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Socio-Economic and Environmental Analyses of Solar Irrigation Systems for Sustainable Agricultural Production

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Abstract: Solar irrigation is a climate mitigation technology to reduce greenhouse gas (GHG) emissions in agricultural production. Despite its potential, small-scale farmers are unable to afford photovoltaic (PV) systems and resort to using the traditional diesel-powered pumps for irrigation. This study aims to analyze the social, economic, and environmental aspects of introducing solar irrigation systems from the perspective of small-scale farmers in developing countries. Applying socio-economic and environmental analyses to the case of the Philippines, the study found the environmental benefits of solar irrigation in terms of the reduction in GHG emissions of up to 26.5 tons CO_2eq/ha/year and the avoidance of emissions of air pollutants such as carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter. The energy savings between 11.36 and 378.54 L/ha of diesel per year resulted in a range of −USD 1255/ha to USD 68,582/ha net present value, 30% to 2958% with an average of 315% returns on investment, and 0.3 to 30 years payback period with an average of 2.88 years. Regardless of the low awareness of environmental sustainability, most farmers were interested to invest in solar irrigation systems with 69% social acceptance, while the 26% were not interested as they consume a minimal amount of fuel and cannot recover the high investment from the cost savings. This study provided policy recommendations to make solar irrigation accessible to small-scale farmers as well as broader implications to make the agricultural sector more sustainable.

Keywords: renewable energy; sustainable agriculture; economic analysis; environmental impact; social acceptance; solar PV

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1. Introduction

Sustainable agriculture is essential in achieving several sustainable development goals such as poverty alleviation, food security, inclusive economic growth, and sustainable production patterns [1,2]. Currently, agricultural production has been more challenging due to the increasing world population, growing demand for food, and declining agricultural land areas [3]. To address these problems, various sustainable production methods are being practiced across the globe such as precision production, conservation, organic agriculture, agroforestry, and integrated agro-farming systems [4].

Another sustainable agricultural production practice is the application of solar photovoltaic (PV) pumps as a substitute for diesel pumps for irrigation. With solar pumps, farmers have access to high-quality power available for irrigation as these systems are portable and can be assembled at any preferred location at any time [5]. Evidence-based literature review shows that PV pumps can enhance farmers' adaptive capacity by raising agricultural productivity and their incomes while mitigating climate change by reducing CO_2 emissions [6]. Additionally, the unused energy from solar irrigation systems can be utilized to power other applications [7]. With the growing utilization of these systems, the costs have decreased substantially, making them an efficient, convenient, and cost-effective solution for grid-isolated rural areas [8]. However, farmers in remote areas are not aware of these advantages of solar-powered pumps; if they are, high initial cost, access to finance, low efficiency, and fluctuating radiation limit the adoption of solar PV pumps for irrigation [9]. It is therefore impetus to study both technical and non-technical aspects of solar PV adoption for a more sustainable agricultural production.

The current literature covers socio-economic and environmental as well as non-technical analyses related to solar PV irrigation. For instance, Islam and Hossain [10] investigated the economic feasibility and environmental benefits of solar irrigation pumps operating in the northern region of Bangladesh. The financial analysis revealed that small pumps are the most profitable option, medium pumps are the worst, while large pumps are moderately profitable but can be improved by introducing additional uses of solar energy. On the other hand, the net environmental benefit for all types of solar pumps analyzed is found almost equal to the provided subsidy for installing them, with small pumps having the highest net environmental benefit per kilowatt peak [10]. In another study, Raza et al. [11] evaluated the socio-economic and climatic impact of PV-operated irrigation such as drip and sprinkler irrigation systems. The results showed that the installation of solar PV increased the adoption of high-efficiency irrigation systems, reduced the high operational costs incurred from old diesel-powered pumping systems, increased farmers' income, reduced 17,622 tons of CO_2 emissions per year, and saved 41% of water usage [11]. Comparing solar PV with diesel-powered pumping systems, Xie et al. [12] analyzed the cost-effectiveness of the two systems for groundwater pumping irrigation under a range of crop and irrigation-method scenarios. The overall results showed that solar PV is a promising energy solution to support groundwater-fed irrigation development as it is more economical; however, the calculated cost-effectiveness is sensitive to the installed cost of solar PV and the escalation rate of diesel prices [12]. Rana et al. [13] also compared solar and diesel pumps and found the advantages of solar pumping systems for a farmer include unattended operation, low operating cost, easy installation, low maintenance, and long life, compared with the high fuel and maintenance cost of a diesel engine. While the initial capital cost of a solar pump may be far greater than a diesel-powered generator, the low maintenance and zero fuel costs of a solar power system can be a cheaper option in the long run [13].

