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Research Article

A framework to assess solar PV irrigation system (SPIS) for sustainable rice farming in Sorsogon, Philippines

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Abstract. Solar PV irrigation system (SPIS) has proven its potential to impact the agricultural sector. It is known for producing zero GHG emissions, and recent studies have proved its effectiveness compared to fuel-based pumps. However, some factors affecting its operations and economic viability that require further study. This study assessed the viability and sustainability of SPIS for providing rice irrigation in the province of Sorsogon, Philippines. Our objectives were to a) identify the optimal deployment locations, b) determine the most effective energy system configurations for rice irrigation, and c) assess the impact on achieving SDGs. Analysis showed that 17% of the province's total land area is suitable for SPIS deployment. A one-hectare land requires 3.302 kWh of energy per day and a water pump with a peak power of 1.1 kW. The optimal energy configuration provided an annual energy of 8,547 kWh from the Solar PV system and an additional 119 kWh delivered by the diesel generator. This setup demonstrates the lowest net present cost (NPC) of ₱ 1,079,642 and the lowest levelized cost of electricity (LCOE) of ₱ 17.79/kWh. A future SPIS project was assessed to have 27 possible synergies and 3 tradeoffs that impact achieving sustainable development goals (SDGs). The participation of stakeholders, along with local farmers, in discussions about adapting SPIS projects will help ensure the sustainability of the application and the acceptance of the technology. The findings of this study introduced new insights and understanding of the critical aspects of solar PV irrigation system applications.

Keywords: Solar PV irrigation system (SPIS), Levelized Cost of Electricity (LCOE), Net Present Cost (NPC), Sustainable Development Goals (SDGs)

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1. Introduction

Rice production in the Philippines is crucial for food security and economic stability. The country is the 7th largest producer of rice globally, contributing approximately 12.63 million metric tons in 2023 (Shahbandeh, 2023). This sector also employs a significant portion of the nation's workforce. However, the dry season significantly impacted rice production in the country since this serves as the primary food source; the effective management and utilization of irrigation systems are crucial to ensuring food security. Over the past three decades in the Philippines, the growth in the production of rain-fed rice fields has been considerably less noticeable (Stuecker *et al.*, 2018). The country has possible areas suitable for irrigated rice development, yet merely 44% of this land is currently equipped with irrigation (Regalado *et al.*, 2019). Although substantial support has been allocated to address challenges in irrigation development, there has been only a slight expansion of irrigated lands in the country (Luyun & Elazegui, 2019). According to National Irrigation Administration (NIA) data, the national irrigation system was the primary source of irrigation, covering 955,653.79 hectares. The community irrigation system covered an estimated 737,402.32 hectares. At the end of 2021, the country's irrigation development reached 65.28 percent of the anticipated total irrigable land nationally, which is 3.128 million hectares. Innovations in agricultural technology have consistently driven the increase in worldwide food production (Stuecker *et al.*, 2018). The application of motorized pumps to utilize surface water and groundwater can expand the small-scale irrigable land, benefiting local farmers increase their yield (Xie *et al.*, 2014). Local farmers have utilized fuel-based water pumps to provide adequate irrigation, particularly in areas of the province far from irrigation networks. However, due to greenhouse gas (GHG) emissions, the country will not fulfill its global commitments to reduce GHG emissions by decreasing fossil fuel-based energy production and consumption systems. Furthermore, the vulnerability of fuel-based water pumps to fluctuations in fuel prices stresses the challenges faced by the agricultural sector in transitioning to more sustainable practices. Renewable application is known for its environmental benefits, reducing dependence on fossil fuel resources (Kumar *et al.*, 2010). Solar PV technology has proven to be a suitable choice for water-pumping applications. This technology is proven to be cost-effective and more efficient than traditional diesel-fueled pumps serving small-scale and non-irrigated lands (Chandel *et al.*, 2015; Elnozahy *et al.*, 2024; Hossain *et al.*, 2015; Mohammed Wazed *et al.*, 2018). Although the increasing variability of rainfall due to climate change affects agricultural productivity in the Philippines, few studies have been conducted to determine

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the feasibility and sustainability of Solar PV irrigation systems as a feasible option to support local farmers. Although it is known for effectiveness compared to fuel-based pumps. Still, some factors affect its operations and economic viability that need further study. To understand the viability and sustainability of SPIS in providing rice irrigation, there is a need to identify the optimal locations for deployment, determine the most effective energy system setups for rice irrigation, and assess its impact on achieving SDGs.

