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Research Article

Enhancing Economic Viability of PV Water Pumping Systems for Alfalfa Irrigation Through Multi-Crop Irrigation

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Abstract

Desertification in Algeria predominantly affects arid and semi-arid steppes, areas that traditionally support extensive livestock farming. These rangelands, which span approximately 32 million hectares, are experiencing severe degradation, negatively impacting livestock productivity and contributing to national shortages of milk and meat. To address this, we propose the installation of optimized photovoltaic water pumping systems (PVWPS) to irrigate crops such as alfalfa, barley, and corn, while ensuring a reliable water supply for both livestock and crops. The goal is to enhance ecosystem resilience and agricultural productivity. An economic and financial analysis was conducted to evaluate the project's feasibility and profitability. An economic and financial analysis was conducted to evaluate the project's feasibility and profitability. Results showed that the system's lowest life-cycle cost is 10,069,710 DZD, with a levelized cost of water of 3.33 DZD/m³. Optimization efforts included selecting appropriately sized PV arrays and storage tanks, as well as adjusting the tilt of the photovoltaic (PV) panels, which improved water yield by 6%. Additionally, integrating alfalfa with other crops improved water efficiency by 26.40%. This integrated approach resulted in positive net present values (NPV), a payback period of 2.87 years, and a benefit-cost ratio greater than 1. Moreover, this solution is scalable to other arid regions, particularly in the Sahel, offering a sustainable method to address water scarcity and enhance agricultural practices in similar ecosystems.

Keywords

PV Water Pumping System, Optimal Configuration, Arid Region, Animal Fodder, Crop Association, Economic Analysis

1. Introduction

Livestock breeding in Algeria has always retained a traditional character, based above all on nomadism and the exploitation of the natural resources of the steppe and the rangelands of the highlands. However, the Useful Agricultural Area (UAA) constitutes only 8.56 million ha, or 19.6% of the Total Agricultural Area (TAA), with just 951,841 ha dedicated to fodder cultivation, representing 21.8% of the TAA and a mere 0.4% of the country's total area [1]. This is insufficient to meet the needs of Algeria's growing population, as depicted in Figure 1 [2]. Consequently, the national fodder balance suffers a deficit of 7.289 billion FU (fodder units), significantly impacting livestock productivity and creating deficits in milk and meat production [3]. This has necessitated reliance on costly imports of animal products to bridge the gap.

The regional disparities in Algeria exacerbate these agricultural challenges. The Sahara, a vast arid region covering 86% of the country's territory (Figure 2), but home to only 13% of its population, contrasts sharply with the northern wilayas,

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which occupy 14% of the land area but are densely populated and better equipped with infrastructure [4]. This North-South imbalance, compounded by coastal-hinterland disparities, limits the equitable distribution of resources critical for agricultural development.

Milk, a staple of the Algerian diet, illustrates the country's dependence on imports. Despite an annual consumption of 5 billion liters—145–150 liters per capita—local production meets only 3.5 billion liters of demand [5, 6]. To address this shortfall, Algeria imports 40% of its milk consumption, primarily as powdered milk, at an annual cost of $1.5 billion USD [6, 7]. Similarly, imports of animal feed reached $2 million USD in 2018, underscoring the country's reliance on foreign markets to sustain its livestock sector [7].

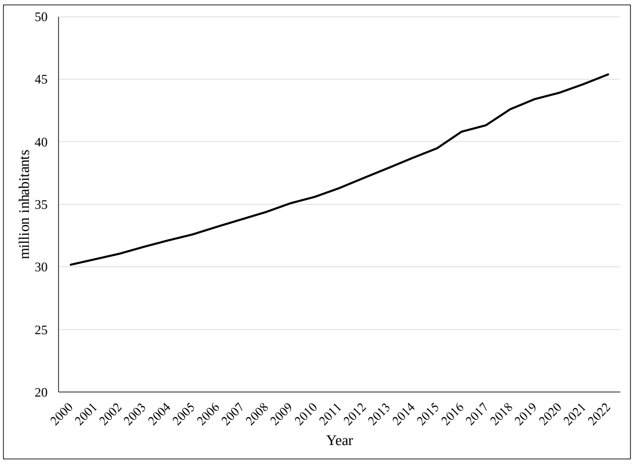

Figure 1. Evolution of the population in Algeria (2000 – 2021).

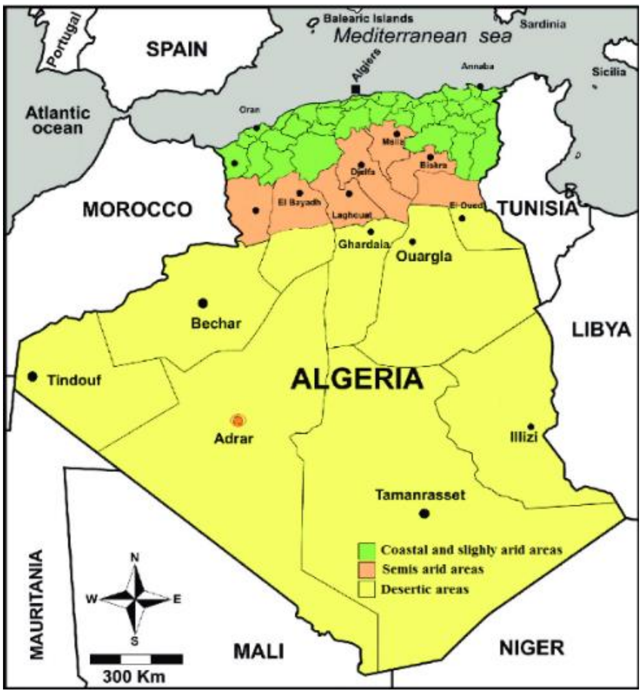

Figure 2. The map of Algeria displays the vast expanse of the Sahara, one of the world's driest deserts.

In response to these challenges, this study proposes a sustainable solution: a techno-economic model for a 5-hectare alfalfa plantation in the Adrar region (Figure 2), irrigated by a photovoltaic water pumping system (PVWPS) and drip irrigation. The region's mild temperatures offer a favorable environment for forage cultivation despite its arid conditions. This project aligns with international sustainability goals by addressing multiple priorities: reducing dependence on imported feed and dairy products, increasing renewable energy use, improving food security, and mitigating desertification. By efficiently utilizing groundwater through drip irrigation, the project also promotes resource conservation while ensuring year-round forage production.

This initiative demonstrates the potential for integrating renewable energy and sustainable agricultural practices to foster economic and environmental resilience in arid regions. Beyond its local impact, the project aligns with the United Nations' Sustainable Development Goals (SDGs), particularly Goal 2 (Zero Hunger), Goal 6 (Clean Water and Sanitation), and Goal 7 (Affordable and Clean Energy). By enhancing livestock productivity and reducing environmental degradation, this model offers a pathway to sustainable agriculture in Algeria and other arid regions globally.

2. Overview of Photovoltaic Water Pumping Systems for Irrigation

In areas without access to the electricity grid, diesel engines are often used as the main source of energy. This is especially common in Saharan regions, where the price of diesel fuel is heavily subsidized. The fuel prices in Algeria and the evolution of CO2 emissions in metric kilotonnes in Algeria are illustrated in Table 1 and Figure 3, respectively [8]. Based on Figure 3, it is clear that greenhouse gas emissions have significantly increased due to energy production, predominantly from fossil fuels, comprising approximately 98% [9]. Additionally, there is a rising trend in the use of diesel engines in off-grid regions.

Table 1. Fuel prices in Algeria (Considered among the cheapest in the world).

Type	Price DZD (Algerian Dinar)[1]	Unit	Starting from
Gasoline (unleaded)	45.62	Liter	06/06/2020
Gas oil	29.01	Liter	06/06/2020

[1] 1 Euro = 145.61 DZD; 1 US Dollar = 134.70 DZD [10].

To reduce greenhouse gas emissions and soil pollution caused by lubricants, renewable energies represent the most appropriate solution for the development of agriculture in Saharan regions, particularly for small farms with areas not exceeding 5 hectares.

In these regions, two main sources of renewable energy are available: photovoltaic solar energy and wind energy. Photovoltaic solar systems, which are widely mastered and readily accessible, stand out for their ability to operate in line with the sun, an abundant resource in these areas.

On the other hand, wind-powered pumping systems face several limitations. Their efficiency is relatively low, their availability remains limited, and the required technology is not yet fully mastered. Moreover, if these systems are not integrated into a hybrid configuration, they risk prolonged periods of non-operation, which could jeopardize crop yields. This situation is primarily due to the specific climatic characteristics of the Algerian Saharan regions, where wind speeds are moderate and often insufficient for only 2 to 3 months of the year.

Solar energy can be used as an alternative to conventional pumping systems that use diesel and electric energy sources for irrigation water pumping [11]. This alternative is considered to be sustainable and economical. Therefore, several countries' national governments are supporting policies and programs to promote the widespread use of solar energy pumps in agriculture for irrigation purposes [12, 13].

Photovoltaic systems offer several advantages, such as high reliability, low operating costs, flexibility, and independence from fossil fuels. Furthermore, the operation of these systems does not cause any pollution due to greenhouse gas emissions, fuel, or oil spills on the ground, which can lead to groundwater contamination [14].

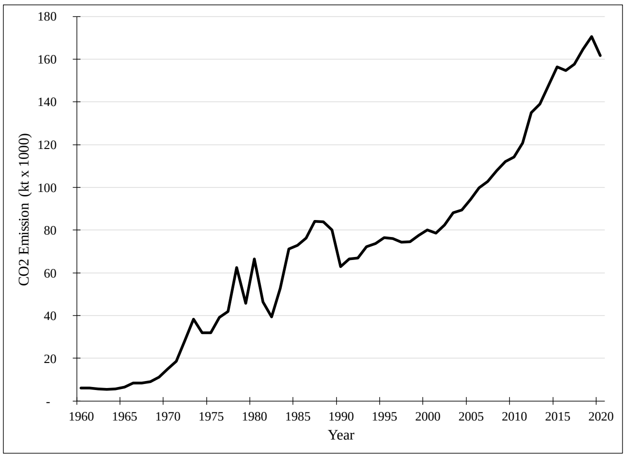

Figure 3. *CO_2 emissions – Algeria.*

The trend toward using PVWPS has changed due to the falling prices of PV modules. This has made PVWPS more competitive. Prices for all module categories have been corrected downward by around 10% [15]. This is a significant decline in panel prices, never seen before in the history of photovoltaic. The monthly evolution of solar panel prices from December 2023 to December 2024 per category is illustrated in Figure 4. The prices shown reflect the average offer prices for duty-paid goods on the European spot market [16].