Despite its cost-effectiveness and promising emission reduction potential, investment in solar PV irrigation systems is also challenged with social sustainability, which is approached from multiple perspectives, such as social or public acceptance, social equity, and social impact. Public or social acceptance is crucial for the introduction of solar PV technology as it is influenced by several factors including the perceived costs, risks and benefits, trust, and distributive fairness [1]. Zhou et al. [14] expounded on this and found that perceived usefulness, perceived ease of use, facilitating conditions, cost tolerance, awareness, and attitude towards solar pump usage influence the adoption of this technology for agricultural irrigation. To boost public acceptance of solar irrigation systems, various critical barriers prevailing at the grassroots level must be overcome such as weak policies, high investment costs, low awareness, poor infrastructure, and lack of a skilled workforce [15,16]. Yet, no study integrates both technical and non-technical analyses of the adoption of solar PV pumps for small-scale farming in off-grid remote areas in developing countries.

This study aims to contribute to the existing literature by proposing a valuation framework for a solar pump irrigation project that integrates social, economic, and environmental aspects from the perspective of small-scale farmers in developing countries. Specifically, economic analysis was employed to calculate the net present value (NPV), returns on investment (ROI), and payback period (PBP). The environmental analysis estimates the energy savings from using solar PV over diesel, and the reduced GHG emissions as well as air pollutants such as particulate matter (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon monoxide (CO) emissions. Thematic analysis was applied to analyze the social acceptance of solar PV irrigation systems from the perspective of small-scale farmers. This study finally aims to suggest policies to support the adoption of solar PV for irrigation systems and to realize the government's goal of a more sustainable agriculture sector.

2. Materials and Methods

2.1. Case Study Background

The Philippines is an agricultural country with 24.5% of the economy based on agriculture, hunting, forestry, and fishing [17]. With a total area of agricultural land of 41.7% of the country, the agriculture sector employs 22.86% of the total workforce in the Philippines [18]. While the country's agricultural production is dominated by rice with a 19.37% share [19], it is rice import-dependent with a 14-year average of 11.35% share of import to total consumption [20]. The country is aiming to achieve self-sufficiency in rice by increasing production, mechanization of farms, and providing support such as improvement of irrigation infrastructures, access to quality seeds, training, and capacity building for production efficiency [21,22].

In response to mitigating the impacts of climate change, the government installed several large solar irrigation projects in different parts of the country. For instance, solar irrigation projects were installed in the provinces of Rizal, Laguna, Camarines Sur, Nueva Ecija, Occidental Mindoro, and Lanao del Sur in the last 5 years. These projects provide a sustainable supply of water in the absence of a conventional irrigation system while offsetting the cost of traditional irrigation fuels, offering low operational costs, and producing zero GHG emissions [23].

There are loads of examples of large-scale solar irrigation projects which help with sustainable water management, but this does not extend to small-scale farmers. While a solar irrigation system is beneficial from an environmental perspective, investing in this system is impractical because of the socio-economic status of small-scale farmers. Hence, it is imperative to investigate the attractiveness of the investment in solar PV irrigation systems, particularly for small-scale farmers that own, tenant, or share rice farmland limited to 2 hectares or less.

2.2. Participants and Data Collection

We conducted the study in the Philippines between June and November 2021. With the help of the Department of Agriculture, we identified 15 sites of agricultural land used for rice farming which do not benefit from the national irrigation system, communal irrigation, and the local and internationally funded irrigation systems. The participants of this study included 39 small-scale farmers from the identified sites. This study performed a purposive sampling according to the following inclusion criteria: (a) rice farmer from the Philippines; (b) owns, tenants (farmers who rent the land), or shares 2 hectares or less of a farm for rice production; (c) owns or uses any irrigation system not provided by the government; (d) voluntary participation in the study; and (e) completeness of the reports, following main survey questions and instructions. We identified the sample size based on "data saturation", which refers to the instance when the responses become repetitive and no information is added by continuing the data collection [24]. Hence, the researchers simultaneously conducted the data analysis and the data collection to be mindful of the data saturation.

The researchers utilized a self-made questionnaire (see Appendix A, Table A1), which aims to gather the data for using a diesel-powered irrigation system. This includes the (a) land area of rice fields, (b) initial investment cost of diesel-powered irrigation system, (c) annual fuel cost, (d) maintenance and other costs for using diesel pump, and (e) farmer's preference for either continuing to use a diesel pump or investing in a solar pump irrigation system. This questionnaire was adapted from the model of estimations of the greenhouse gas emission factor, air pollutant factor, social, and traditional economic valuation approaches such as the return of investment, payback period, and net present value as presented in a previous study in the Philippines [25]. The adapted research instrument which presents the questions in Filipino language, the vernacular of the local farmers, was validated by an economist and sustainable development planner, an agriculturist, the research panel members of Mindoro State University, and an expert from the University of the Philippines Los Baños before the interview. The experts looked at the technicality, clarity, presentation, suitability, adequacy, and attainment of the purpose of the items. Then, the questionnaires were revised based on their recommendations.