2. Literature Review

2.1 Optimal Sites for Renewable Energy Projects

Site selection is a crucial element of energy planning. Since RE potential varies depending on geographical and climatic conditions, Spatial assessment is an essential stage of project development. It identifies the suitability of RE technology and supports the estimation of the energy output and its economic viability (Pojadas & Abundo, 2022; Rios & Duarte, 2021). Several studies have already been conducted to estimate the potential sites for RE deployment in the Philippines. Although these studies focused on expanding the electrification of on-grid and off-grid islands, studies focusing on expanding the productive use of RE in agriculture are still lacking. Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) were used as tools for evaluating viable sites for RE sources; it was also used for managing water resources and other agricultural applications (Supapo *et al*., 2021; Paul *et al*., 2020; Schmitter *et al*., 2018). In the case of the SPIS application, there is still a lack of consensus on the criteria for site selection. Although some criteria for energy generation with PV systems were also used to identify sites for SPIS, criteria such as the presence of water resources (ground and surface water) are critical factors of irrigation, extending irrigation to non-irrigated areas (Cogay *et al*., 2020; Schmitter *et al*., 2018). The distance of SPIS from areas needing irrigation is associated with the cost of infrastructure to extend the irrigation network. However, none of the studies considers the distance to non-irrigated areas as a criterion for suitability assessment. By incorporating this criterion, the prioritization of areas near non-irrigated areas in spatial analysis consider the expenses associated with infrastructure development.

2.2 Technical and Economic feasibility of RE projects

Previous researchers assessed how RE worked well for both grid-connected (Al-Shetwi *et al*., 2023; Dehghan *et al*., 2022; Gbadamosi et al., 2022; Hossein Jahangir et al., 2022; Katche *et al*., 2024; Malik *et al*., 2022; Petrollese & Cocco, 2020; Saheli *et al*., 2022) and stand-alone systems (Ashrafi Goudarzi *et al*., 2019; Dadak et al., 2022; El Hassani *et al*., 2023; Khan *et al*., 2022; Lozano *et al*., 2019; Supapo *et al*., 2024) providing energy for electricity, heating, transportation, agriculture, etc. As stand-alone or grid-connected, few studies have investigated the feasibility and technical performance of PV irrigation systems. The viability of SPIS use to provide irrigation integrated with reverse osmosis desalination (RO) to utilize brackish water was assessed by (Rezk *et al*., 2019). It was concluded that the PV, converter, and battery pumping system outperforms a standalone diesel generator (DG) and utility grid (UG) extension. The economic and technical performance of different configurations with PV systems supplying energy for transportation and irrigation were assessed by (Yan *et al*., 2023). Their findings indicate that, under high solar insolation conditions, using a PV system to pump water for agricultural areas can be the most economical choice. However, the energy from it can only provide limited transportation, whereas charging with the grid is the best option. (Sarkar & Ghosh, 2017a) evaluated the performance of SPIS in supplying agricultural irrigation in Bangladesh. Their study concluded that for irrigation loads below 4 kWh/Day, a standalone is the most efficient choice. However, a hybrid PV-Generator-Battery system is suggested for loads surpassing 4 kWh/Day, alongside a storage tank capacity under 20 kWh. Moreover, they concluded that running a diesel generator solely for irrigation is not feasible. Another study evaluated the implementation of mini-grids to supply electricity for rural areas with smallholder irrigation (Wamalwa *et al*., 2023). It was determined that the levelized cost of electricity (LCOE) could be lowered by 47% with an additional load from irrigation. (Khattak *et al*., 2024) compares the standalone and grid-connected irrigation systems across four locations. The result found that a PV integrated with the grid is the optimal energy system, allowing for both the purchase and sale of energy. To the extent of our understanding, no studies have conducted a techno-economic assessment to assess the viability of SPIS in supplying rice irrigation.

