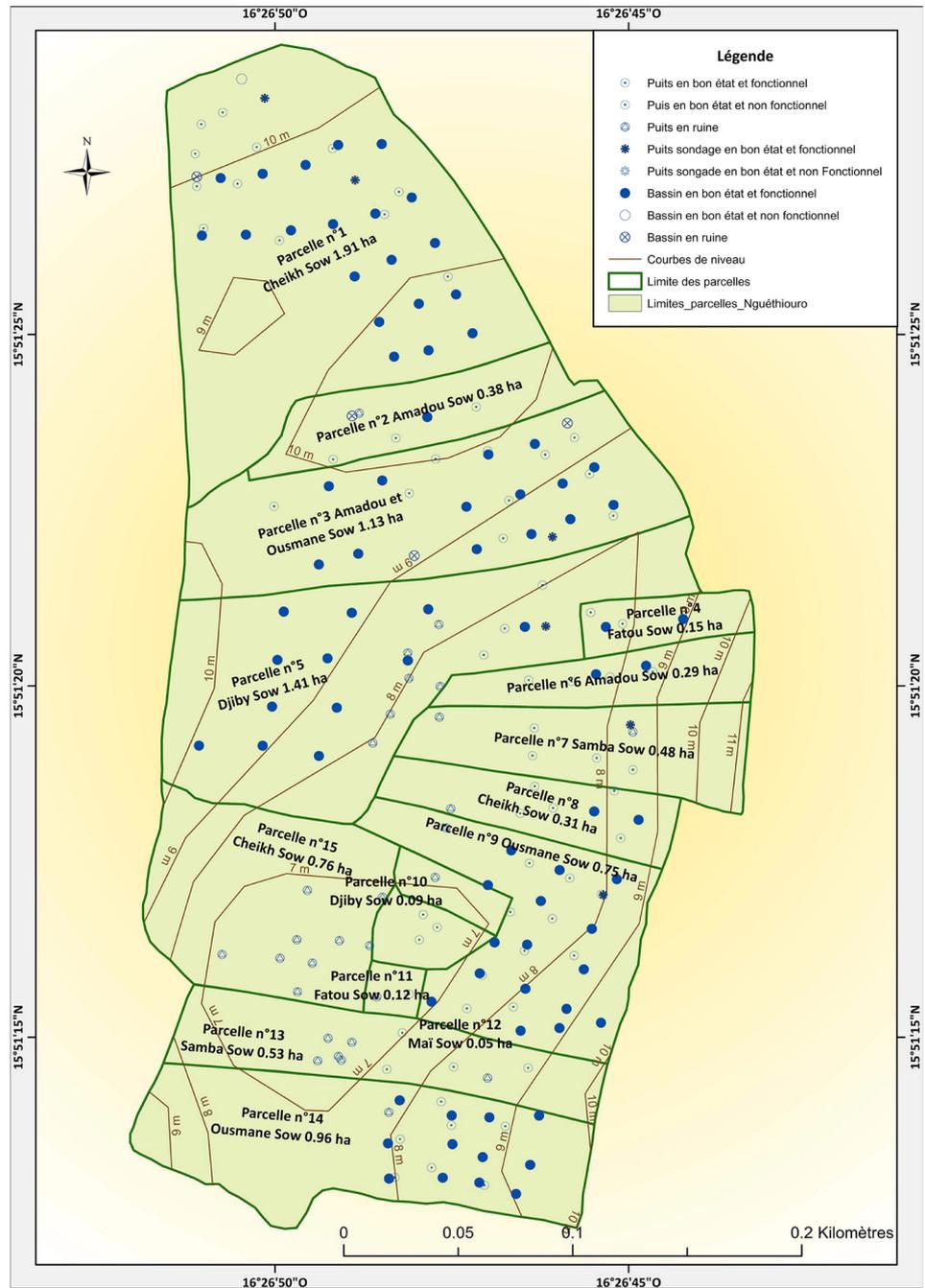


Figure 2. Characterization of the Nguethiouro lowland.

The climate in the Niayes area is of the Sahelian type and is characterized by the average annual rainfall ranging from 500 mm in the south to 300 mm in Gandiolais (in the north) where the dry season lasts nine months. Mean annual temperatures are between 23.7°C and 25°C. The presence of the harmattan wind causes the rise of the temperature at maximum of 31°C in May and June [7].

Nguethiouro is mainly characterized by sandy soils. The moisture content at field capacity and at wilting point as well as soil bulk density are considered as follows (Table 1).

Table 1. Soil characteristics.

Soil type	Bulk density (ρ_b) (mg/m ³)	Soil water content (θ)			TAW (mm/m)
		SAT (%)	FC (%)	PWP (%)	
Sand	1.71	36	13	6	70

Source: [8].

2.2. Technical Feasibility of Solar Irrigation Pumps in Nguethiouro Lowland

The technical feasibility of solar irrigation pumps is studied in Nguethiouro lowland based on three main variants: 1) irrigation management, 2) water distribution, and 3) irrigation techniques (Figure 3).

Photovoltaic Pumping System Sizing

Sizing of solar irrigation systems is performed through three steps: 1) water requirements assessment, 2) determination of solar pump characteristics (Flow rate, Pressure head, and Power), 3) determination of photovoltaic generator size and number of panels.

1) Water requirement assessment

Crop water requirements are determined during the period when water demand is most intense, based on crop types and cropping calendars of each of them. Crop water requirements assessment is realized based on crop evapotranspiration (ET_c) and effective rainfall (P_{eff}). Parameters related to ET_c and P_{eff} are determined based on [9].

ET_c is the product of the reference evapotranspiration and the crop coefficient. It is computed using the formula 1:

$$ET_c = ETo * Kc \quad (1)$$

where ETo is reference evapotranspiration (mm) and Kc is crop coefficient.