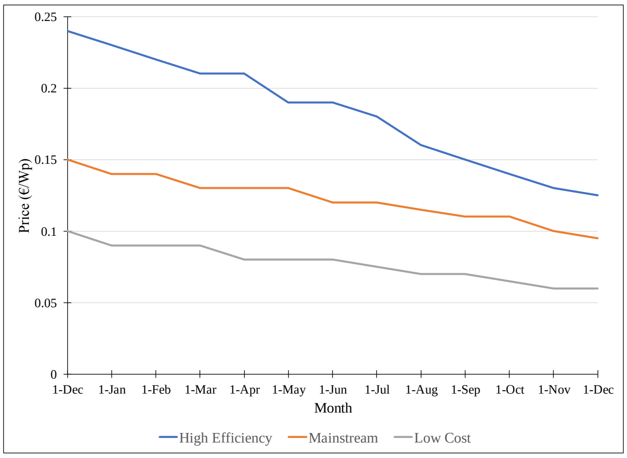

Figure 4. *Panel price evolution (€/Wp).*

In the Saharan regions of Algeria, it is expensive to create an interconnection with the national network because the farms are located far away from the existing network. Even if fuel is available in the villages, it is very difficult to transport it via the tracks to the affected sites. As a result, the use of renewable energies is becoming more attractive for agricultural applications, which are the main financial resources in these remote regions (agriculture and animal breeding).

PV water pumping is highly suitable for arid and semi-arid regions where there is an underground water potential and a significant solar energy potential of more than 6 kWh/m^2d [17].

PVWPS are widely used for irrigation purposes across many countries in Africa, America, Asia, Europe, and Oceania. These systems provide access to electricity in remote and isolated regions, ensuring access to water to improve food production. The use of such systems reduces greenhouse gas emissions linked to fossil fuel-based energy sources, which aligns with the United Nations' objectives for sustainable development. Governments have launched programs to encourage the widespread adoption of photovoltaic systems for water pumping, as evidenced by some authors [11-13].

Through their work, several researchers have praised the use of these water pumping systems intended for irrigation [18-20]. PVWPS for irrigation purposes has gained importance in recent times due to its environment-friendly features, reducing dependence on high GHG emitting diesel fuel, curbing land degradation and valuing them through the availability of pasture [21].

Due to the scarcity of water in these arid regions, the water resources available at the groundwater table must be used very efficiently through water-saving irrigation technologies. As such, a drip irrigation network is suggested to be used downstream of an optimized PVWPS. This system can be optimized through water storage in a reservoir or through energy storage using batteries. However, some researchers have proposed a direct pumping system to avoid the drawbacks of hydraulic or electrical storage in batteries [22, 23]. With this system, water is directly pumped to the drip irrigation network [24, 25]. To ensure improved functionality and effective execution of such systems, various design tools have been developed.

2.1. System Sizing

Calculating the appropriate size is a crucial step in designing water pumping systems for irrigation. It is important to consider various parameters such as water needs, hydraulic energy requirements, available solar energy, and component choices. Procedures for sizing PVWPS intended for irrigation have been developed and presented by [26]. The steps involved in sizing such systems include determining irrigation requires based on soil type and local climate, analyzing hydraulic resources, determining the necessary height of the water tank to stabilize pressure in the distribution network, and determining the required photovoltaic components. PV pump-powered drip irrigation system for arid regions, taking into account various design parameters such as irradiation, pump, water requirements, and drippers has been developed by [27]. A dynamic modeling tool to assess water needs for irrigation has been developed by [28]. An optimization model based on the Loss of Power Supply Probability. (LPSP) and the cost over the life of two systems in two different Saharan regions has been used by [14, 29]. In their study, other authors concluded that, to achieve the desired flow rate for a given head, the required size of the pumping PV system and the pump’s rated power should always exceed the design value [21].

2.2. System Performance

Numerous studies have been conducted to investigate the performance of PVWPS under different configurations, such as hydraulic and electrical storage, DC/DC systems, DC/AC systems, and hybrid systems. A methodology has been developed to predict the performance of a directly coupled PVWPS in South Sinai, Egypt [30]. They simulated the daily hourly performance of the system under different photovoltaic generator orientations. Bora et al. [31] analyzed the performance of a DC motor-driven solar water pumping system and found that tracking the Maximum Power Point Tracker (MPPT) and the position of the sun improved the system's performance. Similarly, a study by Sontake et al. [32] claimed that manual variation of the PV array improved the power produced by 20%.

Some researchers have suggested the addition of certain materials to PV water pumping systems for irrigation to improve their performance. Harishankar et al. [33] recommended a controlled irrigation system in which the outlet valve of the tank is automatically regulated using a controller and humidity sensor to control the flow of water from the tank to the irrigation field. Lopez-Luque et al. [23] used uncompensated transmitters in the olive irrigation network. Pande et al. [34] submitted a model to ensure uniform irrigation in arid regions by using Openable Low-Pressure Compensated (OLPC) drippers and manual monitoring of the PV array.

2.3. Using Agricultural Sectors for Irrigation

Dividing the irrigation area into multiple sectors has various impacts on the technical and financial aspects of the system. Firstly, it reduces pump flow. Secondly, it requires the use of small-section pipes. Lastly, it optimizes the system. Studies have shown the necessity of dividing the total surface area into several sectors to be irrigated, with each sector being controlled by a manual or electric valve.

The irrigation system is divided into different sectors on the farm. Zavala et al. [35] proposed a new model to optimize the operation of a multi-sector direct-pumped photovoltaic irrigation system. The model takes into account the possibility of using a variable number of irrigation sectors simultaneously.

2.4. Excess Energy

The sizing of photovoltaic water pumping systems for irrigation is typically determined by the maximum water consumption of the crops being cultivated. However, there are certain growth stages during which the water needs of the crops may decrease, leading to a surplus of pumped water that needs to be managed effectively [29]. It is important to minimize this excess and prevent wastage by carefully planning its usage and optimizing the system to the best extent possible.

2.5. Storage Analysis

Numerous researchers have conducted studies on photovoltaic water pumping systems (PVWPS), exploring both hydraulic and energy storage solutions to effectively match energy supply with irrigation demand. The most common approach remains the use of elevated water storage tanks, where water is pumped and stored during periods of high solar irradiation, and then distributed to plants via gravity. This method is widely adopted due to its simplicity and reliability. However, in regions where elevated terrain is unavailable, such as the study area, the construction of elevated tanks becomes prohibitively expensive due to the high material and labor costs of cement structures.

To address these limitations, alternative storage solutions have been explored, including the use of battery storage systems and hybrid solutions that combine water and energy storage. Chand & Kalamkar [36] observed that while batteries offer a viable solution for storing energy to operate pumps during periods of low solar availability, they also introduce drawbacks such as increased system cost, reduced overall efficiency, and the need for regular maintenance. This makes batteries less attractive in small-scale agricultural settings where cost constraints are significant.

Alternatively, hybrid storage systems, which combine water storage tanks and battery storage, have been proposed as a more effective solution. Biswas & Tariq Iqbal [37] concluded that hybrid systems provide a balanced approach to meet irrigation challenges by mitigating the limitations of individual storage methods. In hybrid configurations, excess energy generated during peak solar hours is first used to pump water into a storage tank, ensuring a gravity-based water supply when needed. Any surplus energy beyond the water-pumping requirements can be stored in batteries, allowing for continued pump operation during periods of low irradiation or overcast conditions. This combination reduces reliance on any single storage medium and improves the overall system's resilience and adaptability.

While elevated water tanks remain the most common storage solution, hybrid systems that integrate water and energy storage present a promising alternative for overcoming economic and technical challenges. These systems improve energy efficiency, reduce costs, and enhance the reliability of PVWPS, particularly in remote and resource-limited agricultural regions.

2.6. Photovoltaic Array

To enhance the efficiency of the PV array and, consequently, the performance of the PVWPS, a monthly variation will be implemented for the PV array. In regions with high energy potential, such as arid areas with high levels of sunlight, similar to the study region, many researchers have optimized the power produced by the PV array by adjusting its tilt angle relative to the ground [38].

2.7. Limitations of the Models Used and Potential Improvements

While the development of photovoltaic water pumping systems (PVWPS) has seen significant advancements, it is essential to recognize that existing models still have certain limitations that affect their accuracy and applicability in real-world scenarios. These limitations need to be addressed to improve the reliability and efficiency of PVWPS, ensuring their optimal performance across diverse environmental and operational conditions. Below we describe some of the main limitations of current models, followed by potential improvements that could be incorporated into future research and model development.

2.7.1. Limitations of the Models Used

While significant progress has been made in modeling photovoltaic water pumping systems (PVWPS), several limitations still impact their accuracy and practical application:

1) Simplified Assumptions: Many existing models assume steady-state conditions, overlooking the daily and seasonal variations in solar radiation, water demand, and hydraulic loads.
2) Neglect of System Losses: Losses such as thermal inefficiencies in PV panels and mechanical losses in pumps are often underestimated, leading to discrepancies between theoretical and real-world performance.
3) Limited Water Resource Variability: Variations in groundwater levels and hydraulic head are frequently not accounted for, potentially compromising the long-term sustainability of the system.
4) Excess Water Production: The pumping of excess water during periods of low irrigation demand, such as during certain crop growth stages or harvest seasons, is often not considered, leading to unnecessary resource waste.

2.7.2. Potential Improvements

To address these limitations, future models can benefit from the integration of the following:

1) Dynamic Simulations: Tools that incorporate real-time data on solar irradiation, water demand, and system losses, providing a more accurate representation of system behavior.
2) Hybrid Energy Solutions: Combining PV with other renewable sources, such as wind, or integrating backup systems to enhance system reliability and performance.
3) IoT and Machine Learning: Leveraging real-time monitoring and predictive algorithms to optimize system operation, ensuring efficient water production that meets actual irrigation needs.
4) Advanced Irrigation Techniques: Implementing precision irrigation strategies, including soil moisture monitoring and automated water flow control, to reduce excess water usage.
5) Environmental Considerations: Integrating the effects of environmental factors such as dust accumulation and temperature variations, which impact PV panel efficiency.
6) Water Resource Management: Introducing mechanisms to store or redirect excess water during periods of low demand, thereby preventing unnecessary waste and improving resource utilization.

3. Description of The Study Region

3.1. General Geographical Location

Adrar, located in the southwest of Algeria, is over 1,200 km from Algiers. Positioned between longitudes 2 ° E and 6 ° W and latitudes 20 ° and 32 ° N, the region spans an area of 427,368 km ², approximately 18% of Algeria's total landmass (Figure 2). Despite its vast size, Adrar remains one of the most socio-economically underdeveloped regions of the country, with significant challenges in terms of infrastructure and economic opportunity.

The region’s economy is primarily agricultural, centered around traditional oasis farming systems with date palm plantations as the cornerstone. These oases are complemented by small-scale farming of cereals, legumes, fodder, and vegetables, as well as livestock breeding, which contributes to rural livelihoods. In addition, modern agricultural practices, such as cereal cultivation under pivots and vegetable farming in greenhouses, have begun to emerge, offering potential for more diversified agricultural production (Figure 5). However, these sectors face several constraints that limit their full potential.

Figure 5. *Different cultivation methods are practiced in Adrar, including cereal cultivation under pivots and vegetable crops in greenhouses [39].*

3.2. Potential Transformative Impact of the Project

A major challenge is the region’s limited access to reliable energy, particularly in remote areas where diesel generators are the primary source of power for irrigation. This reliance on costly, inefficient energy systems further exacerbates the region's economic difficulties, as farmers struggle with high operational costs. Furthermore, Adrar suffers from a lack of essential socio-economic infrastructure, including healthcare, education, and transportation networks. This deficiency stifles growth and contributes to high poverty rates, especially in isolated communities.

