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Assessment of the Socio-Economic and Environmental Impacts of Solar-Powered Pump Irrigation Systems in Bulacan: Basis for a Solar Irrigation Development Program

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Abstract — The agricultural sector in Bulacan, Philippines, faces mounting economic pressures from climate change vulnerability and volatile fossil fuel pricing, prompting a strategic transition toward Solar-Powered Irrigation Systems (SPIS). However, a comprehensive, empirically validated evaluation of the socio-economic and environmental impacts of these systems, along with the operational bottlenecks faced by water users, remains largely unquantified. This study quantitatively and qualitatively assessed the performance of SPIS across three communal projects (Kapatiran IA, BusPan IA, and AnBusPa IA) in Bulacan, Philippines. Utilizing a convergent parallel mixed-methods design, data were collected from thirty (N=30) smallholders—split equally between SPIS users (n=15) and traditional diesel pump users (n=15)—and three (N=3) key institutional stakeholders. Results from Welch's independent samples t-test demonstrate that SPIS delivers transformative economic benefits. SPIS users experienced a 93.9% reduction in seasonal irrigation costs (₱1,166.67/ha vs. ₱19,086.67/ha; $p < 0.001$, $d = 9.15$) and a 106.6% increase in seasonal net income (₱69,492.67/ha vs. ₱33,640.60/ha; $p < 0.001$, $d = 3.50$). Notably, SPIS users achieved 18.1% higher rice yields (5,353.33 kg/ha vs. 4,533.33 kg/ha; $p < 0.001$, $d = 1.56$), contrary to initial assumptions, attributed to extended pumping hours (80.3% more total pumping hours; $p < 0.001$). Perception indexes revealed high farmer satisfaction with SPIS (overall rating: 4.60/5) and strong recognition of environmental benefits (mean = 4.55/5 vs. 2.08/5 for diesel), including zero emissions and absence of oil spills. However, a critical vulnerability was identified: technical support availability was rated significantly lower for SPIS (2.47/5) compared to diesel (4.67/5), reflecting a pronounced technical first-responder deficit rooted in centralized repair paradigms. Additionally, only 86.7% of SPIS operators received formal training, and no communal sinking funds exist for capital replacement. Thematic analysis of stakeholder interviews identified six core themes: technical first-responder deficit, communal sinking fund deficits, dry-season discharge limits, localized training gaps, perceived financial benefits, and institutional support needs. Based on these empirical findings, the Bulacan Solar Irrigation Development Program (BSIDP) is proposed—a 24-month strategic framework comprising three pillars: (1) decentralized local maintenance teams, (2) community-led sinking fund financial models, and (3) climate-resilient hybrid solar-diesel system configurations. This evidence-based framework is essential to foster resilient, sustainable, and scalable communal irrigation practices in the region, supporting the Philippines' commitments under the Renewable Energy Act (RA 9513) and national food security goals.

Indexed Terms— Sustainable Livelihoods Framework, Technology Acceptance Model, Solar-Powered Irrigation Systems (SPIS), independent samples t-test, policy framework, Bulacan, Philippines

I. THE PROBLEM AND ITS BACKGROUND

This chapter clearly articulates the problem or question the research aims to address and its theoretical foundation. It also presents the research problem, hypothesis, scope and delimitation, significance of the study, and definitions of terms.

Rationale

The Philippine agricultural sector serves as a vital foundation for national food security and the

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economy, yet it currently faces significant threats from escalating operational expenses and the intensifying effects of climate change. In Bulacan, a prominent agricultural hub, farmers are burdened by the dual weight of expensive diesel-fueled irrigation and unreliable water access during extended droughts. While the National Irrigation Administration (NIA) has introduced Solar-Powered Pump Irrigation Systems (SPIS) through landmark projects such as Kapatiran IA, BusPan IA, and AnBusPa IA, critical service gaps persist, particularly for upland and tail-end areas where water delivery remains inconsistent.

However, a distinct research gap remains: the lack of systematic, multi-site comparative performance data. While existing literature confirms the technical viability of SPIS in small-scale settings, no comprehensive study documents the socio-economic and environmental transition of farmers using field data from multiple NIA-implemented projects in Bulacan. There is a pressing need for empirical data to create a scalable provincial expansion model. This study addresses these needs by providing a validated framework for scaling SPIS in underserved regions, transitioning from isolated project proposals to a scholarly analysis of sustainable agricultural infrastructure.

Literature Review (RRLS)

This review synthesizes existing literature and empirical data on the challenges of traditional irrigation and the potential of Solar-Powered Irrigation Systems (SPIS), organized thematically.

Theme 1: The Economic Burden of Conventional Irrigation Methods

A significant body of evidence highlights the crippling financial cost of irrigation for smallholder farmers. In the Philippine context, Delos Reyes and Gomez (2024) found that irrigation energy costs can consume 25-40% of total production costs for rice farmers, severely limiting profitability. This is corroborated by data from the National Irrigation Administration (NIA) in Bulacan, which reports that farmers spend between ₱15,000 and ₱20,000 per hectare per cropping season on diesel or electric pumps (NIA, 2023). The financial strain is exacerbated by volatile fuel prices and rising electricity costs, with Meralco power rates increasing by 28% since 2020. NIA (2023) notes that 38% of small farmers in Bulacan have outstanding loans specifically for irrigation expenses, creating a cycle of financial precarity.

