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ENERGY TRANSITION IN ACTION: THE IMPACT OF SOLAR SYSTEMS IN MOROCCAN PROCESSING UNITS

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A B S T R A C T

This study assesses the feasibility of integrating photovoltaic (PV) systems into agricultural processing units in Drâa-Tafilalet, a region with high solar potential. Faced with rising energy costs, PV systems offer a sustainable alternative for units like Difat Ziz and Zrigat, specialized in date storage and packaging. The study evaluates energy consumption, PV system sizing, and a 15-year economic analysis. Simulations reveal that PV systems can cover up to 75% of energy needs. For Difat Ziz, a 65-kWc system achieves 51% self-consumption, with a 6.89-year payback (5.4 years with energy compensation). For Zrigat, a 9-kWc system covers 78% of needs, with a 5.7-year payback (4.3 years with compensation). Economic performance relies on self-consumption optimization, equipment quality, and installation cost control. The findings highlight PV integration as a cost-effective, sustainable solution, with recommendations for training, subsidies, and supportive policies.

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1. INTRODUCTION

1.1 General Context

The constant rise in energy costs, combined with global climate challenges, is driving many sectors, including agriculture, to seek sustainable and cost-effective solutions (Benedek et al., 2023). The agricultural sector, particularly product processing units, relies heavily on conventional energy for the storage, processing, and cooling of agricultural products. In regions like Drâa-Tafilalet in Morocco, where solar exposure is abundant, the integration of photovoltaic (PV) systems presents a promising opportunity to reduce operational costs while promoting environmental sustainability, especially in regions like Drâa-Tafilalet in Morocco, which receive some of the highest levels of solar irradiation in the world (Natarajan et al., 2023; World Bank Group, 2023).
Climate change and the depletion of fossil resources have accelerated the adoption of renewable energy, with solar energy emerging as a key pillar of the energy transition (Chawla et al., 2024). In arid regions like Errachidia, where energy costs are high and agricultural processing needs are significant, the combination of intense sunlight and limited economic resources provides an ideal setting for the integration of PV systems in agri-food processing units (Yan et al., 2023). This study stands out for its focus on one of Morocco's high solar potential regions, which remains underexploited. Based on real-world data, it offers a detailed analysis of the economic and energy performance of solar systems in small and medium-capacity processing units, providing a model applicable to other arid regions in Morocco.

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1.2 Research Problem

Agricultural units like Difat Ziz and Zrigat, facing high-energy costs, require sustainable solutions adapted to their strong solar potential. The main challenge is to determine the optimal size of a photovoltaic system that meets their energy needs, reduces costs, and maximizes economic benefits.

1.3 Study Objectives

This study aims to evaluate the techno-economic feasibility of integrating photovoltaic systems into agricultural units in the Drâa-Tafilalet region, focusing on the cases of Difat Ziz and Zrigat. Its specific objectives are to:

1. Optimize the size of photovoltaic installations to maximize self-consumption, reduce energy losses injected into the grid, and minimize energy costs.
2. Quantify economic gains, particularly the reduction of electricity bills and the payback period.

2. MATERIALS AND METHODS

This section outlines the methodology used to assess the techno-economic feasibility of integrating photovoltaic (PV) systems into agricultural processing units in the Drâa-Tafilalet region. The study relies on real energy consumption data and analytical simulations, taking into account local climatic and economic conditions. The study was conducted on two units specializing in the storage and packaging of dates, namely Difat Ziz and Zrigat, located in the Drâa-Tafilalet region. This area benefits from high annual solar exposure, making it an ideal setting for PV system integration. The data collection process relied on two primary sources:

Energy Consumption:
Electricity bills from 2018, 2019, and 2020 for the two units were analyzed to obtain detailed information on monthly consumption and energy costs. An estimated hourly load profile was established using the averages provided by the National Office of Electricity and Drinking Water (ONEE).

Solar Irradiation:
Solar exposure data were extracted from Morocco's Solar Resource Atlas (Masen Solar Atlas, n.d.) and corroborated with the Global Solar Atlas (World Bank Group, 2023), providing detailed monthly and annual irradiation information in kWh/m² for the Drâa-Tafilalet region.