Using the validated questionnaires, the researchers conducted a combination of face-to-face and virtual surveys using Google Forms. Minimum health protocols set by the Inter-Agency Task Force for the Management of Emerging Infectious Diseases were observed at all times. A virtual survey was conducted for farmers with gadgets and stable internet connectivity while a face-to-face survey was conducted for those with no means of virtual communication. On both occasions, the survey began with a careful explanation of the nature, purpose, and other details of the study before asking the actual questions.

To ensure the anonymity of the participants, the survey form incorporated codes, and the participants received the coded data to have the opportunity to verify and review their responses. The study followed the Ethical Guidelines set by MDPI on research with human subjects. The study adhered to the Declaration of Helsinki [26] and was reviewed and approved by the Research Committee of Mindoro State University. The researchers explained to the farmers that the study was solely for academic purposes, participation was voluntary, and the participants were free to opt out at any time. Lastly, the researchers guaranteed the confidentiality of the responses, as the data were only accessible to the researchers.

2.3. Environmental Analysis

An environmental impact assessment (EIA) is a process to predict the environmental consequences of a project's development and reduce or mitigate negative impacts of human footprints and maximize positive ones [27]. The assessment of environmental impacts can be performed in different contexts of which three of a fundamentally different nature can be identified: environmental impact assessment, environmental risk assessment, and life cycle impact assessment [28]. By applying EIA in any project valuation, we can assess the environmental effects of each decision and implement a plan that suits our needs the most [27]. In this study, we compared the environmental impacts of solar and diesel irrigation systems in terms of GHG emissions, air pollution, and energy savings.

To calculate the GHG emissions for using diesel-powered irrigation pumps, the average annual fuel consumption (FC) was multiplied by the emission factor (EF) or its CO_2 equivalent as described in Equation (1).

$$\mathrm{GHG} = \mathrm{FC} \times \mathrm{EF} \tag{1}$$

For this study, FC is equal to the average liters of diesel used for irrigation in all cropping seasons of the year while the EF is obtained from the Emission Factors for Greenhouse Gas Inventories as declared by the US Environmental Protection Agency (EPA) in 2021 [29].

For the air pollution, we considered the compounds produced from the direct combustion of diesel including carbon monoxide, nitrogen oxide, sulfur oxide, and particulate matter. Carbon monoxide (CO) is a flammable gas that is odorless, colorless, and tasteless with a density slightly lesser than air but can cause poisoning when its concentration becomes above 35 ppm. Nitrogen oxide (NO_x) is a highly reactive gas that is formed when fuel is combusted at a high temperature. Sulfur oxides (SOx) are a group of important ambient air pollutants including both gaseous and particulate chemical species such as sulfur monoxide, sulfur dioxide, sulfur trioxide, and disulfur monoxide [30]. SO_2 is emitted from the combustion of fossil fuels and other industrial activities [31]. Moreover, particulate matter (PM) is a complex mixture of hazardous particles formed from all the solid and liquid particles in the atmosphere composed of both organic and inorganic particles, such as dust, pollen, smog, soot, smoke, and liquid droplets [31].

For the calculation of air pollutant emissions (APEs), the average annual fuel consumption and pollutant factor were multiplied as shown in Equation (2):

$$APE_i = FC \times PF_i \tag{2}$$

where i is the air pollutant (CO, NO_x, SO_x, and PM), and PF is the pollutant factor based on the conversions provided in the Emission Factors for Greenhouse Gas Inventories as declared by US EPA in 2021 [29].

2.4. Economic Analysis

To make greener energy sources more attractive to farmers who have limited financial capacity, this study analyzed the profitability of their investment in a solar irrigation project through an economic analysis. To compare the financial viability of solar PV and diesel-powered irrigation systems, the researchers adopted the traditional valuation approaches such as returns on investments (ROIs), payback period (PBP), and net present value (NPV) [25] using the specifications below:

- The investment cost of a solar PV irrigation system is the total initial expenditures on solar panels, pumps, and installation;
- Operations and maintenance costs for solar PV irrigation systems are the annual expenses in maintenance, labor, and other expenses;
- Operations and maintenance costs for diesel-powered irrigation systems are the annual expenses in fuel (diesel), maintenance, labor, and other expenses.

The ROI is one of the financial performance measurements that is used to evaluate the efficiency of capital investment and operation or compare the efficiency of several investment projects [32]. In this study, ROI directly measures the revenue of the solar irrigation system against the diesel-powered irrigation system relative to the initial investment, operational, and maintenance cost. To calculate ROI, the benefit or investment return is divided by the cost of the investment as shown in Equation (3):

$$ROI = \frac{\sum_{t=1}^{T} R_t - I}{I} \tag{3}$$

where R is the annual net cash flow, t is the valuation period, T is the technical lifetime of solar PV, and I is the investment cost for a solar irrigation system.