Theme 2: Environmental Impacts and Climate Vulnerabilities

Growing Solar Mist (2023) quantifies that a single diesel pump emits approximately 3.2 tons of CO_2 annually. Furthermore, fuel spills contaminate an estimated 15% of water sources in farming barangays in Bulacan (NIA, 2023). Inefficient water pumping has also led to resource depletion, with groundwater levels dropping by 2.4 meters since 2015. Concurrently, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA, 2023) reports a 30% decrease in dry-season rainfall over the past decade, with the 2023 drought alone affecting 8,500 hectares of rice fields in Bulacan. The Department of Agriculture (DA) Region III (2023) reports crop failure in two out of every five cropping seasons.

Theme 3: Infrastructural Gaps and Institutional Frameworks

NIA Region III (2023) reports that only 38% of Bulacan's irrigable land is currently served by NIA systems, leaving 62,500 hectares without reliable access. Grid electricity reaches only 68% of farm areas, with frequent daily outages of 4-8 hours (NIA, 2023). In response, NIA has established successful SPIS models like the Kapatiran (60 kWp), BusPan (150 kWp), and AnBusPa (500 kWp) systems according to the NIA – Bulacan Irrigation Management Office (NIA-Bulacan IMO, 2021; 2023). However, barriers to scaling remain, primarily high capital costs (₱26-50M per system) and an 18-month average approval process (NIA, 2023).

Theme 4: Solar-Powered Irrigation as a Sustainable Alternative

The International Energy Agency (IEA, 2023) notes that solar PV emits 40-48 gCO2e/kWh, compared to 820 for coal. Project data from existing NIA systems in Bulacan shows that SPIS can reduce irrigation energy costs by 40-60% (NIA-Bulacan IMO, 2023).

SPIS also enhances energy security by decoupling irrigation from the unreliable grid. NIA Memorandum Circular 2020-05 provides a framework for transferring system management to Irrigators' Associations (IAs).

Synthesis

The reviewed literature underscores a critical intersection where economic precarity, environmental degradation, and institutional gaps hinder agricultural productivity. For the Bulacan farmer, the status quo is a "cycle of debt," where 38% of practitioners are forced into loans just to maintain water access. This is compounded by an environmental crisis where 15% of local water sources face contamination from the very fuel used to extract them. These factors make the transition to SPIS an institutional necessity rather than a mere technical upgrade. By integrating economic relief through a 40-60% reduction in energy costs with environmental protection via lower emissions and water conservation, SPIS presents a viable path for large-scale agricultural modernization.

Conceptual Framework

This study will be anchored on two theoretical pillars:
1. Sustainable Livelihoods Framework (SLF) - first conceptualized by the Department for International Development (DFID, 1999) and further developed by Scoones (1998). It posits that access to various capital assets (natural, physical, financial, human, social) determines livelihood outcomes. SPIS directly enhances physical capital (irrigation infrastructure), financial capital (reduced costs), and natural capital (sustainable water use), leading to improved livelihood security for farmers.
2. Technology Acceptance Model (TAM) – developed by Davis (1989, TAM suggests that perceived usefulness and perceived ease of use determine technology adoption. This study will apply TAM to understand farmer adoption of SPIS, where reduced costs (usefulness) and manageable maintenance (ease of use) drive acceptance.

The conceptual framework illustrates the relationship among the study variables:

Table 1. Research Paradigm of the Study

INPUT	PROCESS	OUTPUT
• Existing NIA solar project data (Kapatiran IA, BusPan IA, AnBusPa IA) • Survey data from 30 farmers (15 SPIS users, 15 diesel users) • Stakeholder interviews (NIA technicians, IA officers)	• Descriptive analysis (RQ1) • Comparative analysis – independent samples t-test (RQ2) • Thematic analysis for qualitative data (RQ3) • Policy formulation (RQ4)	• Profile of existing SPIS projects • Comparison of SPIS vs. diesel on cost, yield, income, water • Description of socio-economic and environmental impacts • Proposed Solar Irrigation Development Program

Research Problem

This study aims to assess the socio-economic and environmental impacts of Solar-Powered Pump Irrigation Systems (SPIS) as an alternative to diesel-powered irrigation systems in Bulacan. Specifically, it seeks to answer the following questions:
1. What is the profile of the existing Solar-Powered Pump Irrigation System (SPIS) projects in terms of:
1.2 Area covered;
1.2 Number of farmers served; and
1.3 System capacity?
2. How do Solar-Powered Pump Irrigation Systems (SPIS) and diesel-powered irrigation systems compare in terms of:
2.1 Irrigation cost per hectare per cropping season;
2.2 Rice yield (metric tons per hectare);
2.3 Net farm income per hectare; and
2.4 Water consumption per hectare?
3. How may the socio-economic and environmental impacts of Solar-Powered Pump Irrigation Systems (SPIS) be described in terms of:
3.1 Economic benefits;
3.2 Agricultural productivity;
3.3 Environmental sustainability; and
3.4 Farmer satisfaction?
4. Based on the findings of the study, what Solar Irrigation Development Program may be proposed to

promote the wider adoption of Solar-Powered Pump Irrigation Systems in Bulacan?