The sizing of the PV system was carried out manually, following several key steps:

- Various peak power scenarios were simulated to determine the optimal configuration of the PV system for each unit. The analysis focused on three key criteria: the self-consumption rate, excess energy injected into the grid, and the total system cost over a 15-year period (Sayed et al., 2023).
- A detailed simulation was conducted to validate the theoretical results:
  - Photovoltaic production hourly profiles were superimposed on the load curves for each unit.
  - The simulated data confirmed actual self-consumption and quantified the losses related to energy injection into the grid or additional energy purchases.
- The economic assessment considered installation and maintenance costs, electricity bill savings, and the payback period (PBP). The installation cost was estimated at 11,000 MAD/kWc, with maintenance costs approximated at 1% of the installation cost per year (IRENA, 2024; NREL, n.d.; IRENA, 2023; Benali & Kousksou, 2022).
- The payback period was calculated using different scenarios, including with and without remuneration for the excess energy injected into the grid.
  The formula used to calculate the payback period is:

Payback Period = Installation Cost / Annual Savings (1)

- Annual savings were calculated by multiplying annual self-consumption by the electricity tariff. The total installation cost was obtained by multiplying the installed peak power by 11,000 MAD/kWp. Thus:
- Total savings over 15 years = 15 × Self-consumption × Electricity tariff (2)
- Total cost over 15 years = Installation cost + (15 × Annual maintenance cost) (3)

This formula is essential for assessing the economic viability of the PV system. It represents the number of years required for the savings generated from self-consumption and, potentially, remuneration for energy injected into the grid, to cover the initial installation cost.

3. STUDY RESULTS

This section presents the potential energy production of photovoltaic (PV) systems and the associated economic benefits. The results are structured around several key aspects: current energy consumption of the two units, estimation of solar production, sizing scenarios, and an economic profitability analysis under different assumptions.

3.1 Data from the Two Sites

The Table 1 below summarizes the activities, capacities, electricity consumption, associated costs, as well as location and photovoltaic production data for each site.

Table 1. Data from both sites, source: Regional Office for Agricultural Development of Tafilalet (ORMVAT)

Data from Sites	**GIE DIFAT ZIZ Unit**	**ZRIGAT Unit**
Activity	Date storage and conditioning	Date storage and conditioning
Capacity	400 tons	300 tons
Annual Electricity Consumption	142,041 kWh	11,242 kWh
Total Electricity Consumption Cost	203,221 MAD	19,997 MAD
Location (x, y)	x: 603493.21 y: 93867.02	x: 613655.18 y: 116417.23
PVOUT (Photovoltaic Production)	1,877 kWh	1,873 kWh

3.2 Energy Consumption Analysis

a. Energy Consumption Data: GIE DIFAT ZIZ Unit

Located in Errachidia, the Difat Ziz unit focuses on the valorization of local products, particularly dates, and heavily depends on electricity for its industrial processes. The average annual energy consumption of the Difat Ziz unit over the years 2018, 2019, and 2020 is 142,041 kWh, with a total cost of 203,221.20 MAD, and an average unit price of 1.43 MAD/kWh. The consumption peak occurs in July (16,720 kWh), primarily due to increased cooling and processing needs during the date season. On average, nearly 78% of total consumption occurs during sunny normal hours, which will be covered by solar energy, as illustrated in Figure 1.

The detailed breakdown of the average monthly energy consumption and electricity costs over the period 2018–2020 is presented in Table 2.

Table 2. Average monthly energy consumption (kWh) and electricity bills (MAD including tax) during 2018, 2019, and 2020. Source: (ONEE)

Month	**Energy (kWh/month)**	**%**	**Peak Hours**	**Normal Hours**	**Off-Peak Hours**	**Cost (MAD)**	**Unit Price (MAD)**
January	1,860	11%	426	1,434	-	4,054.80	2.18
February	6,889	41%	1,517	5,372	-	14,811.35	2.15
March	9,770	58%	2,295	7,475	-	20,517.00	2.10
April	11,050	66%	2,559	8,491	-	12,265.50	1.11
May	9,130	55%	2,235	6,895	-	11,595.10	1.27
June	11,800	71%	2,705	9,095	-	13,334.00	1.13
July	16,720	100%	3,710	13,010	-	18,224.80	1.09
August	14,949	90%	3,191	11,758	-	17,340.84	1.16
September	16,610	99%	3,484	13,126	-	16,942.20	1.02
October	16,225	97%	3,395	12,830	-	18,658.75	1.15
November	12,295	74%	2,650	9,645	-	24,958.85	2.03
December	14,743	88%	3,215	11,528	-	30,518.01	2.07
Total	142,041		31,382	110,659	-	203,221.20	1.43