For R, the annual cash flow for each technology is equal to the marginal turnover minus marginal cost. It is assumed that both technologies produce the same quantity of water needed to irrigate 1 hectare of a farm. It is also assumed that both technologies have the same intervening variables such as rice production, labor, fertilizer, weather patterns, and planting periods, among others. Both technologies have the same turnovers and only differ in the variable (fuel) and other operational and maintenance costs. Hence, the R in this study is also equal to the cost savings from replacing diesel-powered irrigation systems with solar. Meanwhile, for the investment cost for solar PV (I), it is assumed that the farmers are already using diesel-powered irrigation pumps. Therefore, its investment cost is accounted for in this study. For all economic analyses, the investment cost is the cost of capital for the solar PV system and its installation.

Another economic tool is the PBP, which is defined by calculating the time needed to recover an investment. The PBP of a certain investment is a possible determinant of whether to proceed with the project because longer PBPs are typically not desirable for certain investors [33]. In this study, the PBP is the amount of time it takes to recover the cost of the initial investment in a solar-powered irrigation pump. It is equal to the cost of the investment, I, divided by the annual net cash flow, R_t, as described in Equation (4).

$$PBP = \frac{I}{R_t} \tag{4}$$

Lastly, the NPV is a strong criterion to determine if a project is profitable or not. It is defined as the difference between the present value of cash inflows and outflows, in which a project is feasible if the value obtained through discounted cash flow is higher than the investment cost [34]. The following points define the role of an NPV: (a) a positive NPV implies that the financial position of the investor is improved by undertaking the project; (b) a negative NPV indicates a financial loss; and (c) zero or null NPV means that the present value of all benefits over the useful lifetime is equal to the present value of all the costs [35].

In this study, the NPV of the project is the value of all future cash flows over the entire life (T) of solar PV irrigation pump operation discounted to the present period at a discount rate of (r), which is described in Equation (5).

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} - I \quad (5)$$

Based on the calculation results, a positive NPV represents a positive surplus and the solar irrigation project may be subject to the availability of funds. On the other hand, the project should not be considered or rejected for negative NPV and the funds can be profitably invested in other projects [35]. Since solar and diesel irrigation projects are mutually exclusive alternative investments, the project with the highest positive NPV should be preferred.

2.5. Thematic Analysis

Thematic analysis is regarded as a foundational method for all qualitative analyses as it is used to identify, analyze, and report patterns (themes) within data [36]. Usually, it is applied to the data gathered from interviews and focus group discussions on finding repeated patterns. Braun and Clarke [37] described the analysis in six phases: data familiarization, generating initial code, searching for themes across the data, reviewing themes, defining and naming themes, and writing themes.

This study adopted the method from Braun and Clarke [38] to determine the sociological aspect or acceptance of the farmers to solar irrigation systems for rice production. After the interview, the answers of the respondents were transcribed verbatim, then it was read and re-read several times before important initial ideas were noted. Significant features of the data were then coded, followed by collating relevant and similar answers. Themes were searched and checked several times for relation to the coded text before finally naming each of them. Finally, a repertory grid was prepared to report significant statements of the respondents.

3. Results and Discussion

3.1. Preliminary Findings

Table 1 shows the small-scale farmers' costs and fuel consumption using a diesel irrigation system based on the survey conducted at 15 farming sites. The average investment cost for this traditional irrigation system costs USD 577 per hectare with a minimum of USD 150 and a maximum of USD 2800 per hectare. This amount includes the price of the diesel generator, water pump, drilling of water source, installation costs, and the organized structure to protect the machinery from extreme weather conditions.

Table 1. Summary of costs and fuel consumption using diesel irrigation system.

Parameter	Unit	Mean	SD [1]	Max	Min
Investment cost	USD/ha	576.92	505.56	2800	150
Diesel consumption	L/ha/yr	74.55	79.48	378.54	11.36
Fuel cost	USD/ha/yr	393.86	419.92	2000	60
Maintenance and other operational costs	USD/ha/yr	475.08	1083.48	6000	50

[1] SD: standard deviation.

The farmer's fuel consumption depends on the amount of water needed by the crops, which are affected by different factors. There are two types of cropping cycles in the case country, the three-season cycle for crops that are grown and harvested for 120 days and the two-season cycle for crops that are harvested after 150 days. Results show that, on average, each farmer uses 74.55 L of diesel per hectare in all cropping seasons of the year at a minimum of 11.36 L and a maximum of 378.54 L. This variability occurs due to the proximity to the national irrigation system, weather conditions, differences in the distance from the water source, topography, and the efficiency of the pump, among others. With this, each farmer allocates an average of USD 394 per hectare annually for fuel costs, with the lowest at USD 60 and the highest at USD 2000 per hectare every year. This is in addition to other costs for operation and maintenance that can reach up to USD 6000 per hectare annually.

Compared with diesel, a solar irrigation system costs an average of USD 2100 per hectare in initial investment and USD 140 per hectare annually for its maintenance and operational costs as shown in Table 2. The investment cost includes solar PV panels, pump and controller, accessories, grounding, PV cable, installation, and mounting labor costs.

Table 2. Summary of costs using solar irrigation systems.