Hypothesis

Null Hypothesis (Ho): There is no significant difference in irrigation cost, rice yield, net farm income, and water consumption between farms using Solar-Powered Pump Irrigation Systems (SPIS) and farms using conventional diesel-powered pumps.
Alternative Hypotheses (Ha): There is a significant difference in at least one of the key agricultural indicators, specifically irrigation cost, rice yield, net farm income, or water consumption between farms using SPIS and farms using diesel-powered pumps.
Assumptions:
- Farmers will provide accurate self-reported data on costs and yields.
- Fuel prices and climatic conditions will remain relatively stable during the study period.
- Existing NIA project reports are reliable and complete.
- The 30-farmer sample is representative of the broader farming population in Bulacan.

Scope and Delimitation of the Study

Scope: The study will cover three existing NIA SPIS projects in Bulacan (Kapatiran IA, BusPan IA, AnBusPa IA). It will involve a descriptive analysis of these projects and a comparative analysis with 30 rice farmers (15 SPIS users, 15 diesel users), measuring economic and agricultural indicators over one cropping season. The study will also describe the socio-economic and environmental impacts of SPIS based on farmer perceptions and stakeholder interviews, culminating in a proposed Solar Irrigation Development Program.

Delimitations: The study is geographically limited to Bulacan province and its findings may not be generalizable to other regions without validation. The analysis is confined to rice farming systems, excluding other crops. The study will not include grid-connected solar systems, analyzing only standalone SPIS. Social and political barriers to adoption will not be quantitatively measured. Methodological delimitations include a small sample size (n=30) for comparative analysis and reliance on self-reported data for some metrics (e.g., diesel expenses, yields). Due to the accelerated three-week timeline, the study utilizes convenience sampling and relies on internal consistency for instrument reliability rather than a two-week test-retest period.

Significance of the Study

The findings of this study are expected to yield practical and theoretical contributions beneficial to the following stakeholders:
Farmers and IAs: The results will provide direct evidence on the cost savings, yield improvements, and income increases achievable through SPIS adoption, enabling farming communities to make informed decisions about transitioning from diesel to solar irrigation and to develop sustainable management plans.

NIA: The study offers a validated assessment of existing SPIS projects and a proposed program for expansion. NIA can utilize these insights to streamline project approval processes, allocate budget resources more effectively, and scale up solar irrigation across other underserved provinces.

Local Government Units (LGUs) of Bulacan: The findings can inform evidence-based policy by quantifying the economic, environmental, and social benefits of solar irrigation. This can guide municipal governments in enacting supportive ordinances, such as streamlined permitting, local subsidy programs, or public-private partnerships to accelerate SPIS adoption.

DA and Other National Agencies: The study highlights the role of renewable energy in enhancing food security and climate resilience. The results can serve as a basis for integrating solar irrigation into national agricultural modernization and climate action plans, supporting the Philippines' commitments under the Renewable Energy Act (RA 9513).

Academic Institutions and Future Researchers: The study bridges theoretical frameworks on sustainable agriculture and renewable energy with empirical data from actual field implementations. This can serve as a reference for curriculum development in agricultural engineering, environmental science, and development economics, as well as a baseline for similar studies in other Philippine regions.

Climate Action Advocates and Environmental Organizations: The findings will provide evidence of the environmental benefits of SPIS, offering a practical, scalable solution for decarbonizing agricultural irrigation and mitigating climate change impacts.

Definition of Terms

The following terms are defined conceptually (based on theoretical literature) and operationally (as used in this study).
Cropping Season — Conceptually, the period from land preparation to harvest. Operationally, for this study, it is defined as 110-120 days for rice in Bulacan province.

IA (Irrigation Association) — Conceptually, a formal organization of farmer-beneficiaries within a specific irrigation system service area. Operationally, it refers to the farmer associations recognized by NIA (Kapatiran IA, BusPan IA, AnBusPa IA) that are eventually responsible for system operation, maintenance, and management after government turnover.

IMO (Irrigation Management Office) — Conceptually, a district or field office of the NIA responsible of managing irrigation sytems within a specific provincial or regional area. Operationally, in this study, it refers to the NIA -Bulacan IMO, which implemented and oversees the SPIS projects under investigation.

kWp (Kilowatt-peak) — Conceptually, the maximum power output of a solar panel system under standard test conditions. Operationally, it is used in this study to describe the capacity of existing NIA SPIS projects (e.g., 60 kWp for Kapatiran IA, 150 kWp for BusPan IA, 500 kWp for AnBusPa IA).

LGU (Local Government Unit) — Conceptually, the basic political unit in the Philippines consisting of provinces, cities, municipalities, and barangays. Operationally, in this study, it refers to the municipal governments of San Rafael, Bustos, Pandi, and Angat in Bulacan province.

NIA — Conceptually, the National Irrigation Administration, the government agency responsible for irrigation development in the Philippines. Operationally, it refers specifically to the NIA-Bulacan Irrigation Management Office (IMO) which implemented the SPIS projects under study.

PAGASA (Philippine Atmospheric, Geophysical and Astronomical Services Administration) — Conceptually, the Philippine government agency responsible for weather forecasting, flood control, and astronomical observations. Operationally, in this study, it refers to the source of climate and drought data for Bulacan province.

SPIS (Solar-Powered Pump Irrigation System) — Conceptually, an irrigation system that uses photovoltaic panels to power water pumps, eliminating the need for diesel or grid electricity. Operationally, it refers to the three NIA-implemented systems in Bulacan (Kapatiran IA, BusPan IA, AnBusPa IA).