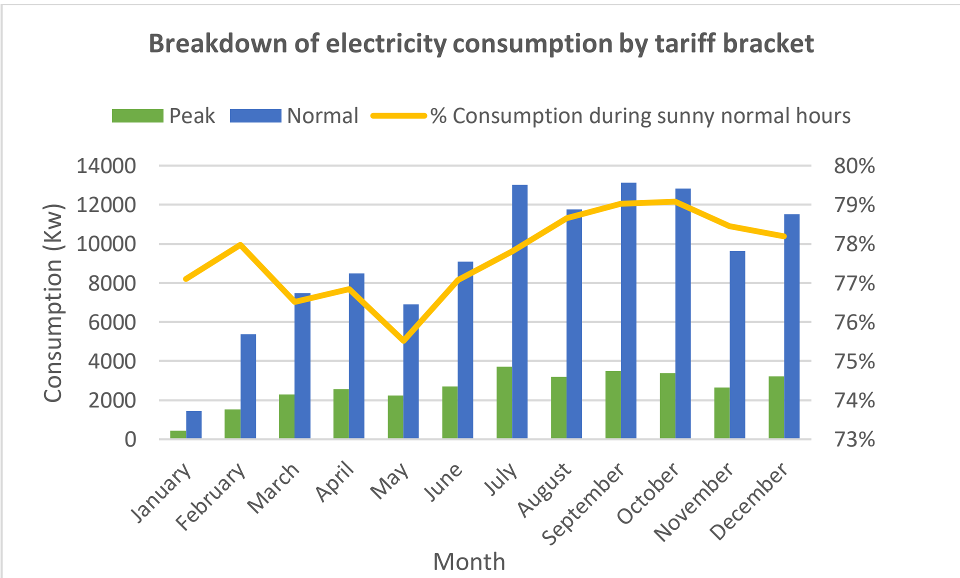

Figure 1. Distribution of electricity consumption by tariff band and percentage of consumption during normal sunny hours

b. Energy Consumption Data: Zrigat Unit

The Zrigat unit, located in the Drâa-Tafilalet region, consumes a significant amount of energy for its operations involving the storage and processing of dates. The energy consumption data, derived from the ONEE electricity bills for the years 2018, 2019, and 2020, are presented in Table 3.

Table 3. Average monthly electricity consumption (kWh/month) and monthly electricity bills (DH TTC/month) for the years 2018, 2019, and 2020. Source: ONEE.

Month	Energy (kWh/month)	% of Max	Peak (kWh)	Normal (kWh)	Off-Peak (kWh)	Cost (DH)	Rate (DH/kWh)
January	720	41%	177	543	-	1520	2.11
February	830	47%	199	631	-	1470	1.77
March	753	42%	184	569	-	1425	1.89
April	1587	89%	401	1186	-	2746	1.73
May	1132	63%	291	841	-	2043	1.80
June	1163	66%	287	876	-	1992	1.71
July	915	52%	234	681	-	1596	1.74
August	135	8%	39	96	-	351	2.60
September	467	26%	115	352	-	832	1.78
October	1774	100%	456	1318	-	3034	1.71
November	1123	63%	293	830	-	1936	1.72
December	643	36%	191	452	-	1052	1.64
Total	**11,242**		**2,867**	**8,375**	**-**	**19,997**	**1.78**

The table highlights the energy consumption of the Zrigat unit, which is significantly lower compared to Difat Ziz. The total consumption amounts to an average of 11,242 kWh over the years 2018, 2019, and 2020, with a total cost of 19,997 DH TTC, corresponding to an average unit price of 1.78 DH/kWh.