Parameter	Unit	Mean	SD [1]	Max	Min
Investment cost	USD/ha	2100	NA	2400	1800
Fuel cost	USD/ha/yr	0	0	0	0
Maintenance and other operational costs	USD/ha/yr	140	NA	180	50

[1] SD: standard deviation; NA: not available. Adapted from: Bencalo, et al. [39].

The solar irrigation system has no variable operational costs as it uses no fuel but runs with energy coming from sunlight. Conversely, the fixed maintenance cost accounts for the labor and transportation costs, as well as the replacement costs of a submersible water pump that needs to be replaced in 8 to 15 years, depending on the siltation and quality of the water source. The solar panel needs no maintenance except for the constant cleaning of the panels to ensure maximum capture of sunlight.

Comparing Tables 1 and 2, it can be observed that the solar irrigation system has a significantly higher investment cost but lower operational cost than a diesel irrigation system. This confirms previous studies discussing the effectiveness of solar PV in pumping water not only for irrigation but also for other purposes, while highlighting the most common disadvantage of high initial investment cost [5,40]. While the data gathered in this research confirm that this technology is 264% more expensive than its diesel counterpart, its operational and maintenance cost is relatively lower at 239% per hectare annually. This means that for the 25 years of its operation, a farmer can save an average of USD 3042/ha and up to USD 52,828/ha on maintenance costs considering the time value of money.

There are several financial investment and business models that offer different options for solar irrigation systems, such as the ones practiced for small-holder solar pump-based irrigation in Ethiopia [41], sub-Saharan Africa [42], and other developing countries across the Middle East, North Africa, and Southeast Asia [43]. When small-scale farmers share the utilization of solar irrigation systems, such as the ones established by the Department of Agriculture in several agricultural provinces, they can finance and cover the initial capital investment through sharing the costs and risks as well as sharing valuable information, knowledge, and skills regarding a more sustainable way of rice farming.

3.2. Economic Analysis

Table 3 shows the results of the economic analysis for shifting irrigation systems from diesel to solar. The results show that for every hectare, a farmer can save between USD 60 to USD 2000 with an average of USD 393.86 of fuel cost annually. If accumulated, the amount can cover the cost of the technology between USD 1800/ha to USD 2400/ha. Despite the high investment cost, results reveal that the best investment opportunity is shifting to solar with an average NPV of USD 4517/ha for the 25-year lifetime of the technology. The result favors farmers consuming a large amount of diesel with an NPV from cost savings that can reach up to USD 68,582/ha. These positive NPVs indicate a feasible investment project. On average, the implementation of the solar irrigation project increases the discounted worth of the investment by USD 4517/ha, more than the current value of the investment of USD 2100/ha. This result supports previous studies; the solar irrigation system is a viable project with a positive NPV [10,44]. Moreover, a small-scale solar irrigation system designed for the 'fees for ownership model' is more profitable than the 'fees for service model' for large and medium-scale systems [10]. On the other hand, farmers consuming less fuel to irrigate the land have lower fuel cost savings. The accumulated present value of future cost savings cannot recover the cost of the solar irrigation system resulting in a negative NPV of –USD 1255/ha; hence, the project is not feasible for these farmers.

Table 3. Economic analysis of shifting to solar irrigation system.

Economic Indicator	Unit	Average	Min	Max
Fuel cost savings	USD/ha/yr	394	60	2000
Returns on investment	%	315	30	2958
Payback period	Years	2.88	0.34	30
Net present value	USD/ha	4517	−1255	68,582

In terms of the PBP, the result shows that the value invested in a solar irrigation project can be recovered in less than a year for farmers consuming 379 L/ha/yr, 30 years for those consuming 11.36 L/ha/yr, and on average, 2.88 years of its operation. This implies that replacing the diesel-powered system with a solar pump system to perform the same average amount of irrigation output and utilization rate per hectare of land per year, can save a farmer by an average of USD 729 ha/yr (from fuel savings and other costs), which can be used to recover the cost of a solar pump system in 2.88 years considering the time value of money. This result is relatively lower compared with the 4–5 years PBP in the literature for a 1-HP solar pump replacement of diesel-powered pumps adequate to irrigate 1 hectare of land from shallow water sources, with negligible operation and maintenance, and pump replacement costs over 15 years [1,45]. This is due to our economic valuation model based on energy and cost savings from shifting from diesel to solar irrigation systems. However, considering the huge difference in diesel consumption, investment in solar irrigation systems does not favor farmers consuming less diesel fuel. Furthermore, it should be noted that the PBP and economic viability of solar irrigation systems can significantly vary with utilization factors.

The ROI, on the other hand, demonstrates a promising investment at 315% on average. This implies that, while the initial cost may be high for a small-scale farmer, the value of an investment can be recovered and quadrupled at the end of the lifetime operation of the technology. For farmers consuming a large amount of fuel, the ROI is greater by more than 2000%. These results are relatively high compared with the ROI reported in previous studies between 25 and 155% [45,46]. Again, this is due to the model based on the cost savings from shifting to solar irrigation systems. With the increasing diesel prices in the world market, cost savings also increase, making solar irrigation systems more economically viable with higher returns. On the other hand, farmers consuming less fuel have lower ROI at 30% which means that the cost savings can only recover 30% of the investment and implies that the better decision is not adopting the solar irrigation system. However, the viability is expected to increase in the next years considering the increasing fuel prices as well as falling prices of PV panels due to increasing market demand, technology learning, and more stringent policies on reducing GHG emissions [8,47].