Tail-end Farmers — Conceptually, farmers located at the farthest points of an irrigation system. Operationally, in this study, they refer to farmers in upland areas of Bulacan who often experience water shortages due to their position in the distribution network.

II. RESEARCH METHODOLOGY

This study will employ a descriptive-comparative research design. The research design incorporates three methodological phases:

A. Descriptive Phase: A descriptive analysis to evaluate the three existing NIA-Bulacan IMO SPIS projects (Kapatiran IA, BusPan IA, and

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AnBusPa IA) to document their profile in terms of area covered, number of farmers served, and system capacity.

B. Comparative Phase: A comparative analysis (quasi-experimental) to directly contrast agricultural productivity, costs, and resource use between farms using SPIS and those powered by conventional diesel engines.
C. Descriptive-Qualitative Phase: A descriptive analysis of the socio-economic and environmental impacts of SPIS based on farmer perceptions and stakeholder interviews, followed by the formulation of a proposed Solar Irrigation Development Program

Locale of the Study

Figure 1. Location Map

The study will be conducted in the province of Bulacan, Philippines, specifically within the municipalities where the NIA – Bulacan IMO has implemented SPIS projects. These include the Kapatiran IA located in San Rafael, the BusPan IA serving Bustos and Pandi, and the AnBusPa IA covering Angat, Bustos, and Pandi municipal service areas. These locations represent a combination of lowland and upland rice producing barangays. To ensure comparability of geographical and climatic conditions, adjacent areas or barangays that continue to rely on diesel powered pumps will serve as the control group sites.

Respondents

The target population consists of rice farmers in Bulacan who are served by the existing NIA SPIS projects, as well as farmers in adjacent areas who rely on diesel-powered pumps. A convenience sample of 30 rice farmers will be selected. The sample will be divided into two distinct groups: an experimental group of 15 farmers who utilize NIA-provided SPIS from the three project sites for at least one full cropping season, and a control group of 15 farmers operating in adjacent areas who rely on traditional diesel-powered pumps. Farmers using electric grid-powered pumps or mixed irrigation systems will be excluded from the study.

Figure 2. Distribution of Respondents

Data Gathering Instruments

GROUP	IRRIGATION SYSTEM	PROJECT LOCATION/ TYPE	NUMBER OF FARMERS	PERCENTAGE (%)
Experimental	SPIS	Kapatiran IA (San Rafael)	5	16.67%
Experimental	SPIS	BusPan IA (Bustos & Pandi)	5	16.67%
Experimental	SPIS	AnBusPa IA (Angat, Bustos, & Pandi)	5	16.67%
Control	Diesel-powered pump	Adjacent areas (non-SPIS barangays)	15	50.00%
Total:			30	100%

The study will utilize three primary data gathering instruments. First, a Document Review Checklist will be used to extract quantitative data from NIA project completion reports (2021-2025), including system capacity in kWp, area irrigated in hectares, and number of farmers served. Second, a Farmer Survey Questionnaire, a structured instrument covering demographic information, irrigation costs, rice yield, water consumption, and income data, will be administered. Third, a Stakeholder Interview Guide containing semi-structured questions will be used for NIA technicians and IA officers regarding operational challenges, maintenance issues, farmer satisfaction, and recommendations for program development. The questionnaire will be developed in Filipino (Tagalog) to ensure comprehension.

1. Description of the Instruments

The Farmer Survey Questionnaire will be developed by the researcher based on NIA's standard monitoring indicators, using closed-ended questions with Likert scales and numerical responses for quantitative analysis, supplemented by three open-ended questions for qualitative insights. The Document

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Review Checklist will be a tabular form designed to systematically record key performance indicators from official NIA-Bulacan IMO documents, including project identification, technical specifications, service coverage, operational data, farmer contributions, and environmental metrics. The Stakeholder Interview Guide will contain eight open-ended questions focusing on system reliability, technical support, farmer training effectiveness, and sustainability recommendations, with separate versions prepared for NIA technicians and IA officers.

2. Administration of Instruments
The document review will be conducted by the researcher requesting access to NIA-Bulacan IMO project files for Kapatiran IA, BusPan IA, and AnBusPa IA, with data extraction completed within one week. The farmer survey will be administered face-to-face at farmers' homes or cooperative meeting places, with each survey taking 20 to 30 minutes, and the researcher or trained enumerators will read questions aloud to accommodate low-literacy respondents.

3. Validity and Reliability of the Instruments
For content validity, the farmer survey questionnaire will be reviewed by a panel of experts consisting of a NIA-Bulacan IMO engineer, and two research methods professors, who will assess relevance, clarity, and comprehensiveness, with the Content Validity Index (CVI) computed and a minimum acceptable CVI of 0.80 required. For construct validity, the questionnaire items will be mapped to the study's conceptual framework variables, namely irrigation cost, yield, income, water use, and emissions. For reliability, a pilot test will be conducted with 10 farmers (5 SPIS users, 5 diesel users) who are not part of the main sample. Due to the accelerated three-week research timeline, internal consistency will be assessed for all survey items using Cronbach's alpha immediately following the pilot test, where an alpha of ≥ 0.70 indicates acceptable reliability, replacing the two-week test-retest interval to ensure timely data collection.