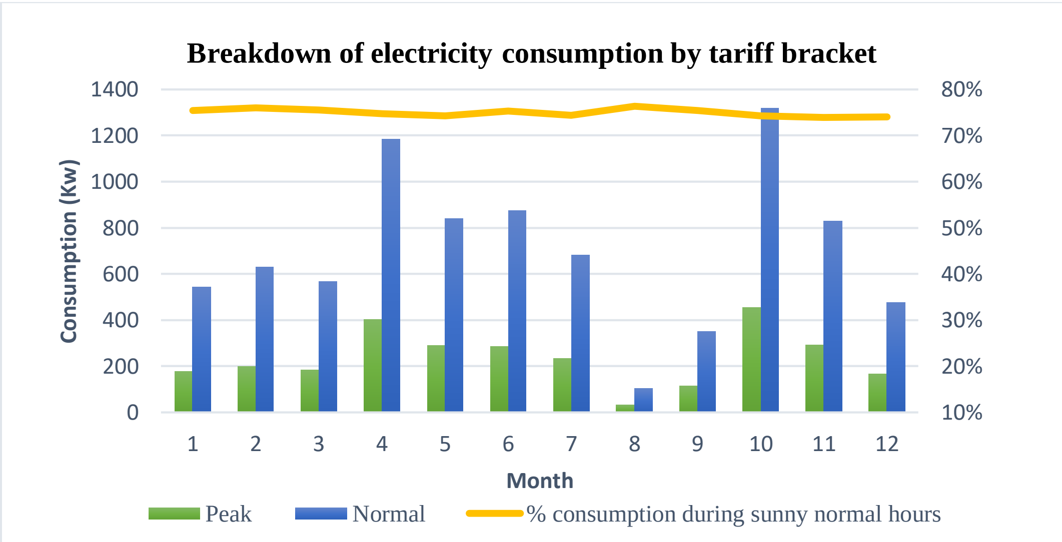

Figure 2. Distribution of electricity consumption by tariff band and percentage of consumption during normal sunny hours

The Figure 2 illustrates that 75% of Zrigat's energy consumption occurs during normal sunny hours, similar to Difat Ziz. This highlights an energy distribution that could be effectively supported by a photovoltaic system.

3.3. Analysis of the Load Curve

The load curve demonstrates the hourly variation in power demand based on the energy needs of a unit. It depicts how electricity consumption evolves throughout the day, month by month, enabling adjustments for appropriately sizing the photovoltaic system (Meunier et al., 2015). The following steps were undertaken to establish this curve:

- Analysis of electricity bills for various tariff periods (peak, normal, and off-peak hours):
    - Peak hours (10 AM - 6 PM): High consumption due to outdoor heat and handling activities.
    - Normal hours (6 AM - 10 AM, 6 PM - 12 AM): Moderate consumption before and after peak heat hours.
    - Off-peak hours (12 AM - 6 AM): Low consumption at night due to cooler temperatures.

- Estimation of average power for each tariff period:

The average power was calculated as:

- $P_{avg} = \frac{E(kWh)}{T(hours)}$ (4)

  E: Total energy consumption in kWh.
  T: Duration in hours

Development of the load curve: Using these average power estimates, hourly load curves were plotted for key months such as January, May, and October, representing periods of low, moderate, and high consumption, respectively are presented in Figure 3 and Figure 4.

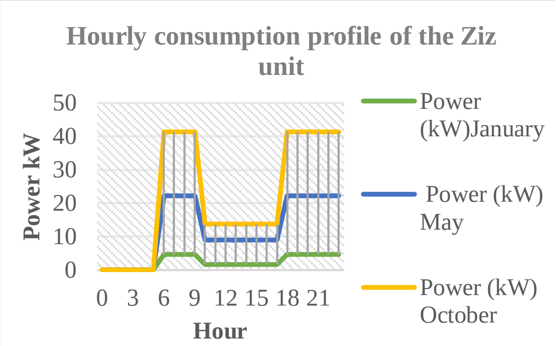

Figure 3. Hourly Consumption Profile Peak consumption of 40 kW in October, 25 kW in May, and 5 kW in January

To fully meet energy demands, a photovoltaic system with a peak capacity of at least 40 kW is required.

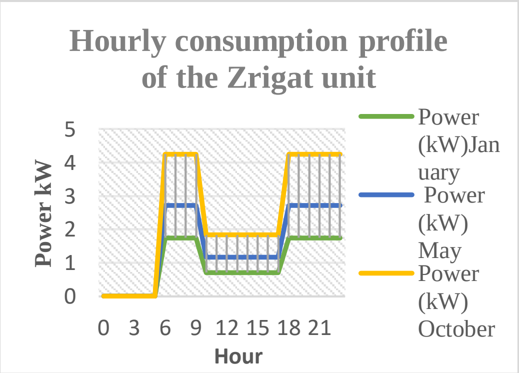

Figure 4. Hourly Consumption Profile Peak energy demand reaches 4.4 kW in October

A photovoltaic system with a minimum peak capacity of 4.4 kWc would suffice to cover the energy needs entirely.

3.4. Dynamic Analysis and Optimization of Peak Power

To ensure optimal performance of the photovoltaic system, an on-grid system was proposed (Mishra et al., 2023), comprising 330 Wc photovoltaic panels, inverters, and protective devices. The technical characteristics of the selected photovoltaic modules are summarized in Table 4.