As a result, many working-age individuals, particularly the youth, are compelled to migrate to urban centers in search of employment and better living conditions, further draining the region’s human capital. This outmigration, combined with insufficient wealth generation, hinders the development of a more diversified and resilient economy, trapping the region in a cycle of underdevelopment.

The introduction of sustainable technologies, such as photovoltaic water pumping systems (PVWPS), offers a transformative opportunity for Adrar. By addressing energy challenges and improving agricultural productivity, these solutions can stimulate local economies, reduce poverty, and help reverse the outmigration trend. In doing so, the project has the potential to significantly enhance living standards and foster long-term socio-economic growth in one of Algeria’s most underserved regions.

3.3. Climate

The Adrar region experiences a Saharan climate regime that is hyper-arid, resulting in permanent drought. The aridity is not only due to high temperatures in summer and low precipitation but also due to the dryness of the air, which leads to significant evaporation. This climate has two seasons: a relatively short cold season and a hot season that lasts for approximately 7 to 8 months, during which the temperature remains significantly above 20 ℃.

Adrar is located in an area with abundant solar resources, receiving an average daily irradiation of 4 to 8 kWh/m^{2}d (Figure 6). The region experiences high temperatures in the summer (often exceeding 40 ℃ in June, July, and August) and cold weather in the winter (sometimes dropping to 0 ℃ in December and January). The humidity levels are generally low, rarely exceeding 50% throughout the year. Adrar receives high daily insolation, with 7 to 8 hours of sunlight in winter and 10 to 11 hours in summer. This results in very high reference evapotranspiration (*ET0*) throughout the year, with a marked winter minimum of 3.2 mm/d and a summer maximum of 23.6 mm/d. The region experiences frequent winds throughout the year, with the highest frequency occurring from May to September. Wind speeds above 5 m/s can cause sandstorms.

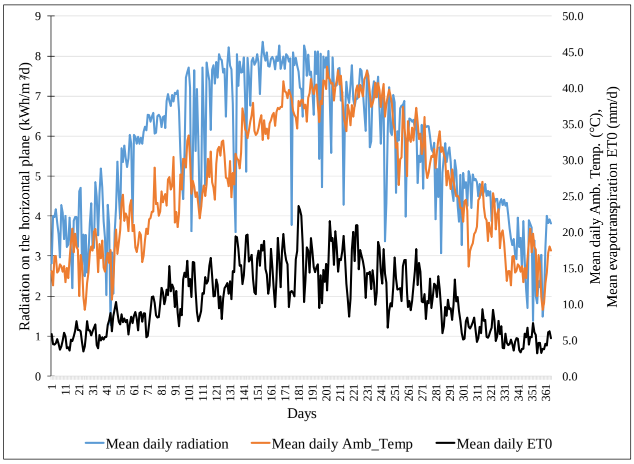

Figure 6. *Irradiation, temperature, and average daily evapotranspiration of the Adrar region.*

3.4. Water Resources

The region has no surface water and very little precipitation. All water resources in the area come from the continental intercalary (CI) aquifer. This aquifer has been known and used for centuries in certain parts of the region. The Northern Sahara Aquifer System (SASS) is shared by Algeria, Tunisia, and Libya. It consists of two important layers: the continental interlayer and the terminal complex. The continental interlayer, also known as the "Albian sheet", is part of this powerful sedimentary series (Figure 7). The water reserves of the basin are estimated at 60,000 billion m^3 distributed over two superimposed aquifers: the continental interlayer (CI), whose depth reaches 3,000 m in certain areas, and the Terminal Complex (TC), with a depth between 300 and 500 m [40]. The static level of the intercalated continental aquifer ranges from 13 to 30 meters relative to the ground level. The Adrar region is located at the southwest limit of the Northern Sahara Aquifer System (SASS).

The use of high flow rates for irrigation, along with rampant illegal drilling, has resulted in permanent damage to the water table. Moreover, the boreholes are randomly located within the agricultural plot, with multiple boreholes often found in the same area, and they operate 24/7 (Figure 8).

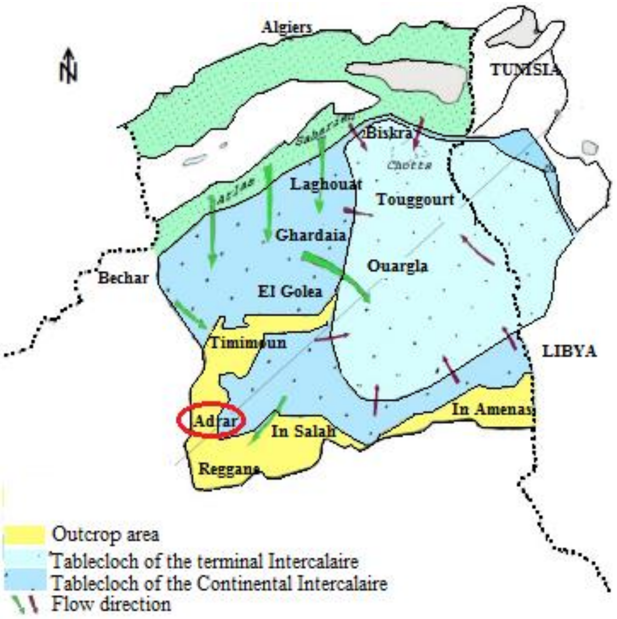

Figure 7. *Extension of the basin of the Albian aquifer.*

Figure 8. *Illegal drilling in an agricultural plot.*

3.5. Assessing Irrigation Requirements and Determining Optimal Storage Tank Elevation

In Algeria, despite the increase in fodder crop areas over the past two decades, they remain insufficient to meet the demands of the existing livestock herds, severely limiting improvements in milk productivity. Given this reality, it is crucial to develop effective strategies to optimize the use of available resources, especially water, to sustainably support the growth of the agricultural sector.

Promoting crops such as alfalfa, known for its nutritional properties, could significantly enhance livestock feed quality while conserving water resources. Alfalfa is well-suited to local conditions and requires less water compared to other crops, making it a prudent choice amid growing water constraints.

Crop water requirements, which compensate for evapotranspiration losses (ETc), vary based on climatic and agronomic factors. These requirements are calculated for each crop using "Eq. (1)" [20].

$$ET_c = K_c \times ET_0 \quad (1)$$

Where

ET_c: Crop evapotranspiration (mm/d)

ET_0: Reference evapotranspiration (mm/d)

K_c: Crop coefficient

Evapotranspiration (ET0) is a critical component of the irrigation plan, estimated using the FAO Penman-Monteith equation with weather and location data "Eq. (2)".

$$ET_0 = \frac{[0.408\,\Delta \times (R_n - G)] + [\gamma(900/(T+273)) \times U_2(e_s - e_0)]}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

Where *ET0* represents reference evapotranspiration (mm/day), *Rn* is global radiation (MJ/m^{2}day), *G* is ground heat flux (MJ/m^{2}day), *T* is average daily air temperature at 2 m height (°C), U_2 is wind speed at 2 m height (m/s), *es* is saturation vapor pressure (kPa), e_0 is vapor pressure at temperature T (kPa), *Δ* is the slope of the saturation vapor pressure curve (kPa/°C), *γ* is the psychometric constant (kPa/°C), and *900* is a constant for daily time step.

Crop water requirements (CWR) were calculated using FAO Cropwat and Climwat software "Eq. (3)" [41].

$$CWR = ET_c / E_i \quad (3)$$

Where

CWR: Crop water requirements (mm/d)

E_i: Irrigation efficiency (%)

The areas are equipped with drip irrigation systems, renowned for reducing salinization and soil waterlogging, achieving up to 95% irrigation efficiency [24, 38].

The agricultural plot that will be studied is presented in Table 2. The farm in Sbaa (Adrar) cultivates 5 hectares of alfalfa for fodder. Monthly evapotranspiration ET0 based on Penman-Monteith is provided in Table 3. The daily and monthly irrigation requirements for alfalfa are provided in detail in Table 4.

Table 2. *Characteristics of the agricultural plot.*

Designation	**Specification**
Location	Sbaa perimeter (28 °12'43" North, 0 °10'30" West), Adrar region, Algeria
Area	5 hectares.
Plot plan	10 plots of 100 x 50 meters each.
Climate	The region has high aridity, with a dry season throughout the year. Temperatures are high with strong insolation, low humidity and strong winds, leading to high evapotranspiration rates that necessitate continuous irrigation.
Soil type	The soil type for the area is sandy, and the ground depth is deep. In terms of cultural skills, the area is suitable for both annual crops and perennial crops
Choice of irrigation system	T-Tape sheath (Aquatape) due to the low operating pressure required
Flow rate from the emitters	2 liters/hour at a pressure of 0.70 bars.
Crop	Alfalfa is grown in a single row (bed); plants are spaced 0.20 meters apart on the row; the rows are spaced 0.75 meters apart.
Number of emitters per plant	1
Water ressources	Tablecloth: Continental Interlayer (CI), Type of structure: Drilling, Depth: 20 meters,
Water requirements	In July, the maximum water required is 8.5 mm/day or 85 m^3/ha/day.
Time needed for irrigating each plot	0.64 hour (38 minutes)
Time needed to irrigate the entire area	6.3 hours (380 minutes)
Pumping energy	DC/AC photovoltaic system with storage tank.

Table 3. *Mothly evapotranspiration ET0 according to Penman-Monteith.*

Month	**Min_Temp**	**Max_Temp**	**Humidity**	**Wind**	**Sun**	**Radiation**	**ET_0**
	℃	**℃**	**%**	**m/s**	**Hours**	**kWh/m ²/d**	**mm/d**
Jan	3.8	20.5	42	1.7	7.9	3.89	2.69
Feb	6.6	23.2	31	2.2	8.6	4.72	3.98
Mar	10.5	27.7	24	2.0	9.8	5.83	5.08
Apr	15.5	33.2	23	1.8	10.7	6.67	6.19
May	19.3	37.2	17	2.4	10.8	7.22	7.97
Jun	25.5	43.2	14	2.0	11.3	7.5	8.34
Jul	27.7	46.0	15	20.	11.4	7.5	8.78
Aug	26.6	44.3	15	1.7	10.8	6.94	7.74
Sept	23.8	40.5	19	1.8	9.8	6.11	6.96
Oct	17.1	33.2	27	1.6	8.7	5	5.04

Month	Min_Temp	Max_Temp	Humidity	Wind	Sun	Radiation	ET_0
	℃	℃	%	m/s	Hours	kWh/m^2/d	mm/d
Nov	10.5	25.5	34	1.5	8.2	3.89	3.50
Dec	5.5	15.5	42	1.8	7.8	3.61	2.43
Average	16.03	32.50	25.25	3.38	9.65	5.74	5.73

Table 4. Daily and monthly irrigation requirements for alfalfa.*

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Irr.Req (mm/d)	1.11	2.94	4.97	6.10	7.71	8.14	8.46	7.29	2.76	2.08	1.42	1.00
Irr.Req (mm/m)	34.4	82.2	154.0	183.1	238.9	244.1	262.4	226.1	82.8	62.8	42.7	31.0

(*The calculation for irrigation does not take rainfall into consideration)

Table 5 summarizes the estimated load losses in the pipes, the tank's height relative to the ground, and the total dynamic head (TDH). For an optimum hydraulic operation, the pressure to be supplied at the head of the network must be around 1.1 bar (11 m). This pressure can be ensured by a raised tank of at least 11 m. A cement storage tank is proposed to be elevated 11 meters above ground level (Figure 9). This height is required to ensure the proper functioning of the irrigation network. However, it should be noted that the cost of constructing such tanks is extremely high and increases with the height of the storage tank (Figure 10).