Data Gathering Procedure

The data gathering will follow eight sequential steps. First, the researcher will secure ethical clearance from the university research ethics board and submit a formal letter to NIA-Bulacan IMO requesting access to project documents and farmer lists. Second, the researcher will extract data from NIA completion reports for Kapatiran IA, BusPan IA, and AnBusPa IA using the document review checklist. Third, the researcher will administer the farmer survey to 10 eligible farmers for pilot testing, then will revise unclear items based on feedback and reliability analysis. Fourth, from NIA farmer-beneficiary lists, the researcher will randomly select 15 SPIS users and from adjacent barangays will identify 15 diesel users matching inclusion criteria, then will obtain informed consent from all participants. Fifth, the researcher will conduct face-to-face surveys with 30 farmers and will record responses on paper forms. Sixth, the researcher will conduct and audio-record (with permission) interviews with NIA technicians and IA officers. Seventh, the researcher will cross-check self-reported diesel expenses and yields against local market prices and barangay agricultural officer records where available. Eighth, the researchers will enter all quantitative data into Microsoft Excel and transcribe the qualitative interview responses.

Data Analysis Technique

Quantitative data will be analyzed using three techniques:
1. Descriptive statistics will be calculated, including mean, standard deviation, frequency, and percentage for all variables, with results presented in tables. This will establish the profile of existing SPIS projects and provide context for describing the socio-economic and environmental impacts.
2. An independent samples t-test will be conducted to compare means between the SPIS group (n=15) and diesel group (n=15) for all key indicators (irrigation cost, rice yield, net farm income, water consumption). The t-test will be performed using Microsoft Excel with a significance level set at $\alpha = 0.05$. Effect size (Cohen's d) will be calculated to determine practical significance.
3. Qualitative analysis of interview transcripts and open-ended survey responses will be performed using thematic analysis, involving coding, categorization,

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and interpretation to describe socio-economic and environmental impacts and inform the proposed Solar Irrigation Development Program.

Ethical Concerns

The study will adhere to seven ethical principles. First, informed consent will be obtained from each participant through a written (or verbal, for low-literacy) explanation of the study's purpose, procedures, risks, and benefits, with participants signing a consent form and refusal to participate resulting in no penalty or loss of NIA-Bulacan IMO services. Second, confidentiality will be maintained by not including farmer names in any report, assigning each respondent a unique code (e.g., SPIS-01, D-01), and storing all data in a password-protected computer accessible only to the researcher. Third, anonymity will be ensured by publishing no identifying information and reporting results only in aggregate. Fourth, voluntary participation will be respected, allowing farmers to withdraw from the study at any time without explanation. Fifth, no deception will be practiced, with the study's purpose and funding sources fully disclosed. Sixth, beneficence will be upheld as the study poses minimal risk (time spent on survey) with potential benefits including improved irrigation policy, and summary findings will be shared with participating communities. Seventh, institutional approval will be secured by submitting the research proposal to NIA-Bulacan IMO for approval before data collection begins, with raw data retained for three years after completion then permanently deleted.

III. RESULTS AND DISCUSSION

1. Socio-Demographic Profile of Respondents

The descriptive demographic profile of the 30 respondent farmers in Bulacan reveals an experienced, smallholder-dominated farming community. The average age of the respondents was 53.7 years, with an average farming experience of 29.7 years, indicating a highly traditional agrarian cohort. The average farm area was 1.64 hectares, with 30% of the respondents holding landowner status, 50% operating as tenants, 13.3% as sharecroppers, and 6.7% as lessees.

Demographic Indicator	SPIS Users (n=15)	Diesel Users (n=15)	Overall Sample (N=30)
Mean Age (Years)	52.5	54.9	53.7
Sex: Male (%)	73.3%	80.0%	76.7%
Sex: Female (%)	26.7%	20.0%	23.3%
Mean Farming Experience (Years)	28.7	30.7	29.7
Mean Farming Area (Hectares)	1.48	1.80	1.64
Tenure: Owner (%)	26.7%	33.3%	30.0%
Tenure: Tenant (%)	53.3%	46.7%	50.0%
Tenure: Sharecropper (%)	20.0%	6.7%	13.3%
Tenure: Lease (%)	0.0%	13.3%	6.7%
Education: High School + (%)	80.0%	86.7%	83.3%

Table 2. Socio-Demographic Profile of Respondents

The socio-demographic breakdown reveals a high degree of homogeneity between the SPIS and diesel user cohorts, which validates the t-test comparative structure. Both groups consist primarily of experienced male farmers in their early-to-mid 50s with similar educational backgrounds. The slightly larger average farm size among diesel users (1.80 ha vs. 1.48 ha) is notable but not statistically significant in the context of this study's comparative design.

2. SPIS System and Operational Profiles

Table 3. SPIS System and Operational Profiles

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System Characteristics	Kapatiran IA	BusPan IA	AnBusPan IA
Location	San Rafael	Bustos & Pandi	Angat, Bustos, Pandi
System Provider	NIA	NIA	NIA
Mean Years in Operation	2.0 years	2.2 years	2.4 years
Operator Training Rate (%)	60.0%	80.0%	60.0%
Reliability Rating: Good/ Excellent (%)	80.0%	100%	80.0%

The data reveals that diesel users have been using their systems for significantly longer periods (7.6 years vs. 2.4 years for SPIS), reflecting the relative newness of solar technology in the area. Notably, only 13.3% of diesel users received their systems from institutional providers (NIA/LGU), with the majority relying on personal purchases or cooperative support. The stark reliability rating differential—86.7% of SPIS users rate their system as Good/Excellent compared to only 46.7% of diesel users—suggests that despite technical challenges, solar users perceive greater reliability than their diesel counterparts.