Table 4. Technical Specifications of Selected Photovoltaic Panels

Characteristic	Value
Nominal Power	330 Wc
Efficiency	17.5%
Dimensions (mm)	1956 x 992 x 40
Weight (kg)	22
Performance Warranty	25 years

After analyzing the load curve and estimating the minimum power required for each unit, the next step involves varying the installed peak capacity and calculating the total cost over a 15-year period to determine the optimal capacity. This corresponds to the power level that minimizes costs while meeting energy demands (Zheng & Zhang, 2023; Astier, 2021).

To determine the optimal peak power for an on-grid photovoltaic system, several factors will be combined, including:

1. Technical characteristics of the equipment (330 Wp PV modules, inverters, etc.).
2. Energy consumption profile (78% of consumption occurs during sunny hours for the DIFAT ZIZ unit and 75% for the ZRIGAT unit).
3. Load curve of the two units.
4. Installation cost: 11,000, and approximate maintenance cost: 1% of the installation cost per year.
5. Savings on the electricity bill.
6. PVOUT for both units' sites: 1,877 kWh for DIFAT ZIZ and 1,873 kWh for ZRIGAT.
7. Performance Ratio (PR): 77%.
8. Analysis period: 15 years.

Additionally, the following equations will be used in our calculations:

Annual effective production (kWh/year)
The annual effective production is calculated for each unit, taking into account the installed peak power, average solar potential (PVOUT), and performance ratio (PR), which includes system efficiency losses. The formula used is:

$P_{effective} = P_{crete} \times PV\ OUT \times PR$ (5)

- $P_{effective}$: Annual Effective Production (kWh/year)
- P_{peak} : Installed peak power (kWp)
- $PV\ OUT$: Average photovoltaic production (kWh/kWp/year)
- PR : Performance ratio (77%)

- Self-consumption (kWh/year)
  To calculate energy self-consumption, a percentage based on the consumption

profiles of the two units is applied: Self-consumption = Effective Production × Self-consumption Percentage
  - For DIFAT ZIZ: Self-consumption = Effective Production × 0.78
  - For ZRIGAT: Self-consumption = Effective Production × 0.75
- Injected energy (kWh/year)
  Injected energy is the difference between the effective production and self-consumption:
  Injected Energy = Effective Production − Self-consumption

Example: DIFAT ZIZ Unit
The objective is to test various peak power values (ranging from 40 kWp to 80 kWp) to identify the one that minimizes overall costs over 15 years, maximizes savings, and meets energy demand.

Table 5. Data for various peak power options

Peak Power (kWp)	Effective Production (kWh/year)	Energy Injected (kWh/year)	Self-consumption (kWh/year)	Additional Purchase (kWh/year)	Installation Cost (DH)	Total Cost over 15 Years (DH)	Total Savings over 15 Years (DH)
40.00	57811.6	12718.55	45093.05	96947.95	440000	506000	967245.88
45.00	64449	14178.78	50270.22	91770.78	495000	569250	1078296.22
50.00	71610	15754.20	55855.80	86185.20	550000	632500	1198106.91
55.00	78771	17329.62	61441.38	80599.62	605000	695750	1317917.60
60.00	85932	18905.04	67026.96	75014.04	660000	759000	1437728.29
65.00	93093	20480.46	72612.54	69428.46	715000	822250	1557538.98
70.00	100254	22055.88	78198.12	63842.88	770000	885500	1677349.67
75.00	107415	23631.30	83783.70	58257.30	825000	948750	1797160.37
80.00	114576	25206.72	89369.28	52671.72	880000	1012000	1916971.06

After analyzing the Table 5 data for various peak power options, it is crucial to select a solution that balances production, self-consumption, savings, and installation costs. The results indicate that a peak power of 65 kWc represents the best compromise, providing a satisfactory self-consumption rate of 51% of the unit's energy needs, 15-year savings of 1557538,98 MAD, and a reasonable installation cost of 715,000 MAD.