ETo is calculated using FAO-Penman-Monteith Method with the formula 2:

$$ETo = \frac{0.408\Delta(Rn - G) + \frac{900}{T + 273}u2(es - ea)}{\Delta + \gamma(1 + 0.34u2)} \quad (2)$$

where: ETo is the reference evapotranspiration (mm·day⁻¹), Rn is the net radiation (MJ·m⁻²·day⁻¹), G is the soil heat flux density (MJ·m⁻²·day⁻¹), T is the mean daily air temperature at 2 m height (°C), Δ is the slope of the saturated vapor pressure curve (kPa·°C⁻¹), γ is the psychrometric constant (66 Pa·°C⁻¹), es is the saturated vapor pressure at air temperature (kPa), ea is the actual vapor pressure (kPa), and $u2$ is the wind speed measured at 2 m height (m·s⁻¹).

2) Water requirement assessment

Net irrigation requirement refers to the amount of water required to compensate evapotranspiration losses from a crop during a specified period. It is calculated based on formula 3 given by [9]:

$$NIR = ET_c - P_{eff} \quad (3)$$

where: ET_c is Crop evapotranspiration (mm) and P_{eff} is Effective rainfall (mm).

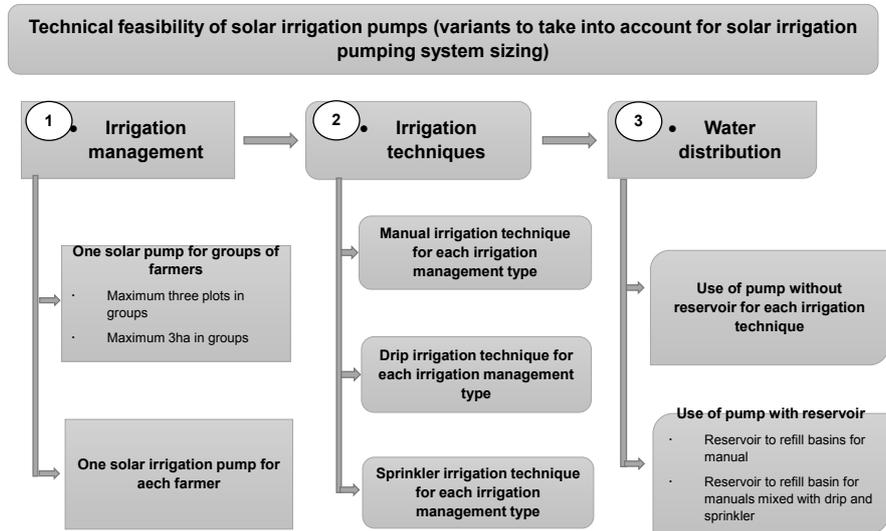


Figure 3. Variants used for solar irrigation pumping system design.

After the determination of net irrigation requirement, gross irrigation requirement is determined based on the three different techniques (formula 4).

$$GIR = \frac{NIR}{E_a} \tag{4}$$

where: *GIR* is gross irrigation requirement (mm), *NIR* is net irrigation requirement (mm), and *E_a* is the irrigation efficiency (0.90 for drip, 0.75 for sprinkler, and 0.85 for manual [10]).

3) Solar irrigation pumping system characteristics determination

Solar irrigation pump characteristics are: pump flow rate, pump pressure head, and pump power.

❖ Flow rate

- Flow rate for manual irrigation system

For the manual irrigation system, the pump flow rate is calculated using the formula 5, given by [11]:

$$Q = \frac{GIR}{Ho} \tag{5}$$

where *Q* is the flow rate (m³/h). *GIR* is the daily irrigation water requirement (m³), and *Ho* is number of hours of operating time (h).

- Flow rate for drip and sprinkler irrigation pump

Flow rate is calculated using the formula 6 [12]:

$$Q_{sys} = Q_e * \frac{L_{li}}{E_{si}} * \frac{L_{ri}}{L_{si}} \tag{6}$$

where *Q_e* is the emitters flow rate (L/h), *L_{li}* is the lateral length (m), *E_{si}* is the space between emitter or sprinkler (m), *L_{ri}* is mainline length (m), and *L_{si}* is the space between laterals (m).

❖ Pressure head

Pressure head is calculated using the formula 7 [13]:

$$H_p = H_d + \Delta Z + hf_1 + hf_2 + H_{em} \quad (7)$$

where H_p is the pressure head, H_d is the dynamic high (static height + draw-down) ΔZ is the difference in elevation between the water source and the most unfavorable supply inlet, hf_1 is the head loss from the pump to the most unfavorable supply inlet, hf_2 is head loss from the inlet to the most unfavorable emitter, H_{em} is pressure needed at the emitter, hf_2 and H_{em} are used for drip and sprinkler irrigation techniques.

Drawdown of 10 m is assumed to ensure the availability of well water. Indeed, according to [14] [15], the drawdown in the Niayes area rarely exceeds 10 m.

In addition, specific formulas are used to calculate some parameters related to the pressure head for the different irrigation techniques. Thus, head loss for manual irrigation technique is calculated using the formula 8:

$$hf = \frac{J * L}{100} \quad (8)$$

where L is pipe length (m) and J represents the head losses (%). It is determined on the basis of water flow, diameter and nature of the pipe. J is determined using the flow rate and diameter curve (%).

Concerning drip and sprinkler irrigation techniques, head losses are calculated using Darcy-Weisbach's formula (formula 9) [16].

$$hf = \frac{8f}{\pi^2 g} * \frac{LQ^2}{D^2} \quad (9)$$

$$f = \frac{0.316}{Re^{1/4}} \quad (10)$$

where hf is the head loss (m), f is the Darcy-Weisbach resistance coefficient, L : the pipe length (m), D is the inside diameter of the pipe (m), Re is Reynolds number (m), Q is the flow in the pipe (m^3/s), and g : the gravitational acceleration, 9.81 m/s^2 .