2.3. Impact of RE Projects in other SDGs

Utilizing renewable energy is highly recognized for accomplishing Sustainable Development Goal 7 (SDG7), ensuring access to affordable and clean energy. Although RE projects create beneficial interactions, conflicts can also be present in other SDG targets (Castor *et al*., 2020). Expanding on this area of interest, (Bisaga *et al*., 2021), adopted an energy-focused approach and performed an evaluation that identified 143 objectives with mutually beneficial outcomes and 65 with conflicting outcomes to SDG7 and decisions regarding energy systems. On the other hand, (Bisaga *et al*., 2021) highlighted the potential tradeoff between the land needed for crop cultivation and the establishment of solar mini-grids. RE power plants require a substantial amount of land, which can have a significant environmental impact on land use footprints (Pojadas & Abundo, 2022). Occupying large agricultural areas can have tradeoffs on food production and food security (Havrysh *et al*., 2022). In the case of water irrigation, excessive water pumping will result in water waste, causing shortages or drops in groundwater levels, threatening the ecosystem in the long run (Khattak *et al*., 2024). In the study of (Mainali *et al*., 2018), explored the adverse effects of RE in the context of developing nations in South Asia and Sub-Saharan Africa. They identified trade-offs between SDG 7 and SDG 2 (sustainable agriculture) and trade-offs in SDG 6 (clean water access), which, according to them, have implications that can vary across countries. Trade-offs raise serious concerns about the long-term effects of RE projects. Assessment is essential to address these concerns properly. Studies have already been conducted to see how SDG 7 is linked to other SDG targets in the case of electrification projects. However, the impact assessment of SPIS in achieving other SDG targets is still lacking. To the best of our knowledge, no study has offered a holistic assessment of employing SPIS for rice irrigation. This research addresses the following gaps. Firstly, our study used proximity to non-irrigated areas as a novel criterion for suitability assessment. This is associated with the cost of extending the water supply infrastructure. Making this a criterion enhances the prioritization of non-irrigated areas during spatial analysis, potentially reducing the cost of infrastructure development by selecting the nearest suitable areas. Secondly, previous studies have not yet assessed the

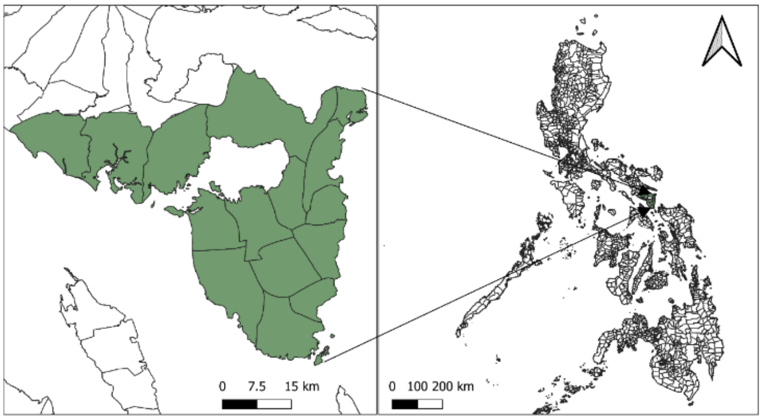


Fig. 1. Map of Sorsogon Province, Philippines

technical and economic feasibility of using SPIS to supply irrigation for rice crops; this will entail an accurate estimation of the load profile of the water pump based on the climatic conditions, soil composition, and crop season of rice planting. Lastly, the impact assessment of SPIS projects on achieving SDG targets is still lacking. It is essential to identify potential tradeoffs that may affect the sustainability of the SPIS application. Addressing the identified gaps in the existing literature, our study introduces a framework for assessing SPIS projects in the province of Sorsogon, Philippines. The findings of this study introduced new insights and understanding of the critical aspects of the technology. The section below outlines the methods applied in this study.

3. Materials and methods

3.1 Study Site

The assessment was conducted in Sorsogon Province, Philippines (12.7600° N, 123.9304° E), presented in Figure 1. It is situated at the southernmost tip of mainland Luzon, bounded by Albay Province to the northeast, Ticao and Burias pass to the northwest, the Philippine Sea to the east, and the San Bernardino Strait to the south. With a land area encompassing 2,141.44 square kilometers, Sorsogon Province boasts a coastline that spans 336 kilometers. Agriculture is vital in driving growth and inclusivity in the economic development of the province. It has an agricultural economy with rice, coconut, corn, abaca, and pili nuts as the major products. The rice fields in the province are concentrated in areas with favorable agricultural conditions, such as suitable soil, adequate water supply, or access to irrigation facilities (Balasubramanian *et al.*, 2007).

The Office of the Provincial Agriculturists of Sorsogon Province reports that non-irrigated lands in the rice sector have a total physical area of 22,498.015 hectares. Out of this, 5,872.4 hectares are used for rice production, resulting in a total production of 10,729.38 metric tons during the dry and wet seasons. The mean yield is 38,830.14 metric tons per hectare, with a collective of 5,834 farmers. Still, irrigated lands consistently maintain their lead by producing higher production than non-irrigated areas (PRiSM, 2024). This indicates that irrigation substantially enhances productivity, an issue that non-irrigated practices have not resolved over these years.