3.3. Environmental Impact Assessment

Table 4 shows the estimation result for the avoided air pollutants and GHG emission reduction per hectare from replacing diesel with solar irrigation systems based on the responses of small-scale farmers. Assuming zero emission from a solar irrigation system, replacing a diesel-based pump reduces an average GHG emissions by 5.21 tons CO_2eq/ha annually and up to 26.50 tons CO_2eq/ha max. This is equivalent to an average of 1.87 Mton CO_2eq and a maximum of 9.5 Mton CO_2eq GHGH reductions annually given the 358,949 hectares [48] of private and outside government association-assisted irrigation systems in the case country. This result is greater than those reported in the literature; for instance, a 4.34 ton CO_2eq/ha emission reduction in the case of Odisha, India [49]. The main reason for this is the small-scale farming considered in this study with less than two hectares of agricultural land. By economies of scale, a proportionate saving in diesel fuel consumption can be gained by an increased level of agricultural production [50]. Hence, a lower level of production incurs relatively higher fuel consumption, with increased costs and GHG emissions.

Table 4. Environmental impact of using solar irrigation system.

Environmental Indicator	Unit	Average	Min	Max
GHG emission reduction	ton CO_2eq/ha/yr	5.21	0.80	26.50
Avoided air pollutants				
Carbon monoxide	g/ha/yr	149.09	22.72	757.08
Nitrogen oxides	g/ha/yr	2.98	0.45	15.14
Sulfur oxides	g/ha/yr	193.82	29.54	984.20
Particulate matter	g/ha/yr	14.91	2.27	75.71
Energy savings (diesel consumption)	L/ha/yr	74.55	11.36	378.54

Note: computed values are based on the reported annual diesel consumption. Solar irrigation system uses no fossil fuels, hence, no emissions.

In terms of air pollutants, the results demonstrate a significant volume of pollutants avoided in shifting from diesel to solar irrigation systems. These include the avoidance of 22.72–757.09 g/ha/yr CO, 0.45–15.14 g/ha/yr NO_x, 29.54–989.20 g/ha/yr, and 2.27–75.71 g/ha/yr PM. Studies show that long- and short-term exposure to these air pollutants has a different toxicological impact on humans including respiratory and cardiovascular diseases, neuropsychiatric complications, eye irritation, skin diseases, and long-term chronic diseases such as cancer [51,52]. Furthermore, air pollution is considered the major environmental risk factor in the incidence and progression of several diseases such as asthma, lung cancer, ventricular hypertrophy, Alzheimer's and Parkinson's diseases, psychological complications, autism, retinopathy, fetal growth, and low birth weight [51]. Therefore, replacing diesel-powered with solar irrigation systems avoids air pollution from the combustion of fuels, while reducing the associated health risks to farmers and the communities nearby.

Finally, in terms of energy savings, the result from Table 4 shows that a farmer can save between 11.36 L and 378.54 L with an average of 74.55 L of diesel per hectare annually after shifting to a solar irrigation system. Considering the 358,949 hectares of land not covered by the national irrigation system [48], this shift implies saving up to 136 million L of diesel demand per year in the country. Currently, the country is too dependent on imported oil from the Middle East and the Association of Southeast Asian Nations [53]. For instance, the diesel consumption of the agriculture sector rose to 1.47 million barrels in 2020 alone, which accounts for the largest share of agriculture's total oil consumption at 0.0136%. Therefore, replacing diesel with solar irrigation systems will significantly decrease the agriculture sector's oil consumption and eventually reduce the country's demand for imported diesel fuel.

3.4. Social Acceptance

Figure 1 shows the percentage of farmers who are willing and unwilling to invest USD 3600 to irrigate 1.4–2 hectares of land with a solar-powered pump system. The majority of the participants voted YES with 69% who are willing to invest in a solar irrigation system, 26% declined, while 5% postponed their investment.