Reynolds number is calculated using the formula 11, given by [16]:

$$Re = 1.273 * 10^6 * \frac{Q}{D} \quad (11)$$

where Re is Reynolds number, Q is the Flow rate (L/s), and D is pipe inside diameter.

In addition, the pressure in plot will be calculated by section using the formula 12 [16]:

$$\Delta H = \frac{J * L * F}{100} + \Delta Z \quad (12)$$

where L is the pipe length (m). J is the head losses (%), is the F : adjustment factor.

Also, head loss less than or equal to 20% compared to the head loss at the previous level is accepted at plot scale (formula 13).

$$\Delta H = 20\% \quad (13)$$

This equation is used to select the appropriate pipe diameter in the network when using drip and sprinkler irrigation techniques.

❖ Pump power

The hydraulic power is calculated using the formula 14, given by [17] [18] [19]:

$$Eh = \frac{\rho g Q H_p}{3600} \quad (14)$$

where Eh is the hydraulic power ($\text{Wh}\cdot\text{day}^{-1}$), H_p is the pressure head (m). Q is the flow rate (m^3/day), ρ is water density ($1000 \text{ kg}/\text{m}^3$), and g is the acceleration of gravity ($9.81 \text{ m}/\text{s}^2$).

Pump power is calculated using the formula 15 [20]:

$$P_{pum} = \frac{Eh}{\eta_{pum}} \quad (15)$$

where Eh is the hydraulic energy ($\text{Wh}/\text{day}^{-1}$) and η_{pum} is overall pumping plant efficiency which will be equal to 70% based on [21].

4) Generator power determination

The photovoltaic generator power, *i.e.* the power of the solar field is calculated using formula 16 [18].

$$P_{gen} = \frac{2.73 * Q * H_p}{P_{sh} * \eta_{pum} * e} \quad (16)$$

where P_{gen} is the generator power (Wh/day), H_p is the Pressure head (m), Q is the Flow rate (m^3/day), η_{pum} is overall pumping plant efficiency which will be equal to 70%, P_{sh} is the number of peak sunshine hours per day ($\text{kW}/\text{m}^2/\text{day}$), and e : electrical efficiency of the system, 2.73 is calculated using ρa is water density ($1000 \text{ kg}/\text{m}^3$), and g is the acceleration of gravity ($9.81 \text{ m}/\text{s}^2$):

$$2.73 = \rho g / 3600 \quad (17)$$

The electrical efficiency of the system (e) is determined based on losses in electric cables (3%), in controller (10%), and losses due to temperature (10%) and dust (2%) on the basis of [18] [19].

The number of panels required is calculated using the formula 18:

$$N_p = \frac{P_{gen}}{P_{panel}} \quad (18)$$

where N is the panels' number, P_{gen} is the power of the generator (kW), and P_{panel} is the power of available panel on the market (kW).

2.3. Economic Feasibility of Solar Pump Irrigation in Nguethiouro Lowland

Thus, variations in the investment cost have been determined based on the different criteria used when choosing pumps. The Net Present Value (NPV), the Benefit-Cost Ratio (BCR), the Internal Rate of Return (IRR) and the Payback Period (PBP) are calculated based on [22] [23] [24].

2.3.1. The Net Present Value (NPV)

NPV estimates the total amount of wealth created by the project. It is expressed as:

$$NPV = Bo - Co \quad (19)$$

where:

- Bo (€): The discounted present value of benefits, calculated as:

$$Bo = \sum Bi * \frac{1}{(1+r)^n} \quad (20)$$

- Co (€): The discounted present value of costs, calculated as:

$$Co = \sum Ci * \frac{1}{(1+r)^n} \quad (21)$$

where: I is the index of year, NPV is the net present value (€), Bi is the benefit flow of the i year, Ci is the cost flow of the i year, r is the interest rate, and n is the time frame of the project.

2.3.2. The Benefit-Cost Ratio (BCR)

BCR is the ratio between the discounted benefit and cost, and expressed as:

$$BCR = \frac{Bo}{Co} \quad (22)$$

The investment is cost-effective when $BCR \geq 1$.

2.3.3. The Internal Rate of Return (IRR)

IRR is the average annual rate generated by the project and is the discount rate which makes $NPV = 0$. It is calculated as: $r = IRR$ when $NPV = 0$. IRR is expressed in percentage (%).

2.3.4. The Payback Period (PBP)

PBP evaluates the time, it'll take to recover the initial investment made in the project. PBP is expressed in year.

3. Results and Discussion

3.1. Solar Irrigation Pump and Generator Characteristics for Drip, Sprinkler and Manual Irrigation for Farmers Individually

The pumps' flow rates, pressure heads and power and the generator power are presented in **Figure 4**.

The flow rate is not much variable considering the three irrigation techniques. It is ranging from 2.5 m³/h to 25 m³/h; 2.7 m³/h to 30.8 m³/h and 2.5 m³/h to 24 m³/h, when using manual, drip and sprinkler irrigation techniques, respectively. Flows rates obtained are relatively low, 86.6% of pumps have a flow rate that is lower than or equal to 15 m³/h when using manual irrigation. This is explained by the fact that cultivated plots in this area are relatively small, ranging from 0.05 ha to 1.91 ha. Thus, these pumps are sufficient to meet the daily irrigation water requirements after 1.5 to 5.9 hours, 1.4 to 4.8 hours and 1.7 to 6.9 hours of operation