In conclusion, opting for a 65 kWc peak power capacity allows for the optimization of both energy efficiency and investment profitability.

b- Zrigat Unit

Table 6. Data for various peak power options

Peak Power (kWp)	Effective Production (kWh/year)	Self-consumption (kWh/year)	Energy Injected (kWh/year)	Additional Purchase (kWh/year)	Installation Cost (DH)	Total Cost over 15 Years (DH)	Total Savings over 15 Years (DH)
3.00	4,326.63	3,244.97	1,081.66	7,997.03	33,000	82,500	86,640.77
4.00	5,768.84	4,326.63	1,442.21	6,915.37	44,000	110,000	115,521.02
5.00	7,211.05	5,408.29	1,802.76	5,833.71	55,000	137,500	144,401.28
6.00	8,653.26	6,489.95	2,163.32	4,752.06	66,000	165,000	173,281.53
7.00	10,095.47	7,571.60	2,523.87	3,670.40	77,000	192,500	202,161.79
8.00	11,537.68	8,653.26	2,884.42	2,588.74	88,000	220,000	231,042.04
9.00	12,979.89	9,734.92	3,244.97	1,507.08	99,000	247,500	259,922.30
10.00	14,422.10	10,816.58	3,605.53	425.42	110,000	275,000	288,802.55
11.00	15,864.31	11,898.23	3,966.08	0.00	121,000	302,500	317,682.81

The primary objective of this analysis is to maximize self-consumption while minimizing the energy injected into the grid.

The comparative results for the different peak power configurations are presented in Table 6.

As shown in Table 6, a peak power capacity of 9 kWp emerges as the optimal solution, as it meets almost all the energy needs of the unit with only 1,507.08 kWh/year of additional energy required from external sources. The installation cost amounts to 99,000 MAD, while the total cost over a 15-year period reaches 247,500 MAD, generating annual savings of 17,328.15 MAD. Increasing the peak power to 10 kWp or 11 kWp leads to higher installation and total costs over 15 years, without offering significant benefits in terms of energy coverage, as the 9 kWp system already meets nearly all energy needs. Therefore, selecting a 9 kWp capacity constitutes the most optimal choice, allowing for minimal investment while maximizing energy coverage.

3.5. Simulation Validation Results

The results of this study were validated using simulations conducted with the PVsyst software, a widely recognized tool for designing and analyzing the performance of photovoltaic systems. These simulations allowed for the estimation of effective annual production, self-consumption, excess energy injection, and optimal peak power capacities for the two units under study: DIFAT ZIZ and ZRIGAT.

To ensure the accuracy and reliability of the results, several key parameters were taken into account during the simulations:

1. Operating Temperature of the Modules

The performance of PV modules declines as their temperature increases. For the simulations, an average ambient temperature of 25°C and a surface temperature of 45°C during the summer were considered. These values align with the climatic conditions of Drâa-Tafilalet, based on data from the Global Solar Atlas (Astier**,** 2021).

- A temperature coefficient of -0.4%/°C for the modules was applied, consistent with the standard specifications provided by photovoltaic panel manufacturers (PVsyst, 2022).

2. System Losses
   - Inverter conversion losses (5%): These losses are standard for inverters with an average efficiency of 95%, as reported by IRENA (2023).
   - Partial shading losses (2%): These losses were estimated based on the specific configurations of the sites and are consistent with similar studies on installations in arid regions (Yan et al., 2023).
   - Cabling and connection losses (2%): These values were derived from technical guidelines for photovoltaic systems (Astier, 2021).
3. Average Solar Irradiation (GHI)
   - Solar irradiation data was sourced from the Global Solar Atlas, indicating an average annual production of 1,877 kWh/kWp/year for modules tilted at 30° and oriented due south, under local conditions in the Drâa-Tafilalet region.
4. PV System Configuration
   - The system was designed with a peak power of 65 kWp for DIFAT ZIZ and 9 kWp for ZRIGAT, using 330 Wp panels with an optimal tilt angle of 30°.

The simulations conducted with PVsyst validated the results obtained through manual calculations and refined several critical system parameters. The key observations are as follows:

1. Simulated Annual Production
   - Difat Ziz (65 kWp): Estimated production of 93,500 kWh/year, closely matching the manual estimate of 93,093 kWh/year.
2. Zrigat (9 kWp): Estimated production of 9,050 kWh/year, in close agreement with the manual estimate of 8,720 kWh/year. Self-Consumption Rate
   - Difat Ziz: The simulation confirmed a self-consumption rate of 51%, validating the manual calculation methodology.
   - Zrigat: The self-consumption rate was almost identical to the manual estimate (79% versus 78% in the manual calculation).
3. Energy Injection into the Grid
   - The simulations indicated that the excess energy injected into the grid for Difat Ziz and Zrigat aligned with manual estimates (20,000 kWh and 2,358 kWh, respectively).
4. Peak Power Optimization
   - The simulations confirmed that a peak power capacity of 65 kWp for Difat Ziz and 9 kWp for ZRIGAT is optimal for maximizing self-consumption while reducing energy surpluses.