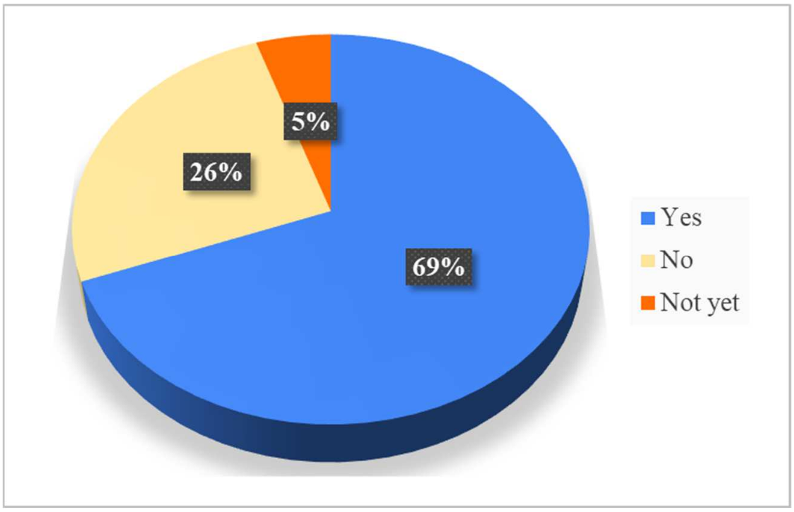

Figure 1. Respondent's willingness to purchase solar-powered irrigation system.

As shown in the repertory grid in Table 5, the primary reason for the farmers who are willing to purchase a solar irrigation system is the continuously rising diesel prices. Hence, it allows them to save fuel and other maintenance costs related to their purchase, such as labor and transportation. Moreover, the willingness of some farmers to buy complements their awareness of the advantages of owning a solar PV pump, which includes a longer life cycle, no noise pollution, and its potential to be automated or be accessed remotely. This is supported by previous studies analyzing the social acceptance of solar irrigation systems among rural farmers [1,14,54]. Along with sex and age, the factors that affect their acceptance include education, awareness, ease of use, and usefulness thereof [14]. Visibility of other co-benefits also help the decision to adopt solar irrigation systems such as the source of potable water, employment opportunity, gender empowerment, providing electricity supply, and informal social group formation [1,54].

Table 5. Repertory grid of selected farmer's responses on acceptance for solar as a replacement to diesel-powered irrigation system.

Code	Answer	Reason
F15	Yes	"This will save money for buying diesel, considering its continuously rising prices nowadays."
F29	Yes	"Solar irrigation may have a longer life span. Furthermore, we can save from fuel and other costs such as labor and transportation to buy diesel."
F12	Yes	"It can be automated which reduces the labor cost, is noise-free, and less maintenance than diesel pumps."
F1	Yes	"I am interested in buying. However, in my opinion, a solar water pump is too expensive, and I am not aware of how long it will last. If it only lasts from 5–10 years, I still prefer to use my diesel-powered pump, which I have been using for 18 years."
F32	Yes	"It is as efficient as diesel-powered pumps."
F24	No	"We do not have enough money to buy the equipment, while the price of rice in the market is very low."
F17	No	"If the tilled land area is limited just like ours, it will cost us a great deal. The solar pump is more appropriate for medium- to large-scale rice farms."
F15	No	"Most of the time, we have a supply of water from the National Irrigation System."
F8	Not Yet	"I just bought diesel pumps and therefore would wait until it needs replacement"
F28	Not Yet	"I will wait until the solar pump is as efficient as diesel in pumping water."

Question: 6. Are you willing to invest in a solar irrigation system (including system cost and installation)? Why or why not?

The same condition is true for other farmers who are willing but are quite hesitant as they are not fully informed of some facts about solar PV pumps, such as the number of years that they will last, and their efficiency compared with diesel-powered pumps. This is supported by the study on the determinants of farmers' decision to adopt solar power pumps [16], which listed perceived benefits and compatibility as the top reasons for the intention to use solar power pumps. These results play a significant role in understanding the barriers and other challenges that hinder the acceptance of solar irrigation systems among farmers. Proper information dissemination is needed to make the farmers more aware of this technology's nature, costs, advantages, and disadvantages to better help them make informed decisions on its adoption.

On the other hand, farmers who declined the purchase of solar PV pumps are aware of its benefits but refused, mainly because of its high initial cost. This supports previous claims that identified investment cost and maintenance cost as the most influencing attributes in the non-adoption of solar-powered pumps [16]. Given the small land area of their rice farm and their small profit from it, they deem it impractical to invest in a solar-powered pump. This reflects the result of our economic analysis with negative NPV, a very long payback period, and low ROI for farmers with small farm areas who consume minimal fuel for irrigation. Other farmers mentioned that they are already used to diesel-powered technology and most likely would stay using them due to familiarity. At the same time, some rely alternately on the irrigation provided by the National Irrigation System as well as the abundant rainfall during the rainy season while using pumps during summer.

Moreover, farmers mentioned postponing investment as they just bought their diesel pumps and therefore would wait until it needs replacement or solar pumps are assured to be as efficient as diesel in pumping water. It is noteworthy that no farmer provided a reason related to the benefits of solar irrigation systems to the environment. Moreover, none mentioned the importance of its potential to reduce air pollution, alleviate global warming problems, or even its health benefits. No one mentioned its potential to increase their farms' output and, by extension, their income and a potential reduction in poverty. This dramatically reflects their limited awareness of sustainability and the full benefits of this technology for financial gain and the environment. These results support previous studies that farmers do not have an in-depth awareness of the environmental impacts associated with agriculture and that they are more aware of financial sustainability than environmental and social sustainability [55,56].