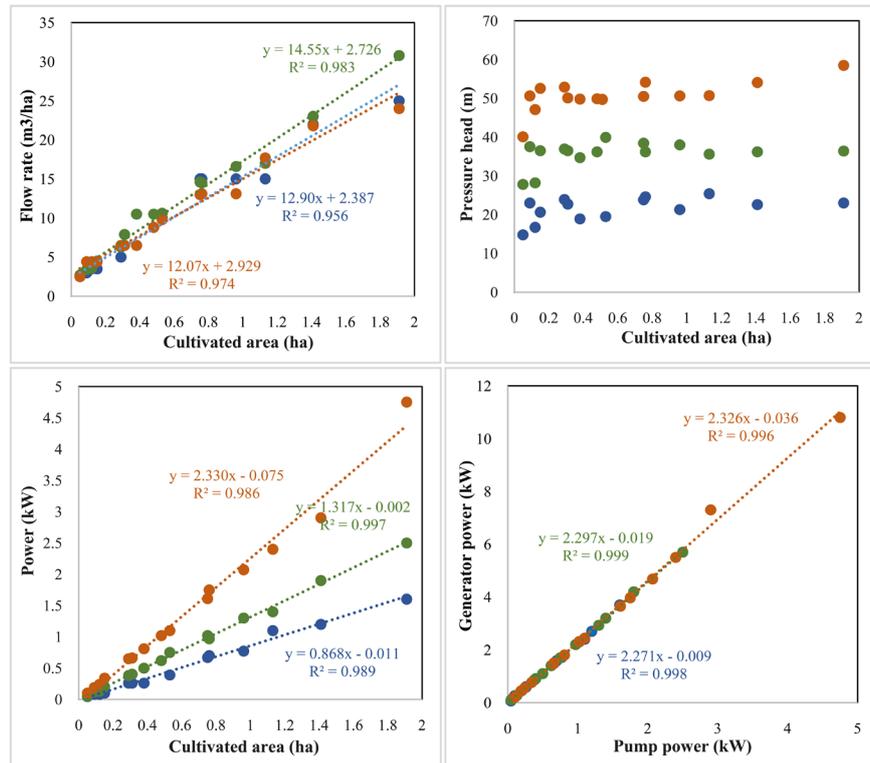


Figure 4. Pumps and generator characteristics for the three irrigation techniques (in blue: manual technique; green = drip irrigation and orange = sprinkler technique).

for manual, drip and sprinkler irrigation respectively. However, the pumps' pressure head and power and the generator power were higher when using drip and sprinkler irrigation techniques. The pressure head is evaluated between 14.8 m to 25.4 m for manual irrigation, 27.8 m and 39.9 m for drip irrigation and 14.8 and 58.5 m for sprinkler irrigation technique. Thus, many factors are affecting pump pressure head in this area. These factors are the differences in elevation observed and the variation in groundwater table. Niayes area is an environment characterized by its dunes and its depressions or slopes [25]. In addition, groundwater level varies between 3.2 and 8.9 m. The pump power ranges from 0.045 kW to 1.6 kW for manual irrigation, from 0.05 kW to 2.5 kW for drip irrigation and from 0.1 kW to 4.75 kW sprinkler irrigation technique. This increase in pump power is mainly due to the increase in pressure required for drip and sprinkler irrigation system operation. The photovoltaic generators for these pumps are also relatively small and vary between 0.06 and 3.7 kW when using manual irrigation. It ranges from 0.11 to 5.7 kW for drip irrigation. Also, the highest value is evaluated à more than 10 kW when using sprinkler irrigation.

The flow rates, pressure head, and power are smaller when using manual irrigation technique with reservoir. It has varied between 2.5 and 21 m³/h when reservoirs are used. Thus, smaller pumps can be used by increasing pump operating time, which is a good way to increase pump's efficiency which can be beneficial to farmers. Use of reservoirs is more beneficial for farmers because, they make it possible to obtain water during periods of low irradiance. However, flow

rate, pressure head, and power are higher when using reservoir when using drip and sprinkler irrigation technique. The increase in pressure is due to the fact that reservoirs are installed at the highest point in plots in order to provide water to basins by gravity.

3.2. Number of Panels Making up the Generator for Different Panel Powers for Farmers Individually

Figure 5 shows the number of panels connected together in the photovoltaic generator for the various solar pumping systems depending on cultivated areas and for panels of different power.

In the case of manual irrigation, the number of panels varied between 1 (0.05 ha) and 46 (1.91 ha) when using panel with power of 80 W and from 1 (0.09 ha) to 11 (1.91 ha) when using panel with power of 330 W depending on panel power. One panel of 80 W, 100 W, or 120 W is sufficient to operate the pump when the cultivated area is equal to 0.05 ha. Concerning drip irrigation, the number of panels varied between 1 (0.05 ha) and 71 (1.91 ha) for 80 W panel's power and from 1 (0.09 ha) to 17 (1.91 ha) for 330 W panel's power. In the same way, 1 panel of 120 W or 150 W is enough to operate the pump when the surface area is 0.05 ha. For sprinkler irrigation, the number of panels varied between 3 (0.05 ha) and 135 (1.91 ha) for 80 W panel's power and from 1 (0.05 ha) to 33 (1.91 ha) for panel with 330 W.