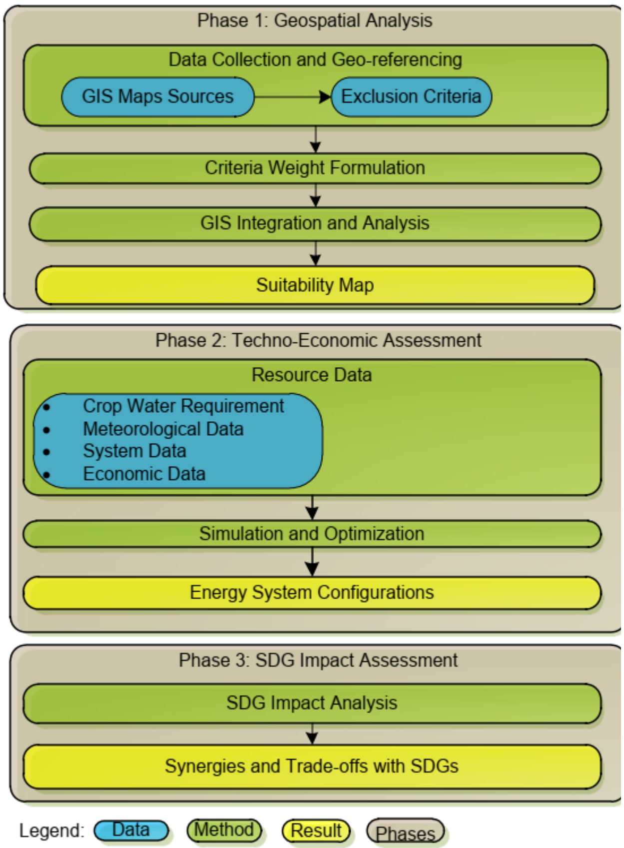


Fig. 2 Framework of the study

3.2. Framework of the study

The framework presented in Figure 2 below is designed to systematically investigate and evaluate SPIS in delivering sustainable irrigation of non-irrigated regions in the province of Sorsogon. This study consists of three phases: Phase 1-geospatial analysis; phase 2- techno-economic assessment; and Phase 3-SDG impact assessment.

3.3. Geospatial Analysis

Geospatial analysis was conducted to identify optimal sites for SPIS installation. The data needed were sourced from publicly

Table 1
Variable Constraints

Variable Constraint	Ranges of values as constraints within the factor
Land Cover	Land cover other than agriculture, grass, shrub, and bare land is not a suitable option for SPIS installation
Elevation	Elevation higher than 2.2 km above sea level
Slope	Slope greater than 15 % for irrigated agriculture
Solar Insolation	Areas with solar insolation lower than 1,300 kWh/m^2 y

Table 2
SPIS Evaluation Criteria and Layers

Data Layer	Criteria	Restriction	Category	Format	Source	Description
Resource Potential	Solar Insolation>1,300 kWh/m^2 y		Technical	Raster	SolarGIS	Energy received from the sun
Proximity to Road networks (m)	< 321 m	Infrastructure	Socio-Economic	Vector	PPDO, Sorsogon	Distance from roads, highways, paved paths, unpaved paths, etc.
Proximity to Water networks (m)	<866 m	Hydrology Environmental	Hydrology Environmental	Vector	PPDO, Sorsogon, OpenStreet, Map, Google Satellite	Lakes, rivers, reservoirs, etc.
Proximity to Non-irrigated Area	<400m	Environmental	Environmental	Raster	International Water Management Institute	Distance from Non-irrigated rice production areas
Groundwater availability	Aquifer productivity	Hydrology Environmental	Environmental	Vector	Mines and Geosciences Bureau, Philippines	Production well yield
Average Annual Temperature (°C)	<27.2	Climate	Environmental	Raster	NASA POWER, Solar GIS	Temperature is the quantitative expression of the degree of hotness or coldness
Slope (%)	<8	Topography	Technical	Raster	PPDO, Sorsogon, NAMRIA	angular measurement of the inclination of a surface typically expressed in degrees or as a percentage
Elevation (m)	>207	Topography Technical	Topography Technical	Vector	PDDO Sorsogon	The vertical distance above sea level.
Land Cover/Use	Avoid	Avoid	Ecology, Environmental	Vector	NAMRIA, PDDO Sorsogon	Residential areas, parking lots, commercial buildings, parks, gardens, and other similar locations.

available GIS databases and local sources provided by national and provincial authorities. The data layers used for the spatial analysis were based on their accessibility, application in previous studies, and relevance to SPIS deployment. The Land use constraints presented in Table 1 were employed to eliminate areas that failed to meet the constraints. Table 2 presents the evaluation criteria employed to assess the eligible sites that meet the requirements of the constraint conditions.