In summary, the PVsyst simulations, supplemented by realistic performance parameters, validated the study's results with high precision. This approach ensures a reliable representation of the system's performance, providing accurate projections for the economic profitability and energy coverage of the agricultural units.

3.6. Profitability Analysis of the PV System

A comprehensive analysis was carried out to assess profitability under two scenarios — with and without remuneration for excess energy injected into the grid — for the DIFAT ZIZ (65 kWp) and ZRIGAT (9 kWp) units. The remuneration for injected energy would allow surplus energy to be sold at the electricity purchase tariff, thereby improving profitability.

For DIFAT ZIZ:

- Without Remuneration: The system achieves a self-consumption rate of 51%, with significant energy surplus injected into the grid. This configuration offers energy cost savings but leaves potential revenue untapped.
- With Remuneration: The system's profitability increases significantly when the energy injected into the grid is remunerated. This scenario allows the unit to generate revenue from the 20,480 kWh/year of surplus energy, further reducing the total cost of energy.

For ZRIGAT:

- Without Remuneration: With a high self-consumption rate of 78%, most of the energy produced is consumed on-site. The remaining 2,358 kWh/year is injected into the grid, but no revenue is generated from it.
- With Remuneration: By monetizing the excess energy at the market rate, the system achieves additional profitability. The return on investment (ROI) period is reduced as revenue is generated from the surplus energy injected into the grid.

The comparison between the two scenarios highlights the importance of favorable remuneration policies for excess energy. Such policies significantly enhance the economic appeal of photovoltaic systems, promoting their adoption in agricultural units and supporting Morocco's transition to clean energy (Fraunhofer ISE, 2023; El Khattabi & Kousksou, 2021.

The detailed technical parameters for both units under the two scenarios are summarized in Table 7, while the corresponding financial indicators are presented in Table 8.

Table 7. Technical Elements

Unit	Difat Ziz (65 kWc)	Difat Ziz with Remuneration	Zrigat (9 kWc)	Zrigat with Remuneration
Total consumption (kWh/year)	142,041	142,041	11,242	11,242
PV production (kWh/year)	93,093	93,093	12,979.89	12,979.89
Injection (kWh/year)	20,480.46	20,480.46	3,244.97	3,244.97
Self-consumption (kWh/year)	72,612.54	72,612.54	9,734.92	9,734.92
Additional purchase (kWh/year)	69,428.46	69,428.00	1,507.08	1,507.08
Self-consumption rate (%)	51%	51%	78%	78%

Table 8. Financial Elements

Unit	Difat Ziz (65 kWc)	Difat Ziz with Remuneration	Zrigat (9 kWc)	Zrigat with Remuneration
Installation cost (MAD)	715,000	715,000	99,000	99,000
Annual bill without PV (MAD)	203,221.20	203,221	19,997	19,997
Annual bill with PV (MAD)	99,385.07	70,098.01	2,668.85	0
Annual savings (MAD)	103,835.93	133,123	17,328.16	23,104.20
Bill reduction (%)	51%	65%	78%	100%
Payback period (years)	6.89	5.4	5.7	4.3

As shown in Table 7, the remuneration scenario does not affect the technical performance of the systems but significantly improves the financial indicators reported in Table 8.

- Difat Ziz: With a remuneration rate of 1.43 MAD/kWh for the 20,480.46 kWh injected, the additional savings amount to 29,287 MAD per year. This reduces the annual electricity bill to 70,098.01 MAD and increases total annual savings to 133,123 MAD. As a result, the return on investment (ROI) period shortens to 5.4 years.
- Zrigat: With a remuneration rate of 1.78 MAD/kWh for the 3,244.97 kWh injected, the additional savings amount to 5,776 MAD annually. This reduces the total electricity bill to zero, increasing annual savings to 23,104.2 MAD and shortening the ROI period to 4.3 years.

Therefore, the remuneration of injected energy significantly enhances the profitability of projects for both units, reducing the ROI period for both systems.

4. DISCUSSION

The results of this study confirm that integrating photovoltaic (PV) systems into agricultural units like DIFAT ZIZ and ZRIGAT is technically feasible and economically advantageous, especially in arid regions like Drâa-Tafilalet. With an annual PVOUT of 1,877 kWh/kWp/year, the region's favorable climatic conditions ensure reliable energy production. However, the profitability of these systems is significantly influenced by self-consumption, surplus energy injection, and installation costs.