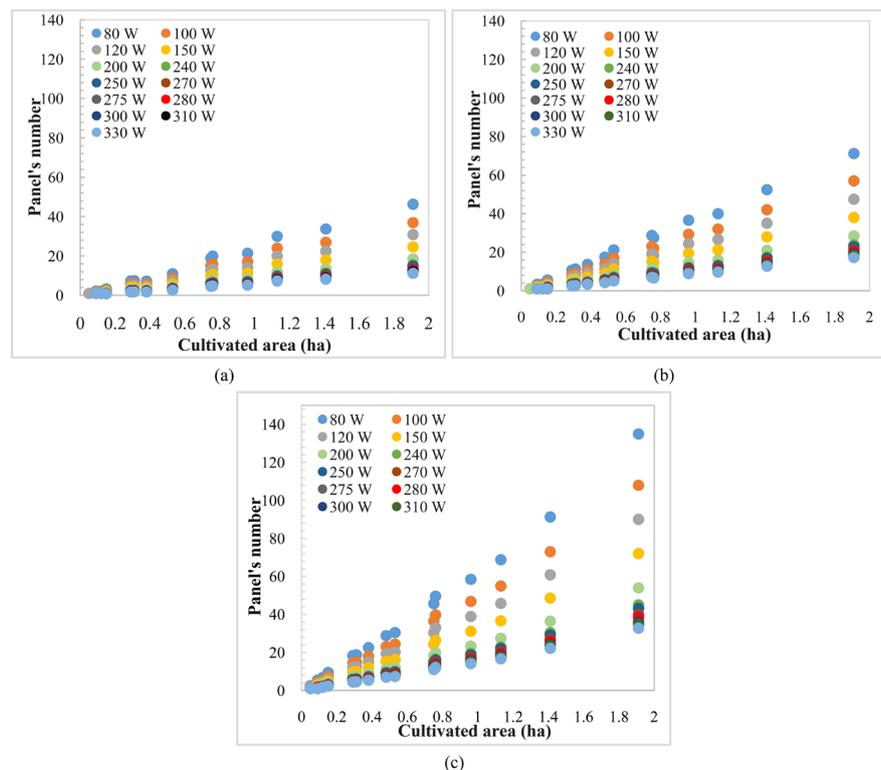


Figure 5. Panels' number function of area, irrigation techniques and power. (a): Panels' number for manual irrigation. (b): Panels' number for drip irrigation. (c): Panels' number for sprinkler irrigation.

3.3. Solar Irrigation Pump and Generator Characteristics for Drip, Sprinkler and Manual Irrigation for Farmers in Groups

The irrigated area when farmers are using pumps in group has varied between 0.92 ha and 2.54 ha. The flow rate of the pumps varies between 16 m³/h and 32 m³/h. the pressure varies between 22 m and 35.7 m. the pump power varies between 0.8 kW and 2.3 kW, and the power of the photovoltaic generator varies between 1.7 kW and 7.7 kW. Irrigation water requirements are met after an operating time of 4 to 6 hours when using manual irrigation. For drip irrigation, results show that pump flow rate varies between 18 m³/h and 41.3 m³/h, pressure head ranges from 53.1 to 75.5 m³/h, pump power varies between 1.5 kW and 4.5 kW, and photovoltaic generator power varies between 3.4 and 1 kW. Concerning sprinkler irrigation, results show that pump flow rate varies between 15.3 and 30.5 m³/h. The pressure head varies between 74.5 and 92.1 m. pumps power is between 2.6 and 8.9 kW and photovoltaic generator power varies between 6.5 kW and 20.3 kW for cultivated areas that vary between 0.79 and 2.29 ha.

The same variation observed when farmers are using pump with reservoir individually is observed when farmer are using pumps with reservoir in groups.

3.4. Number of Panels Making up the Generator for Different Panel Powers for Farmers in Groups

Figure 6 shows the number of panels connected together in the photovoltaic generator for the various solar pumping systems depend on cultivated areas and panel powers.

Figure 6 shows that the number of panels is very high when the plots are grouped together. Results show that the number of panels varied between 21 (0.93 ha) and 64 (2.29 ha) when using panel with power of 80 W and from 5 (0.93 ha) to 15 (2.29 ha) when using panel with power of 330W, depending on panel power, when using manual irrigation. In the case of drip irrigation, the number of panels varied between 43 (0.79 ha) and 126 (2.29 ha) for 80 W panel's power and between 10 (0.79 ha) to 31 (2.29 ha) for 330 W panel's power. Concerning sprinkler irrigation, the number of panels varied between 79 (0.79 ha) and 254 (2.29 ha) for panels with power equal to 80 W and between 19 (0.05 ha) and 62 (2.29 ha) for 330 panel's power. Moreover, these multiple panels can cover a large area in the plots. This can lead to a reduction in cultivated areas. Thus, the use of larger panels' power may be beneficial in these cases.

3.5. Investment Cost Evaluation

The investment cost varies depending on the brand of pump selected. Result of the investment when using manual irrigation show that Lorentz pumps are more expensive (cost varies from 2315 euros (1,518,500 CFA) for 0.05 ha to 4090 euros (2,683,000 CFA) for 0.53 ha), followed by Difful pumps (varying from 1808 euros (1,186,000 CFA) for 0.38 ha to 4798 euros (3,147,500 CFA) for 1.41 ha). In contrast, solar pump, JUQIANG, and SHIMGE pump brands are cheaper (investment cost varies between 669 euros (438,500 CFA) and 1265 euros (825,000 CFA)).