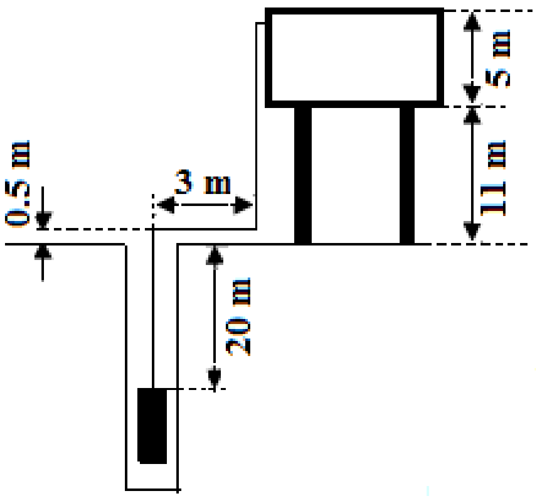

Figure 9. Schematic diagram of the water source and storage tank.

Table 5. Summary of the calculation of head losses.

Designation	Load losses (in mCE)
Load losses in the irrigation network (Calculated according to the Swamee model)	10.59
Load losses in the discharge pipe (Calculated according to the Swamee model)	0.9
Total Dynamic Height (TDH)	36.9

4. Photovolatic Water Pumping System Sizing

4.1. Design and Operational Considerations of the Pump Unit and Water Storage System

The pump unit consists of a three-phase asynchronous AC motor coupled to a multi-stage centrifugal pump designed according to the required flow rate and pumping height. The motor and pump are submerged to avoid heating and theft problems.

The power of the pump unit can be calculated using "Eq. (4)".

$$P_{mp} = \frac{Q \times TDH \times \rho \times g}{\eta_{mp}} = 11.59\ kW \quad (4)$$

With

$$Q[m^3/h] = 70;\ TDH = 36.9\ m;\ \rho = 997\ kg/m^3;$$
$$g = 9.81\ m^2/s;\ \eta_{mp} = 0.668$$

In this study, we opted for a locally manufactured cement tank for water storage in our study, despite its higher cost compared to a battery bank. This choice was based on several reasons. Firstly, the hot and arid climate of the site, with temperatures exceeding 6 months per year, makes electrochemical batteries unsuitable. Secondly, constructing a technical room to house the battery bank is mandatory, which is an additional cost. Thirdly, using batteries may reduce the availability of the pumping system as they need to be replaced at least 5 to 6 times during the life of the PVWPS due to the site's climate. Fourthly, the system's reliability could be compromised due to the availability of suitable batteries in the local market. Finally, there is an increased risk of theft as batteries are small and expensive. The water is distributed by gravity to the plot to be irrigated. Irrigation is carried out by a drip distribution network.

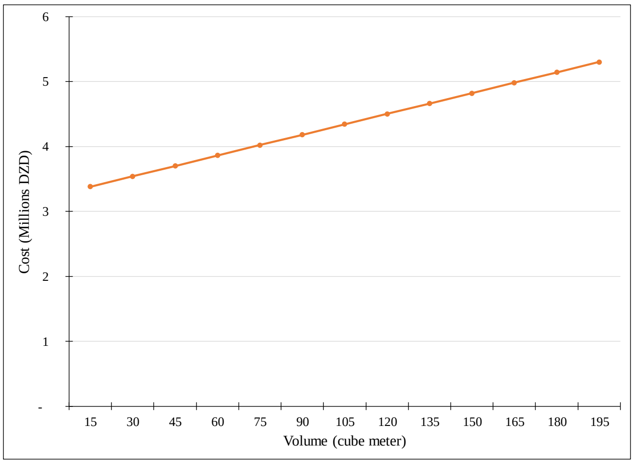

Figure 10. *Cost of water storage tank based on volume at 11 m above ground.*

4.2. Optimization Approach and Models Description

The optimization approach is derived from the study conducted by Bouzidi [42], where the design of the pumping system was based on two critical parameters: the array size (N_{PV}) and the tank's storage capacity, or storage coefficient (Ks).

We propose the Loss of Power Supply Probability (LPSP) method to determine the optimal system configuration. The LPSP method calculates the ratio between the deficit volume and the requested demand “Eq. (5)”. In situations where the crop's daily needs to exceed the daily volume produced by the system, there is a deficit, and the LPSP method helps us estimate it. This method is represented by the following equation [29, 42].

$$LPSP = \frac{\sum_{d=1}^{Tp} Q_{def}(d)}{\sum_{d=1}^{Tp} D_r(d)} \tag{5}$$

The following parameters are crucial in optimizing the performance of a photovoltaic water pumping system (PVWPS): *Tp, Qdef (d), Dr(d), and Ks*. *Tp* represents the analysis period in days, while *Qdef* (d) refers to the daily water deficit in cubic meters [m3], and *Dr(d)* is the daily water requirement [m3]. For this study, we have selected LPSP equal to 5%. Ks (dimensionless) is the storage coefficient, which is the ratio of the maximum volume that can be extracted from the storage tank (Cn) and the need for water (Dr). The formula for Ks is as follows [29, 42] “Eq. (6)”:

$$K_S = C_n / D_r \tag{6}$$

Thus, we determine the pairs (Npv; Ks) that satisfy a given reliability (LPSP).

While these two parameters are significant, two others must be considered as well. The tilt angle of the PV array plays a crucial role in the amount of irradiation captured by the PV panel. Therefore, the PV array will be equipped with a manual means to adjust its tilt angle monthly. Additionally, the Water Use Rate (WUR) is a significant factor in optimizing the system. During certain phases of crop growth, when water consumption is low, the pumped water may not be used efficiently. As a result, the WUR may be low, and the pumping system may not meet the farmer's objectives. The higher the WUR, the more viable the system. “Eq. (7)” defines the Water Use Rate (WUR).

$$WUR = \frac{Quantity\ of\ water\ consumed}{Quantity\ of\ water\ produced} \tag{7}$$

The flowchart of the procedure, shown in Figure 11, is based on detailed simulations of the PVWPS conducted over the course of a year, with hourly and daily time steps.

The proposed PVWPS is essentially composed of a photovoltaic array and an energy conditioner, including a DC/AC inverter and a submerged motor-pump. The DC/AC inverter's primary function is to convert the direct current (DC) produced by the PV array to alternating current (AC). The proposed DC/AC variable frequency inverter adjusts the pump speed based on the intensity of the exposure. This technique allows the pump to operate even at low irradiation (the first and last hours of the day). It continually optimizes its operation based on the available solar radiation and environmental conditions.

Tables 6 and 7 display the technical and electrical characteristics of the PV panel and the motor-pump, respectively.

5. Economic Study

Choosing an alternative energy source for remote areas depends on several factors, including cost, reliability, quality of service, and convenience of operation. To determine the feasibility and profitability of a photovoltaic installation, an economic analysis is necessary, which includes calculating the Net Present Value (NPV), Payback Period (PBP) of the investment, and the benefit-cost ratio (B/C). Investors must also consider the risks associated with the intermittency of solar power, regulatory uncertainties, and public acceptance.

The financial management of the project involves two types of expenses: capital expenses (CAPEX) and operating expenses (OPEX). Operating expenses include recurring costs such as maintenance and replacement costs. Life Cycle Cost Analysis (LCC), presented by several authors, is considered the most widely adopted method for assessing the cost of a desired system [18, 20, 29, 42]. The Life-Cycle Cost of the project is given by the "Eq. (8)".

$$LCC = CAPEX + OPEX - S \tag{8}$$

Where CAPEX is the capital cost and OPEX is the total discounted operational cost over the lifetime of the PVWPS and the salvage cost (S) which is the net value of the system in the last year of the lifecycle. This is a revenue in the cash flow analysis. OPEX is given by the "Eq. (9)".

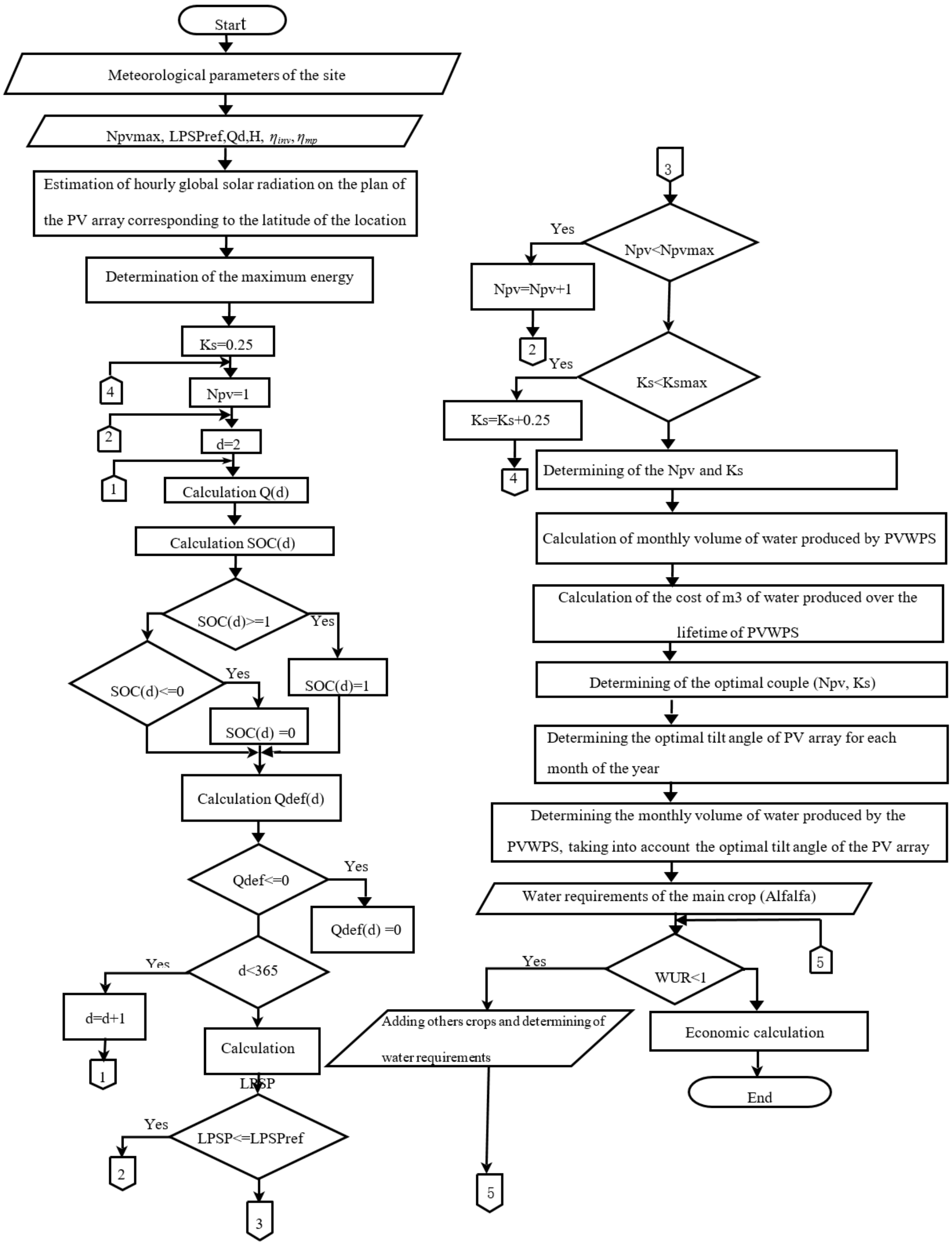

Figure 11. *Flowchart of the procedure.*

Table 6. Electrical characteristics of the photovoltaic panel (Condor 2024).