4. Conclusions

Solar irrigation systems play a key role in sustainable agriculture, addressing global issues including greenhouse gas emissions, pollution, and sustainable production. An increasing number of studies are discussing the role of renewable energy technologies in agriculture from technical, economic, and environmental points of view. This study contributes to the existing literature by offering a multidisciplinary approach to analyzing the feasibility of solar irrigation from the perspective of small-scale farmers in developing countries. Using the case of the Philippines, this research applied various methodologies including economic analysis, environmental impact assessment, and social acceptance comparing the advantages of using solar over diesel-powered pump systems for irrigation.

The findings showed that solar irrigation is more expensive than its diesel counterpart in terms of initial investment. However, its maintenance and operational costs are relatively lower. Hence, farmers can save on fuel costs in its entire lifecycle. Given the volume of diesel used by farmers per hectare, results demonstrate that by shifting to solar PV, a significant amount of greenhouse gases and other air pollutants can be kept from interspersing in the air. Using the volume of agricultural consumption of diesel and the country's annual fuel demand, shifting to solar technology to irrigate rice farms can significantly increase the energy savings of the agricultural sector. The project valuation method indicates that, on average, the solar irrigation system is a good investment with its positive net present value (USD 4517/ha), profitable returns on investment (315%), and a relatively short payback period (2.88 years). However, the huge variation in costs and actual usage of diesel pumps resulted in a wide range of the analyzed indicators such as −USD 1255/ha to USD 68,582/ha net present value, 30% to 2958% returns on investment, and 0.34 to 30 years payback period. These reflect the mixed social acceptance with 69% of the marginal farmers interested in investing in a solar irrigation system, while the 26% not interested are farmers with small land areas who use minimal fuel for irrigation. While the awareness of the financial aspect of investing in irrigation systems is high, the in-depth awareness of environmental sustainability is low.

To facilitate the adoption of solar irrigation systems, results recommend the government to increase information dissemination on the advantages of using renewable energy technology, highlighting its economic and environmental benefits for more sustainable agriculture production. Subsidy and other financing schemes should be developed to assist farmers who cannot afford the initial cost of solar technology. Such financial assistance can be provided to both small-scale farmers and to cooperatives of farmers and tenants who do not benefit from the projects under the national irrigation system. Furthermore, the government should increase the incentives and funding for research and development of sustainable technologies for agriculture production to make solar irrigation systems more technologically and cost-efficient.

The main limitations of this study include the data and scope of analysis. Future studies should support economic, social, and environmental analyses with experimental data about the solar panel and the pump and the possibility of producing water powered by solar pumps for farms especially during the dry season when irrigation is necessary. Furthermore, the analysis may consider several demographic variables to enrich the discussion and make the results more meaningful. Despite the high investment cost and negative environmental impacts, other benefits of using diesel pumps should be accounted for in the analysis such as providing water for farms during all seasons of the year, and they can be rented by other farmers at any time. Further studies should be conducted to equate decision-making factors such as the cradle-to-grave emission, solar irradiance, land and water availability, water abstraction and quality, and lack of skilled farmers. For policy-making purposes, respondents of the study should be more inclusive, considering various stakeholders in agriculture production. This should be complemented by making socio-economic and environmental analyses more holistic through the inclusion of legal, policy, and technical aspects of the multidisciplinary analysis. Despite these limitations, we believe that this study can be a good benchmark for further analysis of the adoption of cleaner and more sustainable agricultural practices.

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Appendix A

Table A1. Survey questionnaire.

Socio-economic and Environmental Analyses of Solar Irrigation System
for Sustainable Agricultural Production
(Translated)

This survey aims to document the agricultural irrigation practices using diesel pumps and the preference to invest in solar irrigation system. This further aims to recommend policies to support the adoption of solar irrigation systems and to realize the government's goal of a more sustainable agriculture sector.

We kindly ask for your time to help us achieve our objectives by answering the questionnaire. Your participation in this study is voluntary and you are free to opt-out at any time. We guarantee the anonymity of the participants and that the responses will be used solely for academic purposes and not for commercial use. Before the submission for publication, we will contact you again to check whether you agree/disagree with the contents to be published.

Your cooperation is highly appreciated for the success of this research.

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Part I. Personal Information
Name: ______(optional) _____________ Location of Farm: _______________________
Part II. Agricultural Irrigation Practices

1. What is the total area of your rice farm (in sq. meters)? _______________________
2. Are you using a diesel water pump for irrigation (Yes/No)? ____________________
3. How much did you spend to buy and install the water pump? ________________
4. How much diesel do you spend to irrigate your rice farm in a year? _____________
5. Other than fuel, how much do you spend for operations and maintenance of irrigation system in a year? _____________________
6. For PHP 180 thousand (for 1.4 to 2 hectares land), are you willing to invest in a solar irrigation system (including system cost and installation)? Why or why not? ____

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