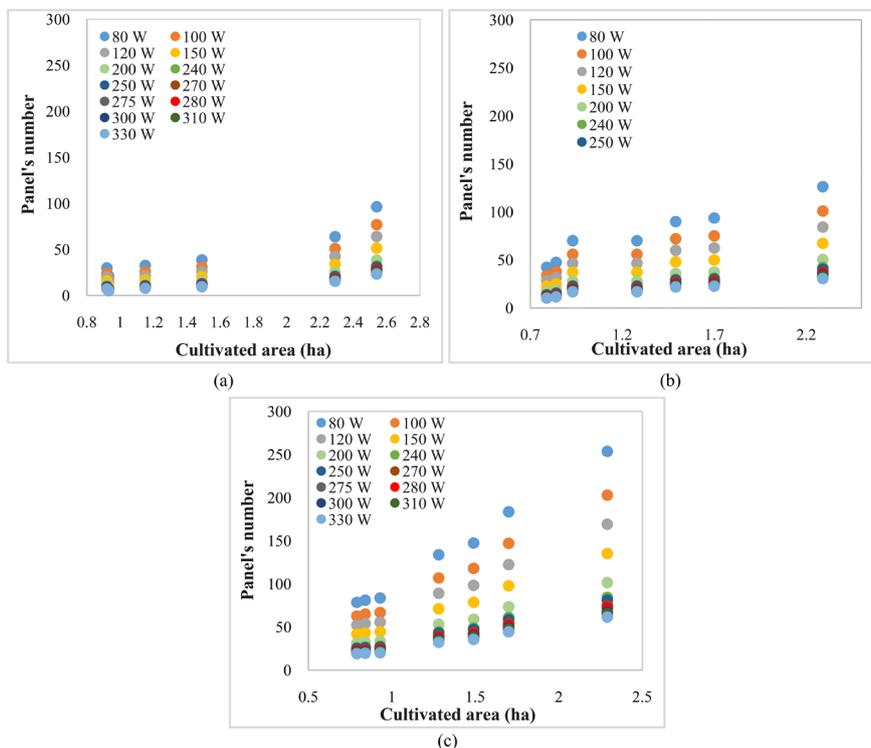


Figure 6. Panel's number for plots' group function of irrigation technique and power. (a): Panels number for manual irrigation. (b): Panels number for drip irrigation. (c): Panels number for sprinkler irrigation.

However, the investment cost for solar pumping system implementation is higher when using drip irrigation technique compared to manual irrigation technique. This increase in cost is more pronounced when using 900 μ drip lines. The investment cost varies between 1281 euros and 18,999 euros when using 600 μ drip lines and between 1303 euros and 20,600 euros when using 900 μ drip lines. Indeed, the high investment cost is explained by the high cost of drip irrigation system. In fact, the irrigation system accounts for two-thirds (2/3) and half (1/2) of the pumping system when using the 900 μ and 600 μ dripper lines, respectively.

Concerning sprinkler irrigation, the result show that the investment cost ranges from 819€ to 14,723€ when using PVC pipes, while it ranges from 990€ to 21,403€ when using aluminum pipes. For this purpose, the implementation of a solar pumping system when using the sprinkler irrigation technique with PVC pipes is cheaper compared to the use of the drip irrigation technique. This is because the investment cost of setting up the sprinkler irrigation system with PVC pipes is cheaper. It represents one third (1/3) of the total investment cost. In contrast, the implementation cost of sprinkler irrigation with aluminum pipes represents half (1/2) of the total investment cost.

These investment costs are higher when using a reservoir because of the additional cost of these reservoirs and because of the increase of the pump size when using drip and sprinkler irrigation techniques.

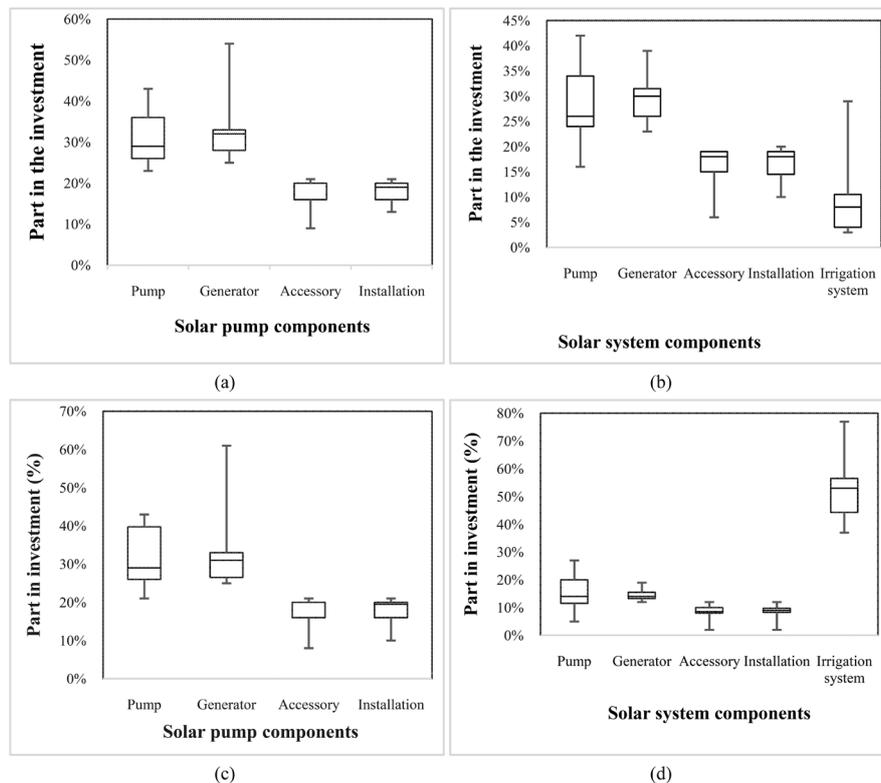
In addition, the investment cost is lower when farmers are using pumps in groups in the case of using manual and drip irrigation technique (Table 2).

3.6. Part (%) of Solar Irrigation Pumping System Components in the Investment Cost

Results in Figure 7 show that the pump and the PV generator are the most expensive components when considering the pumping system without the irrigation system cost. Thus, the generator can account for up to 54%, 61%, and 65%

Table 2. Investment cost at the whole lowland for farmers individually and in groups.