Designation	Unit	Value
Monocrystalline 60 cells	CEM265M-60	
Nominal power	Wc	265
Open circuit voltage (V_{oc})	V	38.26
short circuit current (I_{sc})	A	9.00
Voltage mpp (V_{mpp})	V	31.11
Current mpp (I_{mpp})	A	8.52
Max system voltage V_{dc}	V	1000
Normal Operating Cell Temperature (NOCT)	℃	45±2
Power temperature coefficient	%/℃	-0.41
Current temperature coefficient	%/℃	0.06
Voltage temperature coefficient	%/℃	-0.32

Table 7. Technical and electrical characteristics of the motor-pump (Grundfos).

Motor-pump model	SPE 77-3
Pump speed on which pump data are based	3000 rpm
Actual flow	70.32 m³/h
Actual pump duty point	39.81 m
Pumped liquid	Water
Density	998.2 kg/m³
Rated power - P2	12.5 kW
Power (P2) required by pump	12.5 kW
Mains frequency	50 Hz
Rated voltage	3 x 400 V
Rated current	29.2 A
Rated speed	1650-3000 rpm
Motor efficiency at full load	92.4%

$$OPEX = \sum_{j=1}^{n} \frac{yOPEX(j)}{(1+i)^j} \quad (9)$$

Where yOPEX(j) is the yearly operational cost for year j, i is the discount rate and n is the lifetime of the PVWPS.

In our case, the cost of capital is defined as follows:

$$CAPEX = CAPEX_{pv} + CAPEX_{mp} + CAPEX_{inv.} + CAPEX_{Ks} + CAPEX_f \quad (10)$$

Where $CAPEX_{pv}$ is the PV panels capital cost, $CAPEX_{mp}$ is the motor-pump capital cost, $CAPEX_{inv.}$ is the inverter capital cost, $CAPEX_{Ks}$ is the tank capital cost and $CAPEX_f$ is the fixed capital cost. $CAPEX_{pv}$, $CAPEX_{mp}$ and $CAPEX_{Ks}$ depend on the size of the equipments (PV array, power of the motor-pump, power of the inverter and the size of the storage tank).

One of the objectives of this study is to find the best combination between the size of the PV array (number of PV panels, Npv) and the size of the storage tank (Ks) to minimize costs. Then, we determine the capital cost of the PV panels $CAPEX_{pv}$ and the capital cost of the storage tank $CAPEX_{Ks}$

We collected data on the capital cost of PV panels from local manufacturers (Condor) and storage tanks for different PV panel watt peak and tank capacity, represented by the storage coefficient (Ks) in Figures 12 and 13.

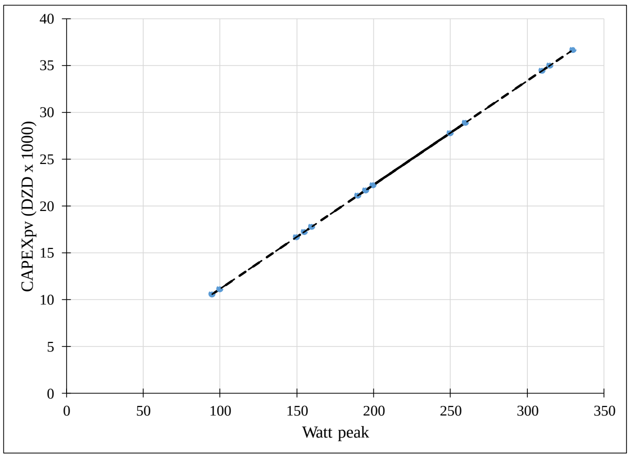

Figure 12. $CAPEX_{pv}$ as a function of the PV panels watt peak.

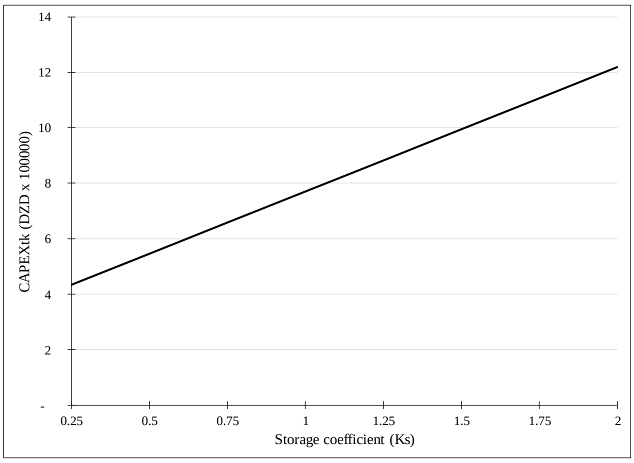

Figure 13. $CAPEX_{Ks}$ as a function of the storage coefficient (Ks).

We obtain the expression of $CAPEX_{pv}$ as a function of P_{pv}, from the collected data presented in Figure 12.

$$CAPEX_{pv} = 111.15 \times P_{pv} \quad (11)$$

We do the same for the data of Figure 13 for the storage tank;

$$CAPEX_{ks} = 10667 \times K_s + 3\,219\,970 \quad (12)$$

On the other hand, the yearly operational cost is composed of a yearly replacement cost $yOPEX_{rempl.}$ and yearly maintenance cost $yOPEX_{maint.}$;

$$yOPEX(j) = yOPEX_{rempl.}(j) + yOPEX_{maint.}(j) \quad (13)$$

The financial profitability of the investment can be measured using net present value (NPV). NPV is the sum of the discounted cash flows (CFj) generated by the project from start to finish. The investment project is financially profitable if the NPV is positive. NPV is calculated using the following equation:

$$NPV = -CAPEX + \sum_{j=1}^{n} \frac{CF_j}{(1+i)^j} \quad (14)$$

Where CAPEX represents the capital expenditure invested at the initial date t = 0, CFj represents the net free cash flow generated for period j, i represents the discount rate and n represents the life of the project (years).

6. Results and Discussion

The photovoltaic array is designed to receive maximum solar radiation and is oriented towards the south with a variable tilt angle configuration. A program has been developed to calculate the optimal tilt angle for each month of the year, resulting in maximum power production and a greater quantity of water pumped. A total of 12 tilt angles (one for each month) are used. The optimal tilt for each month of the year is shown in Table 8.

Table 8. *Monthly optimal angle of the photovoltaic array.*

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tilt (°)	50	45	35	15	0	0	0	10	25	45	55	55

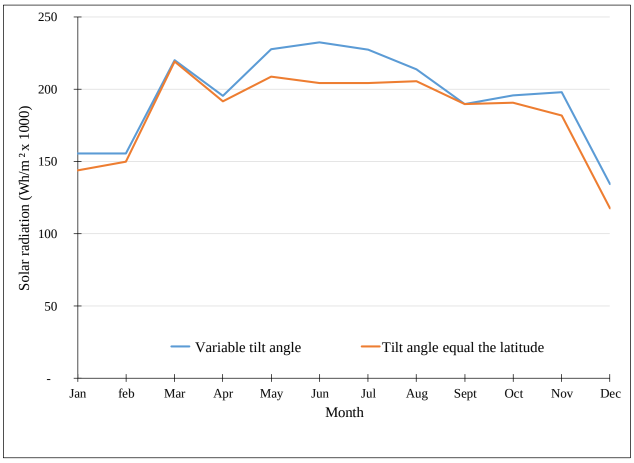

Figure 14. *Impact of the variation of the tilt angle on the monthly irradiation received on the array plane.*

Figure 14 shows the difference between the monthly irradiation received on the array plane when the tilt angle is fixed and equal to the latitude of the site, versus when the tilt angle is variable for each month of the year. We also observe the impact of changing the tilt angle on the monthly irradiation received on the array plane. There is a noticeable increase in the amount received in January and December, as well as between May and August. However, the variation in the tilt angle has no effect on the amount received in March and September.

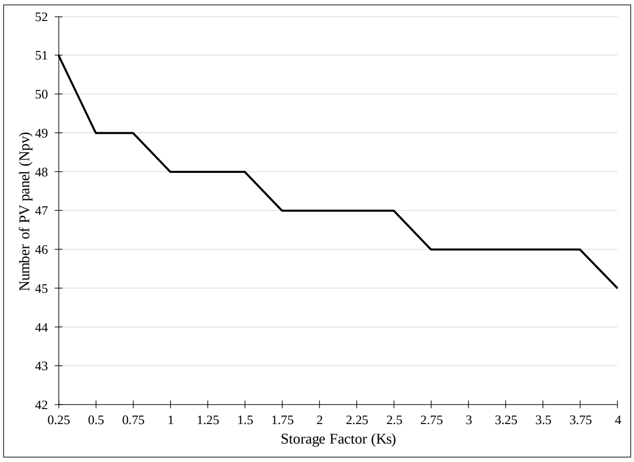

Figure 15. *Couples (Npv, Ks) leading to a LPSP = 5%.*

The proposed model is based on the Loss of Power Supply Probability concept, and we varied the number of PV panels (Npv) between 1 and 200 with a step of 1, and the storage factor (Ks) between 0.25 and 4 with a step of 0.25 to arrive at different couples (Npv, Ks). We opted for a load loss probability of 5%. The isofiability curve of the system is shown in

Figure 15, which presents all possible configurations of couples (Npv, Ks). Each point on this curve represents the number of PV panels and the storage coefficient (Npv, Ks). All the points on the same curve correspond to different configurations leading to the same reliability.

6.1. Determination of the Optimal Sizing of the Pumping System.

Determining the optimal sizing of a pumping system is crucial for its optimization and viability. The couple (Npv, Ks) plays an important role in this process. The changes in life cycle cost (LCC) and levelized cost of water (LCOW) are illustrated in Figure 16. As shown in Figure 16, LCOW varies depending on the couple (Npv, Ks). The LCOW is influenced by the size of the storage tank, increasing as the storage capacity increases.

Choosing the couple (Npv, Ks) = (51, 0.25) results in the LCC equal to 10,069,710 DZD and the LCOW equal to 3.33 DZD/m3. Therefore, the couple (Npv, Ks) = (51; 0.25) corresponds to the lowest LCC and LCOW for an LPSP equal to 5%.