3. Quantitative Comparison: SPIS vs. Diesel
3.1 Economic Performance Comparison

Table 4a. Economic Performance Comparison (Costs)

Variable (per hectare)	SPIS Mean	Diesel Mean	t-stat	p-value
Fuel Cost (₱)	0.00	14,933.33	-34.68	<0.001
Maintenance (₱)	1,066.67	2,753.33	-6.92	<0.001
Rental Cost (₱)	0.00	600.00	-4.45	<0.001
Other Cost (₱)	100.00	800.00	-6.87	<0.001
Total Irrigation (₱)	1,166.67	19,086.67	-41.46	<0.001

Table 4b. Economic Performance Comparison (Yield and Income) *Note: p < 0.001 indicates statistical significance at α = 0.05; Cohen's d = effect size*

Variable (per hectare)	SPIS Mean	Diesel Mean	t-stat	p-value	Cohen's d
Rice Yield (kg/ha)	5,353.33	4,533.33	5.92	<0.001	2.16
Gross Income (₱)	108,992.67	91,327.27	5.44	<0.001	1.99
Other Prod. Costs (₱)	38,333.33	38,333.33	0.00	1.000	0.00
Net Income (₱)	69,492.67	33,640.60	9.93	<0.001	3.63

The quantitative comparison shows that the Total Irrigation Cost per Hectare for SPIS users is significantly lower (M=₱1,166.67, SD=₱523.27) compared to traditional diesel pump users (M=₱19,086.67, SD=₱1,590.09; $t(28)=-41.46$, $p<0.001$). This dramatic 93.9% reduction in operating expenditure is driven by the total elimination of seasonal fuel purchases (₱0.00 for SPIS vs. ₱14,933.33 for diesel) and lower recurring maintenance costs (₱1,033.33 vs. ₱2,753.33).

Crucially, SPIS users achieved 18.1% higher rice yields (M=5,353.33 kg/ha, SD=314.23) compared to diesel users (M=4,533.33 kg/ha, SD=434.52; $t(28)=5.92$, $p<0.001$, $d=2.16$). This finding is particularly noteworthy as it contradicts the initial assumption that yields would be similar between the two systems. The yield improvement can be attributed to more reliable water delivery and extended pumping hours enabled by zero-marginal-cost solar energy.

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Since other production costs (seeds, fertilizer, labor) were identical between both groups ($p=1.000$), the lower irrigation costs and higher yields directly translated into a significantly higher seasonal net income for SPIS users (M=₱69,492.67, SD=₱9,716.06) compared to diesel users (M=₱33,640.60, SD=₱10,058.32); $t(28)=9.93$, $p<0.001$, $d=3.63$). This confirms that SPIS acts as an extremely powerful driver of household farm profitability, allowing smallholders to expand net profits by 106.6%—more than doubling their seasonal income.

3.2 Water Consumption and Pumping Behavior

Water extraction patterns, detailed in Table 5, reveal that solar pumps operate for significantly longer durations and across more days per season compared to diesel pumps. SPIS users reported an average of 7.02 daily pumping hours, compared to 5.28 hours for diesel users with a difference of 33.0%. More significantly, SPIS pumps operated for 53.4 days per season versus 39.20 days for diesel, resulting in 80.3% more total pumping hours per season.

Table 5. Water Consumption and Pumping Behavior

Pumping Characteristic	SPIS Mean	Diesel Mean	t-stat	p-value	Cohen's d
Average Daily Pumping Hours (Hours/day)	7.02	5.28	7.21	<0.001	2.63
Average Pumping Days per Season (Days/Season)	53.40	39.20	7.71	<0.001	2.82
Total Pumping Hours per Season	373.84	207.40	10.90	<0.001	3.98

This extended pumping behavior reflects a zero-marginal-cost pumping pattern enabled by solar energy; since solar power is free, farmers can irrigate more thoroughly and for longer periods without financial constraint. This likely explains the observed 18.1% yield improvement, as more consistent and thorough irrigation reduces crop water stress during critical growth stages. However, this finding also raises important questions about long-term groundwater sustainability, underscoring the need for water management protocols and potential hybrid backup systems during peak dry seasons.

4. Socio-Economic and Environmental Impacts

4.1 Farmer Perception Index

Farmer agreement ratings across the 18-item perception survey confirm strong socio-environmental alignment for SPIS but reveal a glaring technical gap. Table 3.5 summarizes the mean satisfaction ratings (1 to 5 Likert scale) for both cohorts, organized by the four core analytical dimensions.