The cases studied	Investment cost without using reservoir		Investment cost when using reservoir	
	Maximum investment (€)	Minimum investment (€)	Maximum investment (€)	Minimum investment (€)
<i>Manual irrigation</i>				
For farmer individually	44,103	28,681	48,717	28,715
For a group of farmer	27,845	26,236	31,450	28,538
<i>Drip irrigation</i>				
For farmer individually	49,828	39,644	68,581	61,522
For a group of farmer	44,652	33,927	67,032	
<i>Sprinkler irrigation</i>				
For farmer individually	62,153	39,911	86,371	75,165
For a group of farmer	68,068	62,222	83,702	83,702



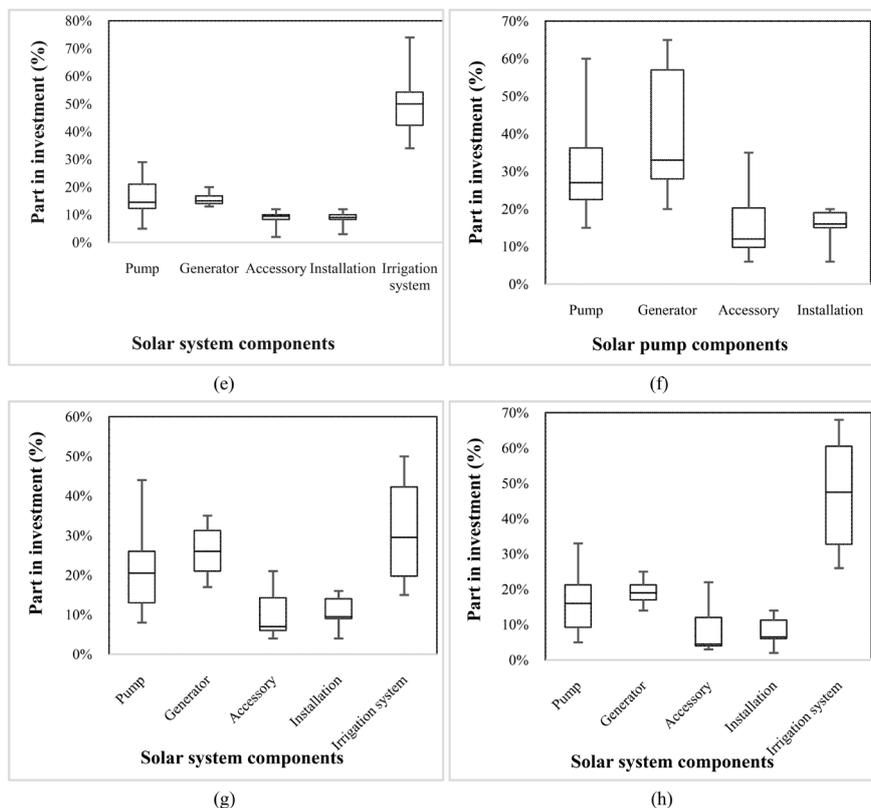


Figure 7. The proportion of irrigation system components in the investment cost of solar pumping system without using reservoir. (a): Proportion for manual for pumping system. (b): Proportion for manual with irrigation system. (c): Proportion for drip for pumping system. (d): Proportion for drip (900 μ). (e): Proportion for drip (600 μ). (f): Proportion for sprinkler for pumping system. (g): Proportion for sprinkler (PVC). (h): Proportion for sprinkler (Aluminum).

of the investment cost when using manual, drip and sprinkler irrigation techniques respectively and the pump can account for up to 43% in manual and drip irrigation and up to 60% in sprinkler irrigation. In fact, pump and photovoltaic generator costs remain higher when using manual irrigation systems, and the irrigation system, in this case, represents at most 29% of the investment cost. However, the irrigation system cost represents the largest proportion when using drip (77% and 74% of the investment cost when using 900 μ and 600 μ drip lines respectively) and sprinkler (50% and 68% of the investment cost when using PVC and aluminum pipes respectively). These percentages decrease slightly when using reservoir. In fact, the cost of the reservoirs represents the smallest proportion and constitutes 3% to 6% of the investment cost.

3.7. Benefit-Cost Analyze

The benefit-cost analysis is conducted based on the NPV, BCR, IRR and PBP (Figure 8).

NPV is higher when using sprinkler irrigation system with PVC pipes and when using drip irrigation technique with the exception of plot 1 (1.91 ha). NPV

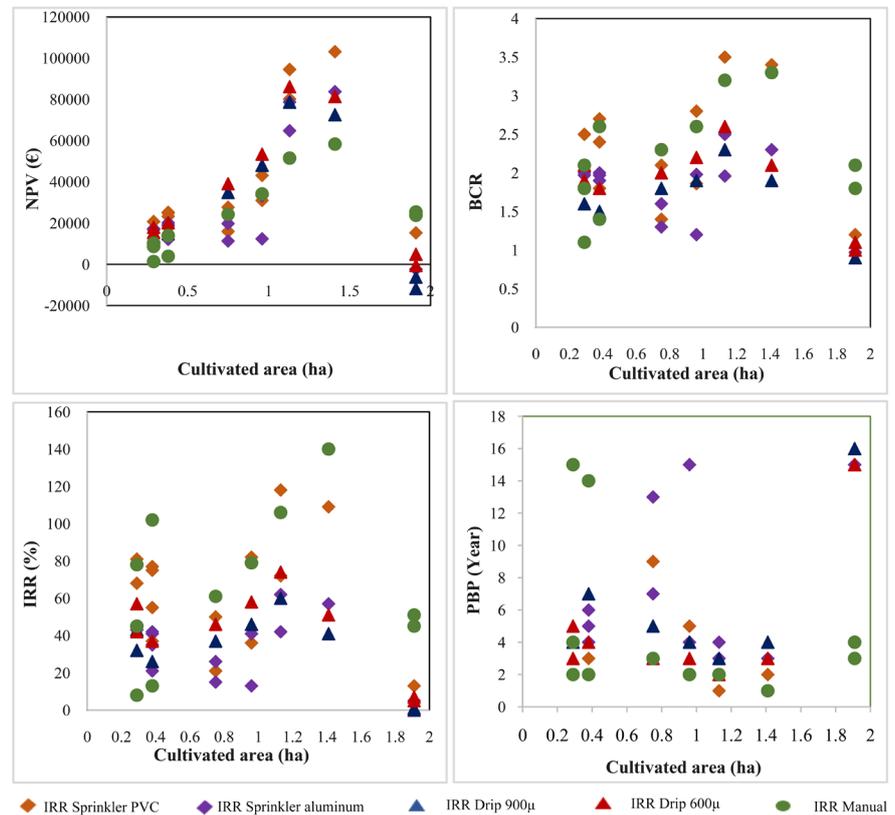


Figure 8. NPV, BCR, IRR and PBP for manual, drip and sprinkler irrigation techniques.

varies between 15,993€ (0.75 ha) and 103,139€ (1.41 ha) when using the sprinkler irrigation technique with PVC pipes and between 13,064€ and 86,139€ when using the drip irrigation technique. Additionally, the results obtained on plots 2 (0.38 ha) and 6 (0.29 ha) when using Lorentz pump brand for manual irrigation techniques showed very low NPV due to the high cost of Lorentz brand.