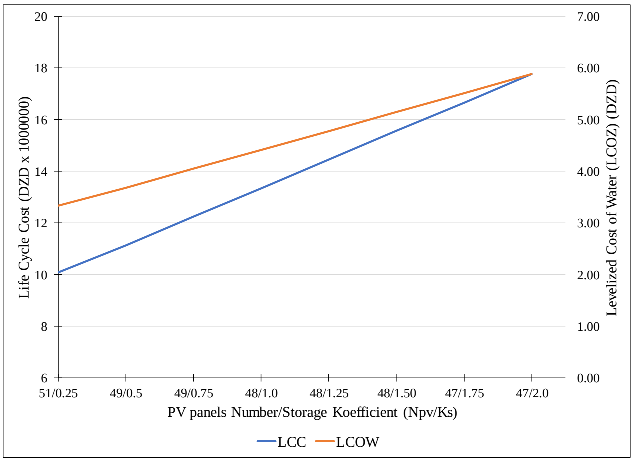

Figure 16. *Influence of the couple (Npv, Ks) on LCC and LCOW.*

6.2. The Water Balance of the Installation

The monthly water requirements of the alfalfa crop and the amount of water produced by the system with the optimal sizing parameters (Npv, Ks) = (51, 0.25) are shown in Figure 17.

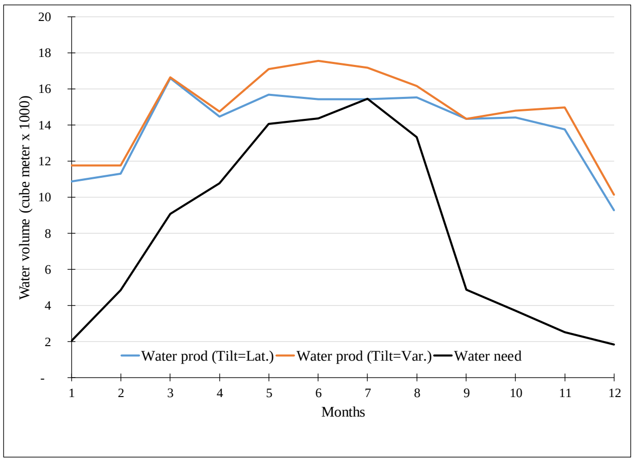

Figure 17. *Monthly harvest water requirements and water volumes produced by the PVWPS for fixed and variable tilt.*

We have observed that the monthly water requirements of the alfalfa can be met by the PV pumping system, with the PV array's tilt angle fixed to the latitude of the location. However, we have also noticed that the system produces an excess of water that needs to be managed. This surplus becomes particularly significant during the first and last quarters. The surplus was expected, especially during the early stages of plant growth when water needs were minimal.

To further optimize the system, a monthly variation in the tilt angle of the photovoltaic array will increase the monthly volume of water pumped by the system. Adding other crops will absorb this surplus and therefore improve the viability of the entire installation.

A water balance is presented in Table 9. We can see the monthly water volumes pumped by the system for the 2 variants (fixed and variable angle). It also shows the following points: The reference month is the month of July for the calculation of the sizing. The surplus water pumped is greater during the 1st and 4th quarters, coinciding with the plant's low need. Therefore, this implies a very low WUR during these 2 periods.

To make the installation more viable and optimized, certain crops must be added to reduce the excess water produced by the pumping system while benefiting from the variation in the angle of inclination of the PV array. The new monthly water requirements, when additional crops (potatoes, sweet melons, green beans, corn, and barley) are included, are shown in Table 10. Other crops can be added, taking into account the specificities of the region and the needs of the farmer, particularly during the first and fourth quarters. We can also notice a significant improvement in the WUR.

Table 9. *Water balance.*

Site location: Adrar - Algeria	**Irrigated type: Localized (drip)**					**Total height: 36,9 m**			**Irrigated area: 05 Ha**			
Maximum need: July	**Irrigation efficiency: 85%**						**Crop: Alfalfa**					
Parameters	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Number of days in the month	31	28	31	30	31	30	31	31	30	31	30	31
ET0 – mm/day	2.69	3.98	5.08	6.18	7.96	8.33	8.78	7.75	6.95	5.04	3.5	2.43
ETc - mm/month	34.4	82.2	154.1	183.1	238.7	244.1	262.4	226.2	82.8	62.8	42.7	31
Water requirements – mm/month	34.4	82.2	154.1	183.1	238.7	244.1	262.4	226.2	82.8	62.8	42.7	31
Water supply – mm/month	40.47	96.71	181.29	215.41	280.82	287.18	308.71	266.12	97.41	73.88	50.24	36.47
Total water supply m3/month (5 Ha)	2023.5	4835.3	9064.7	10770.6	14041.2	14358.8	15435.3	13305.9	4870.6	3694.1	2511.8	1823.5
Total water supply m3/day	65.3	172.7	292.4	359.0	452.9	478.6	497.9	429.2	162.4	119.2	83.7	58.8
Monthly solar radiation (Tilt=Lat.)(Wh/m^2)	143677	149628	219137	191616	208455	204253	204194	205456	189629	190559	181586	117496
Reference month (need/Ei)	0.014	0.032	0.041	0.056	0.067	0.070	0.076	0.065	0.026	0.019	0.014	0.016
Monthly solar radiation (Tilt=var.)(Wh/m^2)	155266	155311	219137	195227	227510	232253	227272	213682	189629	195620	197698	134116
Water pumped by PVWPS – m3/month (Tilt=Lat.)	10866	11304	16573	14454	15680	15430	15423	15520	14329	14401	13749	9272
Water pumped by PVWPS – m3/month (Tilt=Var.)	11749	11738	16573	14724	17077	17556	17173	16143	14333	14787	14975	10138
WUR (Tilt=Lat.)	18.6%	42.8%	54.7%	74.5%	89.6%	93.1%	100%	85.7%	34.0%	25.7%	18.3%	19.7%
WUR (Tilt=Var.)	17.2%	41.2%	54.5%	73.1%	82.2%	81.8%	89.9%	82.4%	34.0%	25.0%	16.8%	18.0%
Surplus pumped water – m3/month (Tilt=Lat.)	8842.7	6468.9	7507.9	3683.8	1638.5	1071.0	-12.8	2214.4	9458.6	10707.3	11237.2	7448.9
Surplus pumped water – m3/month (Tilt=Var.)	9725.0	6902.4	7507.9	3953.8	3036.1	3196.9	1738.1	2837.0	9462.4	11092.6	12463.1	8314.4

Table 10. *Quantity of water for certain crops that can be added and Water Use Rate (WUR)*.*

Crop	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Potato (m^3)	439	2235	2251	2023	622			1237	1963	1816	1120	173
Maize / Potato (m^3)	309	1088	1954	1696	152			1237	1963	1816	1120	173
Gr Beans/Barley (m^3)	463	1063	1651						887	1726	1230	496
Gr Beans/SMelon (m^3)	463	1063	1651						1051	1281	1117	680
Alfalfa (m^3)	2024	4835	9065	10771	14041	14359	15435	13306	4871	3694	2512	1824
Needs (Alfalfa + others crops (m^3)	3698	9113	16177	14490	14815	14359	15435	15780	10735	10333	7099	3346
Water Prod. (Tilt=Var.)	11749	11738	16632	14724	17077	17556	17173	16143	14333	14787	14975	10138

Crop	1	2	3	4	5	6	7	8	9	10	11	12
WUR (Alfalfa alone) (%)	17	41	55	73	82	82	90	82	34	25	17	18
WUR (Alfalfa + others crops) (%)	31	78	97	98	87	82	90	98	75	70	47	33

*The water needs of different crops are taken from the CROPWAT software.

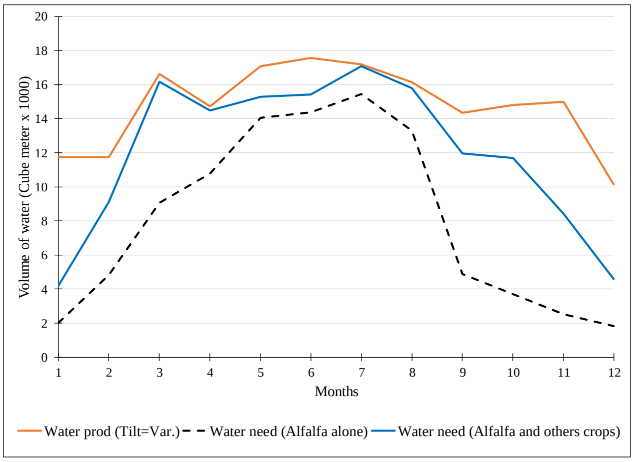

Figure 18*. Reduction of surplus water production.*

We conducted a study on the viability of a PVWPS in the Adrar region, taking into account the harsh environmental conditions there. The study recommended the cultivation of other crops such as potatoes, green beans, sweet melon, maize, and barley to increase the efficient use of pumped water.

After adding these crops, a clear improvement in WUR was achieved. We can notice in Figure 18, that the water surplus has been reduced.

After adding these crops to the main crop (alfalfa) the average rate of use of the water produced reached 73.83% compared to 51.33% for a mono crop (alfalfa). Thanks to this addition of agricultural products, properly distributed, it has made it possible to increase water needs and therefore reduce this excess water. We also note that this procedure has made it possible to significantly improve WUR.

Table 11*. PV water pumping system costs for irrigation – CAPEX.*

Material	Qty	Rate	Total amount (DZD)*
$CAPEX_{pv}$	13 515	111.15 DA/Wp	1 502 192
$CAPEX_{inv.}$ (RSI 18,5 kW/38 A)	1	625 650	625 650
$CAPEX_{mp}$	1	1 392 750	1 392 750
$CAPEX_{Ks}$	1	5 460 040	4 340 005
Subtotal 1			7 860 597
Breakdown of $CAPEX_f$			
PV panels structure			100 000
Wire			15 000
Pipe and accessories			45 000
Fondation			40 000
Transport (workers and material)			100 000
Installation charge (10% of the main equipments)			368 059
Subtotal 2			668 059
CAPEX			8 528 656

The viability study of the PVWPS system was carried out on the assumptions and cost details presented in Tables 10, 11, and 12. Taking into account the very hostile environment of the Adrar region (sand wind, temperatures very high and significant temperature gradient), the system components must be of better quality. The photovoltaic panels are manufactured in Algeria, while the other subsystems, the inverter and submersible pump, are imported. Given its capacity and its elevation above the ground, the storage tank constitutes an important element of CAPEX. Data relating to fixed capital expenditures (CAPEXf) are shown in Table 11. This information was provided by local traders and consulting firms. Table 13 displays the crop areas allocated to each crop variety. All equipment replaced during the life of the pumping system, along with the discount rate, are listed in Table 14 [29, 42].

In order to obtain a more accurate economic estimate, we took into account the prices of potatoes, sweet melons, and green beans in relation to each other. We only focused on the sales of these three crops, while the harvests of alfalfa, barley, and maize were reserved for the farmer's animals. The selling prices of the crops were based on the local market. It is important to note that our economic analysis did not include the impact of alfalfa, barley, and maize consumption on the farm's animals.