For DIFAT ZIZ**,** self-consumption reaches 51% of the effective production, but around 22% of the energy produced is injected into the grid. This scenario underscores the importance of synchronizing energy-intensive activities with solar production to maximize local energy use. Incorporating intelligent load management devices or battery storage could reduce dependence on the grid for additional purchased energy while minimizing energy injection losses.

In the case of ZRIGAT, where the self-consumption rate is higher (78%), the unit's reliance on external energy sources is already significantly reduced. The possibility of remunerating this injection at 1.78 MAD/kWh further enhances its economic profitability. However, this also highlights the need for stable policies to ensure consistent returns on investment.

These results align with international research, which demonstrates that PV systems in arid regions can significantly reduce energy costs in agriculture (Nikiema, 2023). A recent review confirms the crucial role of this integration for food security and the development of allied sectors (Naman & Kaundal, 2025). For instance, a study by Yan et al. (2023) revealed that optimized PV systems in similar environments could cover up to 80% of energy needs while reducing CO_2 emissions. This environmental dimension could be explored further to maximize the overall impact of solar projects, especially within the framework of energy transition strategies, as emphasized by IRENA's 2023 report.

The findings of this study also open avenues for expanding these systems to other Moroccan regions with similar characteristics, such as Souss-Massa or the Oriental. These regions, benefiting from high solar irradiation, could leverage PV solutions for agricultural applications like irrigation and crop storage. The development of detailed regional solar atlases, combined with specific feasibility studies, could support the large-scale adoption of these technologies.

Technological advances in PV system performance optimization also represent a key area of focus. Recent innovations in photovoltaic panels, particularly bifacial and high-efficiency modules, could significantly increase the performance ratio (PR), enabling maximum energy production without increasing installed peak capacity. According to the Fraunhofer Institute report (2023), improvements in panel efficiency could substantially boost effective annual production for the same capacity, resulting in additional cost savings.

Finally, this study highlights the potential for photovoltaic systems to transform agricultural units into autonomous and resilient energy players. The adoption of these technologies, supported by stable public policies, could make a significant contribution to the energy transition in Morocco and beyond.

5. CONCLUSION AND RECOMMENDATIONS

This study successfully dimensioned and optimized photovoltaic systems for the DIFAT ZIZ and ZRIGAT units, both located in the arid Drâa-Tafilalet region. The findings demonstrate that the integration of these systems is both technically feasible and economically viable. For DIFAT ZIZ, an optimal peak power of 65 kWp offers a balance between self-consumption (covering 51% of energy needs) and investment costs. For ZRIGAT, a peak power of 9 kWp maximizes self-consumption (covering nearly 78% of energy needs) while minimizing costs.

Recommendations:

1. Enhancing Self-Consumption
   - Load Optimization: Synchronize energy-intensive activities with photovoltaic production to reduce injection and maximize self-consumption.
   - Intelligent Energy Management: Use devices that adjust energy loads according to solar production.
2. Exploring Storage Solutions
   - Battery Integration: Assess the feasibility of battery integration to store excess energy, particularly for ZRIGAT, to reduce dependence on the grid during off-peak hours.
   - Hybrid Systems: Evaluate the costs and benefits of a hybrid system combining battery storage and surplus energy sales to the grid.
3. Valorization of Energy Injection
   - Energy Buyback Mechanisms: Collaborate with local authorities and electricity operators to improve energy buyback mechanisms, thereby increasing revenues from surplus energy.
4. Monitoring and Evaluation
   - Performance Tracking: Implement a system to monitor the actual performance of the PV systems, compare it with initial estimates, and adjust energy management strategies accordingly.
5. Reinforcement of Policy Support
   - Subsidies and Incentives: Promote subsidies and incentives to lower initial installation costs, which remain a significant barrier to widespread adoption of PV systems.
6. Technological and Agricultural Integration
   - Solar-Powered Applications: Use photovoltaic systems for specific applications related to agricultural product conservation (e.g., cold storage) and irrigation. International experiences in arid zones could serve as useful benchmarks.

In conclusion, the adoption of well-designed photovoltaic systems in arid regions like Drâa-Tafilalet can significantly reduce energy costs while reinforcing energy resilience. The adoption of these systems, supported by strong public policies, could make a significant contribution to Morocco's energy transition and beyond.

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