The use of the manual irrigation system gives the highest BCR value followed by the use of sprinkler irrigation with PVC pipes and drip irrigation. This is due to the lower investment cost when implementing manual and sprinkler irrigation system with PVC pipes. On the other hand, the very low BCR values especially when using modern irrigation techniques on plot 1 (1.91 ha) is related to the low income because of these low yields.

The use of solar irrigation pumps is very cost-effective and risk-free for the different irrigation techniques used with the exception of plots 1 (1.91 ha) for sprinkler irrigation technique, plots 9 and 14 when using sprinkler with aluminum pipe and Lorentz brand, and in plot 6 (0.29 ha) when using manual irrigation technique and Lorentz brand (15).

The results show that PBP is shorter when using manual and sprinkler irrigation techniques with PVC pipes. This is explained by the lower investment cost compared to the others. According to the results, the project starts to be profitable in the first or second year when using brands such as LIKOU and Asaman, which are very affordable. On the other hand, the return on investment is slow-

er, up to 10 years when using Lorentz brand pumps and more frequently when using sprinkler irrigation technique with aluminum pipes.

4. Conclusion

The study aims to evaluate the technical and economic feasibility of solar irrigation pump in the Nguethiouro lowland. Pumps were designed on the basis of irrigation management, irrigation techniques and water distribution. Concerning the economic feasibility, it is studied based on an investment cost estimation and a benefit-cost analysis approach. Results show that pumps' flow rate does not much varied considering the different irrigation techniques. However, the pumps' pressure and power and the generator are higher when using drip and sprinkler irrigation techniques. In addition, the flow rate, the pressure, and the pump power are lower when using manual irrigation technique combined with a reservoir whereas they are higher when using modern irrigation techniques combined with a reservoir. In addition, results show that pumps' characteristics are higher when farmers are organized in groups. With regard to the economic feasibility, results show that the investment cost ranges from 669€ to 4090€ when using the manual irrigation, from 1281€ to 20,600€ when using the drip irrigation technique and from 819€ to 21,403€ when using sprinkler irrigation technique for individual pumps. Also, the investment cost is higher when farmers are organized in groups considering the whole lowland. Results show that the use of solar irrigation pumps with the sprinkler irrigation technique with PVC pipes and with the drip irrigation technique is more profitable for the farmers based on the NPV, BCR, IRR, and PBP. However, optimization in the amounts of water extracted and used during the implementation of solar irrigation pumps would be interesting in order to avoid groundwater overexploitation by farmers.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

<i>BCR</i>	Benefit Cost Ratio
<i>Bi</i>	Benefit flow of the i year
<i>Ci</i>	Cost flow of the i year
<i>D</i>	Inside diameter of the pipe
ϵ	Electrical efficiency
<i>Eh</i>	Hydraulic energy
<i>ea</i>	Actual vapor pressure
<i>es</i>	Saturated vapor pressure at air temperature
<i>Esi</i>	Space between emitter or sprinkler
<i>Etc</i>	Crop evapotranspiration
<i>Eto</i>	Reference evapotranspiration
<i>f</i>	Darcy-Weisbach resistance coefficient
<i>FC</i>	Field Capacity
<i>G</i>	Soil heat flux density
<i>g</i>	Gravitational acceleration
<i>GIR</i>	Gross Irrigation Requirement
<i>Hd</i>	Dynamic high
<i>Hp</i>	Pressure head
<i>Hem</i>	Pressure needed at the emitter
<i>hf</i>	Head loss
<i>hf1</i>	Head loss from the pump to the most unfavorable supply inlet
<i>hf2</i>	Head loss from the inlet to the most unfavorable emitter
<i>Ho</i>	Number of hours of operating time
<i>IRR</i>	Internal Rate of Return
<i>J</i>	head losses in percentage
<i>Kc</i>	Crop coefficient
<i>L</i>	Pipe length
ρ	Water density
<i>Lli</i>	Lateral length
<i>Lri</i>	Mainline length
<i>Lsi</i>	Space between lateral
<i>n</i>	Time frame of the project
<i>NIR</i>	Net irrigation requirement
<i>η_{pum}</i>	Overall pumping plant efficiency
<i>NPV</i>	Net Present Value
<i>PBP</i>	Payback Period
<i>Peff</i>	Effective rainfall

Continued

<i>Pgen</i>	Generator power
<i>Ppanel</i>	Power of available panel on the market
<i>Psh</i>	Number of peak sunshine hours per day
<i>PWP</i>	Permanent Weir Point
<i>Q</i>	Flow rate
<i>Qe</i>	Emitters flow rate
<i>r</i>	Interest rate
<i>Re</i>	Reynolds number
<i>Rn</i>	Net radiation
<i>SAT</i>	Saturation
<i>T</i>	Mean daily air temperature
<i>TAW</i>	Total Available Water
<i>u2</i>	Wind speed measured at 2 m height
<i>γ</i>	Psychometric constant
<i>Δ</i>	Slope of the saturated vapor pressure curve
<i>ΔZ</i>	Difference in elevation between the water source and the most unfavorable supply inlet