Table 6. Farmer Perception Index Mean Ratings (1 to 5 Scale)

Analytical Dimension (Likert Scale)	SPIS Mean	Diesel Mean	Core Insight
F1. Economic Benefits	4.28	1.83	Solar dramatically improves cost savings; diesel users strongly disagree on any economic benefit
F1. Agricultural Productivity	4.50	3.27	SPIS users strongly agree on dry season farming capability; diesel users are neutral
F3. Environmental Sustainability	4.55	2.08	Solar is highly rated for zero smoke emissions (5.00/5) and zero oil spills (4.53/5)
F3. Farmer Satisfaction	3.84	3.81	Similar overall, but suppressed by low technical support ratings for SPIS (F4.4 = 2.47)

SPIS users expressed near-perfect satisfaction with Economic Benefits (F1 = 4.28) and Environmental Sustainability (F3 = 4.55), with the most striking individual ratings being:

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- No smoke/fumes: 5.00/5 (SPIS) vs. 1.67/5 (diesel)
- Environmentally friendly: 5.00/5 (SPIS) vs. 1.60/5 (diesel)
- Reduced farming costs: 4.53/5 (SPIS) vs. 1.53/5 (diesel)

However, overall satisfaction (F4 = 3.84) was noticeably weighted down by a critical item: 'Technical support is readily available when needed' (F4.4), which received an average score of just 2.47/5 for SPIS compared to 4.67/5 for diesel users. This 2.20-point gap reveals that when a solar pump, inverter, or automatic transfer switch malfunctions, farmers are left virtually helpless due to a complete lack of local troubleshooting expertise.

Additionally, SPIS users rated the system as less easy to operate and maintain (F4.3 = 3.47) compared to diesel users (4.73), suggesting that solar technology introduces complexity requiring more training—yet only 66.7% have received formal training.

4.2 Thematic Analysis of Key Informant Interviews

Table 7. Thematic Analysis of Stakeholder Key Informant Interviews

Core Theme Identified	Operational Definition
Technical First-Responder Deficit	Delay in simple maintenance due to centralized technical control and absence of community troubleshooting skills
Communal Sinking Fund Deficits	Complete absence of long-term cooperative savings to self-fund future expensive inverter or battery replacement
Dry-Season Discharge Limits	Seasonal drop in surface water or groundwater discharge rates, requiring physical pumping backups
Localized Training Gaps	Structural lack of basic, practical operations and bookkeeping workshops for communal water-users
Financial Benefits Perceived	Farmers recognize tangible income improvements from solar adoption
Institutional Support Needs	Demand for more responsive NIA support and sustainable maintenance systems

The qualitative feedback highlights a deep institutional vulnerability. While SPIS eliminates day-to-day diesel expenses and delivers transformative economic benefits, it introduces a high dependency on specialized technical support and long-term financial coordination. The Technical First-Responder Deficit theme directly explains the low technical support rating (2.47/5) observed in the perception index that when an inverter fails, farmers must wait for a technician from the city, causing crop water stress during critical growth periods.

Similarly, the Communal Sinking Fund Deficits theme reveals that while farmers enjoy immediate fuel cost savings, no structured financial mechanism exists to replace expensive components (inverters costing ₱40,000-60,000) when warranties expire.

The Dry-Season Discharge Limits theme underscores the need for hybrid backup systems, as solar pumps cannot lift water when groundwater levels drop during peak summer heat. The Localized Training Gaps theme reinforces the quantitative finding that only 66.7% of operators received formal training.

Without resolving these training gaps, establishing dedicated sinking funds, and deploying hybrid backup systems, the communal solar systems are highly vulnerable to premature structural failure or permanent abandonment when initial warranties expire.

Based on these results, the null hypothesis (Ho) is rejected for all tested variable. Since p-values are all <0.001 and the large effect sizes (Cohen's d ranging from 1.56 to 9.15) confirm these differences are both statistically and practically significant. Therefore, the Alternative Hypothesis (H_a) is accepted that there is a significant difference in irrigation cost, rice yield, net farm income, and water consumption between farms using SPIS and farms using diesel-powered pumps in Bulacan.

IV. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary of Findings

The objective of this study was to assess the socio-economic and environmental impacts of Solar-Powered Pump Irrigation Systems (SPIS) in Bulacan compared to traditional diesel-powered pumps. Based on the descriptive, comparative, and thematic analyses conducted on 30 smallholder farmers and key institutional stakeholders, the following core findings were established, organized according to the four research problems:

1. Profile of Existing SPIS Projects: SPIS users operate systems exclusively provided by the National Irrigation Administration (NIA) across three project sites: Kapatiran IA (San Rafael), BusPan IA (Bustos & Pandi), and AnBusPa IA (Angat, Bustos, & Pandi). The systems have been in operation for an average of 2.2 years (ranging from 2.0 to 2.4 years across the three sites), with capacities of 60 kWp, 150 kWp, and 500 kWp respectively. While 86.7% of operators received formal training, the systems demonstrated high perceived reliability, with 80-100% of users across the three project sites rating their systems as Good or Excellent.
2. Comparison of SPIS vs. Diesel: SPIS adoption yielded transformative financial and agricultural benefits. SPIS users experienced a 93.9% reduction in seasonal irrigation costs spending ₱1,166.67/ha compared to ₱19,086.67/ha for diesel users ($p < 0.001$, $d = 15.14$). The total elimination of fuel expenses allowed SPIS farmers to increase their seasonal net income by 106.6%, earning ₱69,492.67/ha compared to the diesel cohort's ₱33,640.60/ha ($p < 0.001$, $d = 3.63$). Additionally, because solar energy carries zero marginal cost, SPIS users pumped water for 80.3% more hours per season than diesel users. This extended irrigation led to an 18.1% higher rice yield for SPIS farmers, achieving 5,353.33 kg/ha versus 4,533.33 kg/ha ($p < 0.001$, $d = 2.16$).
3. Socio-Economic and Environmental Impacts: SPIS farmers reported near-perfect satisfaction with environmental benefits specifically zero smoke emissions (5.00/5), eco-friendliness (5.00/5), and no oil spills (4.53/5) with an overall environmental perception mean of 4.55/5 compared to 2.08/5 for diesel users. Economic benefits were rated 4.28/5 (vs. 1.83/5 for diesel), and agricultural productivity was rated 4.50/5 (vs. 3.27/5 for diesel). However, a critical technical vulnerability emerged: SPIS users rated the availability of technical support at a very low 2.47 out of 5, compared to 4.67 for diesel users. Thematic analysis of stakeholder interviews revealed profound structural gaps, notably a "Technical First-Responder Deficit," an absence of "Communal Sinking Funds" for future battery/inverter replacements, and operational limits during the dry season.
4. Proposed Solar Irrigation Development Program: Based on the findings, the Bulacan Solar Irrigation Development Program (BSIDP) is proposed. A 24-month strategic framework comprising three pillars: (1) decentralized local maintenance teams to address the technical support gap, (2) community-led sinking fund financial models to ensure capital replacement, and (3) climate-resilient hybrid solar-diesel system configurations to overcome dry-season water discharge limits. This program provides a scalable model for expanding SPIS adoption across underserved areas in Bulacan and other provinces.

Hypothesis Testing: The null hypothesis (Ho) was rejected for all tested variables. Since p-values were all <0.001 and the large effect sizes (Cohen's d ranging from 1.99 to 15.14) confirmed these differences are both statistically and practically significant, the Alternative Hypothesis (Ha) is accepted. This formally establishes that there is a highly significant difference in irrigation cost, rice yield, net farm income, and water consumption between farms using SPIS and farms using diesel-powered pumps in Bulacan

Conclusions

Based on the empirical findings addressing each research problem, the study concludes the following:

1. SPIS Projects are Reliable but Lack Full Institutional Support: The existing SPIS projects in Bulacan demonstrate high technical reliability and farmer acceptance. However, the post-turnover institutional framework remains incomplete. Specifically, the limited training coverage of 86.7% and the complete absence of cooperative sinking funds threaten long-term system viability.
2. SPIS is Economically and Agriculturally Superior to Diesel: SPIS delivers transformative benefits, including a 93.9% cost reduction, 18.1% higher yields, and a 106.6% income increase. The free nature of solar energy encourages longer and more frequent pumping, which optimizes crop health and increases yield but raises future concerns regarding groundwater sustainability if left unmonitored.
3. Farmers Recognize Environmental Benefits but Face Technical Dependency: Farmers strongly value the environmental benefits of SPIS, such as zero emissions, no oil spills, and general eco-friendliness. However, SPIS replaces economic vulnerability (volatile fuel costs) with technical dependency (centralized repair networks), as reflected in the low technical support rating of 2.47/5.
4. A Structured Development Program is Needed for Scaling: The current SPIS deployment model lacks the necessary post-turnover institutional support. The Bulacan Solar Irrigation Development Program (BSIDP), through its three pillars of decentralized maintenance, communal sinking funds, and hybrid systems, provides a strategic pathway to sustain and scale these solar irrigation benefits for future generations of farmers.

Recommendations

To address the identified gaps and ensure the sustainability of solar irrigation in the province, this study strongly recommends the implementation of the Bulacan Solar Irrigation Development Program (BSIDP), structured upon three strategic pillars:

Decentralized Maintenance Training (Pillar 1): NIA, in partnership with local government units (LGUs) and TESDA, must establish a localized "First-Responder" technical training program. Selected members of the Irrigators' Associations (IAs) should be trained in intermediate electrical troubleshooting to bypass the current delays in centralized repair scheduling.

Mandatory Communal Sinking Funds (Pillar 2): To mitigate the high capital replacement costs of inverters and batteries, IAs must implement a mandatory sinking fund policy. Farmers can easily afford to contribute a fraction of their nearly ₱15,000 seasonal fuel savings into a cooperative trust fund, ensuring financial independence when warranties expire.

Climate-Resilient Hybridization and Monitoring (Pillar 3): To combat dry-season water discharge limits identified by stakeholders, future SPIS installations should incorporate hybrid capabilities (allowing diesel generators to connect via automatic transfer switches during severe droughts). Additionally, NIA should introduce groundwater monitoring protocols to ensure the extended pumping hours of solar users do not lead to aquifer depletion.

Limitations of the Study

This study is limited to 30 respondents in Bulacan province over a single cropping season, relying on self-reported data. Findings may not be generalizable without further validation across other regions and cropping cycles.

For Future Researchers

It is recommended that longitudinal studies be conducted over multiple cropping seasons to track the degradation rate of solar panels and the long-term stability of the communal sinking funds.

The evidence is clear: SPIS delivers transformative economic and environmental benefits for farmers in Bulacan. However, without addressing the institutional vulnerabilities identified such as inadequate training, unreliable technical support, and absence of sinking funds, the long-term sustainability of these systems remains at risk. The proposed Bulacan Solar Irrigation Development Program provides a strategic pathway to sustain and scale these benefits for generations to come.

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