Table 12. *Cash flow analysis for PVWPS.*

	Qty/Cost
Maximum power from PV array (Wp)	13 515
Operating days per year (days)	360
Average operating hours per year (hours)	2160
Water requirement per day (m^3/day)	420
CAPEX (DZD)	8 528 656
$yOPEX_{maint.}$ (DZD) (1% of main components)	35 206
Selling price of potato (DZD/kg)	25
Selling price of green beans (DZD/kg)	100
Selling price of sweet melon (DZD/kg)	60
Potato yield per hectare (t/ha)	25
Green beans yield per hectare (t/ha)	4
Sweet melon yield (t/ha)	15
Estimated Alfalfa production cost (DZD/ha)	115 000
Estimated potato production cost (DZD/ha)	170 000
Estmated Green beans production cost (DZD/ha)	200 000
Estimated Sweet melon production cost (DZD/ha)	45 000
Estimated maize production cost (DZD/ha)	114 000
Estimated barley production cost (DZD/ha)	75 000

Table 13. *Area occupied by crops.*

	Alfalfa	Potatoes	Gr Beans	Sw Melon	Barley	Maize
Area (ha)	5	3	2	1	1	1

Table 14. *Economic analysis parameters.*

Designation	Value
Discount rate (%)	10
Lifetime of PV panels (years)	20
Lifetime of motor-pump (years)	10
Lifetime of inverter (years)	05

Two approaches were considered in the economic analysis. The first approach involves planting crops intended for animal consumption (alfalfa, barley, and corn). The second approach involves combining other crops intended for sale (potatoes, green beans, and sweet melons).

6.3. Planting Alfalfa, Barley and Corn Only (Self-consumption)

Planting only alfalfa, barley, and maize for self-consumption has a strongly negative net present value of NPV = -16,111,472 DZD, and the PBP is significantly greater than the life of the project. Furthermore, the WUR is very low, making the project non-viable if the impact on animal feed isn't taken into consideration.

6.4. Association of Other Crops Intended for Sale

To make the irrigation system more viable and optimized, other crops such as potatoes, sweet melon, and green beans will be combined with the previous ones. Varying the selling prices of different crops will have a significant impact on the NPV, PBP, and benefit-cost ratio.

Variation in the selling price of potatoes from 10.00 DZD/kg to 25.00 DZD/kg and green beans from 50.00 DZD/kg to 100.00 DZD/kg with a fixed price of sweet melon at 60.00 DZD/kg would result in positive NPV for potato prices at 25.00 DZD/kg and the price of green beans greater than or equal to 50 DZD/kg. The prices of potatoes at 20 DZD/kg and green beans greater than or equal to 60 DZD/kg would also result in a positive NPV, as shown in Figure 19. The PBP varies from 3.69 years to 2.87 years, as shown in Figure 20. For these two cases, the B/C is greater than 1, as shown in Figure 21. In other cases, the project is not viable.

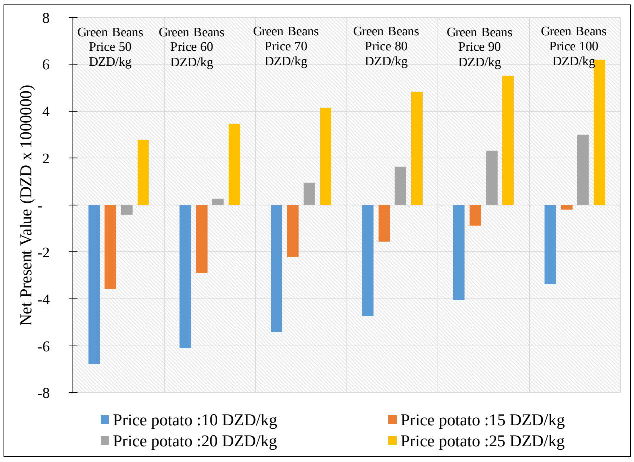

Figure 19. *Variation of NPV based on variation in selling price of potatoes and green beans.*

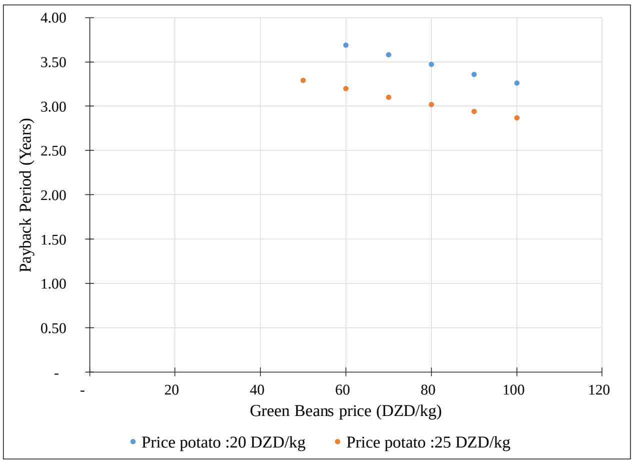

***Figure 20**. Variation of PBP based on variation in selling price of potatoes and green beans.*

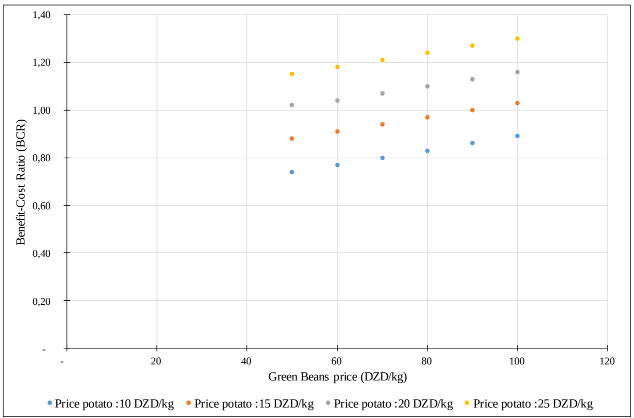

***Figure 21**. Variation of B/C based on variation in selling price of potatoes and green beans.*

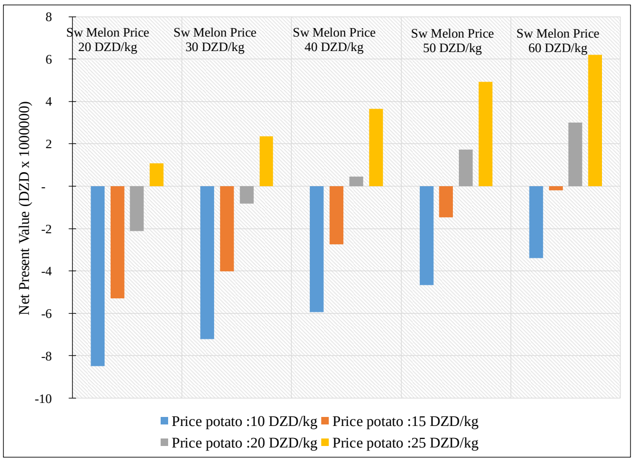

***Figure 22**. Variation of NPV based on variation in selling price of potatoes and sweet melon.*

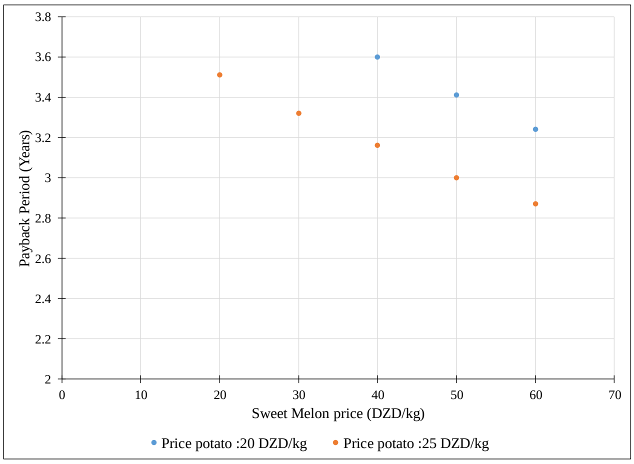

***Figure 23**. Variation of PBP based on variation in selling price of potatoes and sweet melon.*

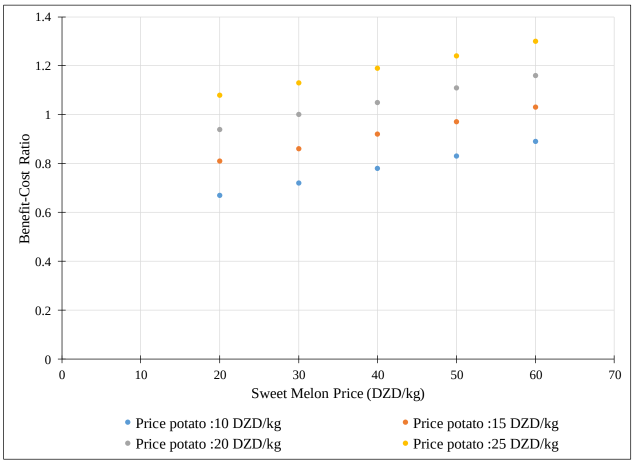

***Figure 24**. Variation of B/C based on variation in selling price of potatoes and sweet melon.*

Variation in the selling price of potatoes from 10.00 DZD/kg to 25.00 DZD/kg and sweet melons from 20.00 DZD/kg to 60.00 DZD/kg with a fixed price of green beans at 100.00 DZD/kg would result in positive NPV for potato prices at 25.00 DZD/kg and the sweet melon price greater than or equal to 20.00 DZD/kg. The prices of potatoes at 20.00 DZD/kg and sweet melons greater than or equal to 40.00 DZD/kg would also result in a positive NPV, as shown in Figure 22. The PBP varies from 3.6 years to 2.87 years, as shown in Figure 23. For these two cases, B/C is greater than 1, as shown in Figure 24. In other cases, the project is not viable.

6.5. Sensitivity Analysis

Economic analyses in agricultural systems often rely on several key assumptions, including the discount rate, which can significantly influence the results. As the discount rate reflects the time value of money, its variation can substantially affect long-term investments' net present value (NPV). Since the variability in crop prices has been discussed earlier, this section focuses on assessing the sensitivity of the results to changes in the discount rate, which is also subject to fluctuations due to economic and market uncertainties.

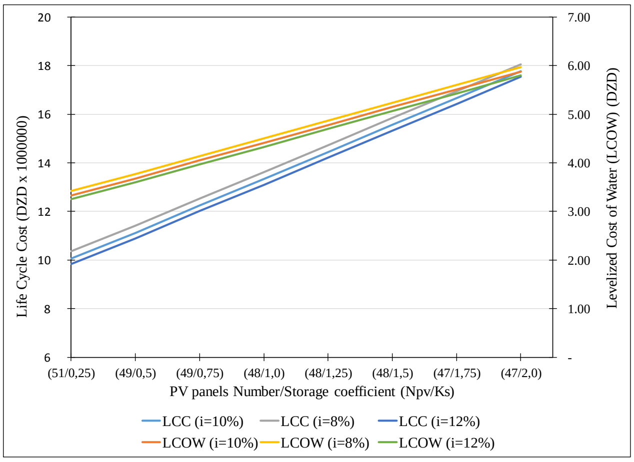

Figure 25. *Influence of the discount rate on LCC and LCOW.*

In this study, sensitivity analysis examines how different discount rates impact the economic outcomes of the proposed system. By altering the discount rate within a range of plausible values, the study evaluates the robustness of the results (Figure 25). It highlights the potential risks associated with varying economic conditions, such as changes in interest rates or inflation.

As shown in Figure 25, the effect of the discount rate on both the Life Cycle Cost (LCC) and the Levelized Cost of Water (LCOW) is evident. At a discount rate of 8%, the LCC is 10,357,151 DZD, and the LCOW is 3.42 DZD. In contrast, when the discount rate increases to 12%, the LCC decreases to 9,835,701 DZD, and the LCOW also declines to 3.25 DZD.

6.6. Comparative Analysis of Key Findings and Observations in the Study

This subsection summarises the main distinctions between the primary conclusions and secondary observations derived from the study. Table 15 highlights the differences in key aspects, including optimal tilt angle, system configuration, water usage efficiency, crop diversification, economic viability, and environmental adaptation. By organizing these points, the table offers a clear comparison that helps to understand better the critical factors influencing the overall performance and sustainability of the system under study.

Table 15. *Comparative analysis of key findings and seconcary observation.*

Aspect	Key Findings	Secondary Observations
Optimal Tilt Angle	Monthly tilt angle optimization increases the annual irradiation received, especially in January, December, and May-August.	No significant difference in received irradiation in March and September due to equal solar zenith angles.
System Configuration	The optimal configuration is (Npv = 51, Ks = 0.25), yielding the lowest LCC (10,069,710 DZD) and LCOW (3.33 DZD/m^3) for LPSP = 5%.	Variations in storage size increase LCOW; balance needed between storage and PV array size for cost-effectiveness.
Water Usage Ratio (WUR)	Adding crops increases WUR from 51.33% (alfalfa only) to 73.83% (diverse crops).	Excess water is most pronounced in the first and fourth quarters, requiring better management strategies.
Crop Diversification	Including potatoes, green beans, and sweet melons improves NPV, PBP, and B/C ratio under favorable price conditions.	Crop combinations should consider local market demands and environmental conditions for optimization.
Economic Viability	Selling potatoes at $\geq$ 20 DZD/kg, green beans at $\geq$ 50 DZD/kg, and sweet melons at $\geq$ 40 DZD/kg ensures positive NPV.	Planting only for self-consumption leads to negative NPV (-16,111,472 DZD) and unviable project economics.
Environmental Adaptation	System remains viable under harsh Adrar conditions with quality components and tilt angle adjustment.	Local production of PV panels reduces CAPEX; imported components increase overall costs.

6.7. Comparison with Similar Studies in Arid Regions

The results of this study contribute to the growing body of research on photovoltaic water pumping systems (PVWPS) in arid regions. In similar studies, key factors such as the optimization of tilt angles, crop diversification, and economic viability have been examined. However, our findings offer unique insights and applications specifically tailored to the conditions of the Adrar region.

1) Optimization of Tilt Angle: Previous studies have shown that optimizing the tilt angle significantly increases annual irradiation and water flow in arid regions [43-45]. This study supports that conclusion, particularly noting increased irradiation during critical months like January and December. However, our research also identifies periods in which variations in tilt angle have negligible effects (e.g., March and September), a detail that has not been widely discussed in other literature.
2) Water Usage Efficiency: Several authors have reported improvements in the water use rate (WUR) through optimized irrigation schedules and system configurations [29, 46, 47]. Our findings expand on this by demonstrating that crop diversification can increase the WUR from 51.33% to 73.83%. This significant improvement emphasizes the viability of incorporating additional crops that can take advantage of the seasonal surplus of water produced.
3) Economic Viability: In their economic analyses, several authors have emphasized the importance of local crop prices in evaluating the feasibility of PVWPS [29, 42, 48]. This study reinforces these insights, showing that incorporating high-value crops like potatoes, green beans, and sweet melons can lead to a positive net present value (NPV) and shorter payback periods, given favorable market conditions. Unlike other studies, our research specifically quantifies the economic trade-offs for various crop price ranges, providing actionable insights for farmers in the region.
4) Adaptation to Harsh Conditions: Few studies have focused on the technical resilience of photovoltaic water pumping systems (PVWPS) components in environments characterized by high temperatures, sandstorms, and significant temperature fluctuations. This research highlights the importance of using high-quality components and local manufacturing—such as photovoltaic panels produced in Algeria—to minimize costs and ensure the system's reliability in such challenging conditions.
5) Key Contributions: Unlike previous studies, this research uniquely combines technical, environmental, and economic considerations to develop a comprehensive approach for optimizing PVWPS in arid regions. It provides practical recommendations for managing tilt angles, diversifying crops, and ensuring economic viability, all tailored to local conditions. By addressing both water surpluses and economic challenges, this research offers a replicable model for other arid regions facing similar environmental and socio-economic constraints.

7. Conclusions

The production of sufficient quantities and quality of fodder is essential to meet the population's demand for milk and meat. However, traditional livestock farming in Algeria, which relies on natural rangelands and meadows, is facing significant challenges due to recurring droughts and increasing human activities. These factors have led to a substantial deficit in livestock feed, which is a major constraint on the growth of livestock breeding in Algeria. To address this issue, this study proposes an economically and technically feasible solution that involves providing farmers with an optimized photovoltaic water pumping system for irrigating crops such as alfalfa, barley, and corn, as well as for watering animals. To enhance the project's profitability, farmers can also grow and sell commercial crops like potatoes, green beans, and sweet melons. A technical and economic study has been conducted to demonstrate the feasibility and viability of the project. The study indicates that the proposed pumping system can increase water production by 6% by varying the angle of inclination of the photovoltaic (PV) generator monthly. By combining the cultivation of commercial crops with fodder, water use efficiency can be improved, reaching 26.40%. The selected sizes for the PV system and storage tanks result in the lowest life cycle costs (LCC) of 10,069,710 DZD and the lowest life cycle water costs (LCOW) at 3.33 DZD/m^3. The economic analysis shows the project is profitable and viable under certain conditions. Positive net present values (NPVs) are observed when potato prices are at 25.00 DZD/kg, and the price of green beans is at least 50.00 DZD/kg. In another scenario, with potato prices at 20.00 DZD/kg, the price of green beans must also be at least 60 DZD/kg. The price of sweet melon is set at 60.00 DZD/kg. The payback period (PBP) ranges from 3.69 years to 2.87 years. In both cases, the benefit-cost (B/C) ratio is greater than 1, indicating economic viability. Conversely, in other situations, the project is not viable. Additionally, positive NPVs are obtained when potato prices are at 25.00 DZD/kg and sweet melon prices are at least 20.00 DZD/kg, or when potato prices are at 20.00 DZD and sweet melon prices are at least 40.00 DZD/kg, with green bean prices at 100.00 DZD/kg. The PBP in these scenarios varies from 3.6 years to 2.87 years, with B/C ratios greater than 1, confirming the project's economic feasibility. In other instances, the project remains unviable. This project can yield significant economic benefits for Algeria by potentially enhancing the milk and meat sectors, increasing access to drinking water in rural areas, boosting national agricultural production, and mitigating desertification. Therefore, it is crucial for the Algerian government to promote the profitability of such initiatives, which could create employment opportunities for thousands of unemployed youths. To further enhance the economic viability of the proposed system, it is important to explore financing mechanisms and potential subsidies. Access to favorable financing options can significantly reduce initial investment costs, thereby improving the overall economic feasibility of the system. Options such as low-interest loans, government-backed programs, or public-private partnerships could alleviate the financial burden on stakeholders. Additionally, subsidies or incentives for renewable energy projects and sustainable agricultural practices can make the system more attractive. Government subsidies, tax breaks, or direct financial support for equipment and technology could lower operating costs, making the system more affordable and viable, especially for small farmers or businesses. Such mechanisms are vital for facilitating the widespread adoption of sustainable agricultural practices and supporting the transition to renewable energy systems in rural areas. The implementation of the proposed photovoltaic water pumping system has substantial potential to improve agricultural productivity and water management in Algeria. However, to fully validate the findings and optimize the system under real-world conditions, further research and pilot projects are necessary. These projects should focus on testing the system's performance across different climatic zones and agricultural environments, taking into account variables such as soil types, crop varieties, and seasonal variations. Additionally, conducting field trials with actual farmers would provide valuable insights into practical challenges, including system maintenance, water management practices, and the economic impact on smallholder producers. Such research is essential for refining system design, optimizing crop selection, and assessing long-term economic and environmental sustainability, which will enable broader implementation in similar arid regions, particularly within the Sahel countries.

Abbreviations

PVWPS	Photovoltaic Water Pumping System
DZD	Currency Unit of Algeria
NPV	Net Present Value
PBP	PayBack Period
B/C	Benefit-Cost ratio
UAA	Useful Agricultural Area
TAA	Total Agricultural Area
FU	Fodder units
Ha	Hectare
CO2	Carbon Dioxide
PV	Photovoltaic
€/Wp	Euro/Watt peak
kWh/m^{2}d	Kilowatt Hour/Square Meter/Day
GHG	Greenhouse Gas
LPSP	Loss of Power Supply Probability.
DC	Direct Current
AC	Alternating Current
MPPT	Maximum Power Point Tracker
OLPC	Openable Low Pressure Compensating
ET0	Reference Evapotranspiration
CI	Continental Intercalary
SASS	Northern Sahara Aquifer System
TC	Terminal Complex
ET_c	Crop Evapotranspiration
K_c	Crop Coefficient
FAO	Food and Agriculture Organization of the United Nations
Rn	Global Radiation
G	Ground Heat Flux
T	Average Daily air Temperature at 2 m Height
U_2	Wind Speed at 2 m Height
Es	Saturation vapor Pressure
e_0	Vapor Pressure at Temperature T
Δ	Slope of the Saturation Vapor Pressure Curve
γ	Psychometric Constant
CWR	Crop water Requirements
E_i	Irrigation efficiency
TDH	Total Dynamic Head
Q	Pump Flow Rate
ρ	Density of Liquid Water
g	Standard Gravity
η_{mp}	Motor Pump Efficiency
N_{PV}	Array Size
Ks	Storage Coefficient
Tp	Analysis period in Days
$Qdef$ (d)	Daily Water Deficit
$Dr(d)$	Daily Water Requirement
WUR	Water Use Rate
CAPEX	Capital Expenses
OPEX	Operating Expenses
LCC	Life Cycle Cost
S	Salvage Cost
yOPEX(j)	Yearly Operational Cost for Year j
i	Discount Rate
n	Lifetime of the PVWPS
$CAPEX_{pv}$	PV panels Capital Cost
$CAPEX_{mp}$	Motor-pump Capital Cost
$CAPEX_{inv}$	Inverter Capital Cost
$CAPEX_{Ks}$	Tank Capital Cost
$CAPEX_f$	Fixed Capital Cost
$yOPEX_{rempl.}$	Yearly Replacement Cost
$yOPEX_{maint.}$	Yearly Maintenance Cost
CF	Cash Flows
LCOW	Levelized Cost of Water

Author Contributions

Belkacem Bouzidi is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Fields

Belkacem Bouzidi: Photovoltaic solar energy, stand-alone solar energy system, photovoltaic solar energy pumping system