3.3.1 Criteria Weight Formulation

This study utilized the analytical hierarchy process (AHP) to determine the weight of the criteria. Decision-makers estimate the relative weight of the criteria through pair-wise comparisons. This approach involves contrasting pairs of factors to determine their relative importance in relation to one another based on their significance levels. The level of significance is presented in Table 3.

AHP have validation process to ensure consistency. Equations 1 and 2 outline the calculation of the CI and CR respectively.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

In the equations, λ_{max} represents the maximum eigenvalue of the comparison matrix, while "n" denotes the number of elements being compared in the matrix.

$$CR = \frac{CI}{RI} \quad (2)$$

Where, RI is the Random Consistency Index.

3.3.2. GIS Integration and Analysis

To ensure uniformity, all spatial data obtained from various sources will be standardized to the Luzon 1911 / Philippines zone IV coordinate system (EPSG:25394). The data were then compiled into an integrated geographic database compatible with QGIS version 3.34.3. The data were organized and subsequently transformed into a raster format to facilitate spatial analysis. Geospatial analysis encompassing various techniques, including surface analysis, geometric and distance operations, was utilized in this study. Following this, each criterion layer underwent a reclassification process. This involved assigning scores within the layers, which is critical for assessing land suitability based on the criteria established for the analysis. The Land Suitability Index (LSI) is determined by summing the product of the criteria and its corresponding weight (w). The LSI is calculated using Equation 3. The suitability map developed uses binary values of 0 and 1. "0" denotes unsuitable areas, while "1" denotes the suitable locations.

$$LSI=C_1*w_1+C_2*w_2+C_3*w_3+C_n*w_n\ldots\ldots \quad (3)$$

3.4 Techno-Economic Assessment

This assessment was carried out using HOMERPro software to identify the best and most cost-effective energy systems that are economically and technically viable in meeting the energy needs of crop water requirements. The inputs include solar energy potential, load demand, and technical and economic parameters. It simulates by working out energy balance equations for 8760 hours a year. The technical and economic performance indicators, including LCOE, NPC, energy production, renewable fraction, and excess energy used in this study, are discussed below.

3.4.1 Performance Indicators

3.4.1.1 Energy Production

The aggregate quantity of electrical energy generated by the power system within a span of one year. The total electrical energy generated by all system components.

3.4.1.2 Renewable Fraction (RF)

It is the metric used to measure how much renewable energy sources contribute to meeting the overall energy demand. It refers to the proportion of the load met by energy generated from RE technology; in this study, it is the energy from PV. The equation below provides the value of RF. The equation below represents E_{gen}, which indicates the annual energy production from renewable sources. E_{dem}, on the other hand, represents the total load demand.

$$RF = \frac{E_{gen}}{E_{dem}} \quad (8)$$

3.4.1.3 Excess Energy (E_{excess})

An excess of electricity has been detected in both simulated scenarios and real-world applications. The surplus electricity, which incurs no additional cost, poses significant long-term challenges. The surplus energy generated by renewable energy sources is denoted as E_{Excess}, while the yearly production of electrical energy is $E_{produce}$ both measured in kilowatt-hours per year (kWh/yr).

$$E_T = \frac{E_{excess}}{E_{produce}} \quad (9)$$

3.4.1.4 Levelized Cost of Electricity (LCOE)

The levelized cost of energy (LCOE) or COE is a metric used to determine the average cost of electricity per kilowatt-hour ($/kWh) for a given system. In order to calculate the levelized cost of electricity (LCOE), HOMER divides the annual cost of electricity production by the total electricity generation capacity. This can be determined using the equation below:

$$LCOE = \frac{C_{yearly,tot}}{E_{DC,prim}+E_{AC,prim}+E_{grid,sales}} \quad (10)$$

3.4.1.5 Net Present Cost (NPC)

This represents the total discounted value of all the expenses associated with the installation and operation of the system throughout its lifespan. The calculation considers various costs, including initial capital expenditures, replacement charges, O&M expenses, fuel prices, emissions fines, and the price of selling to or buying from the utility grid. This can be calculated using the equations below with the system's total annualized cost ((₱/yr) denoted by $C_{Yearly,tot}$. The projected lifespan (in years) is denoted by N. The real interest rate (in percent) is denoted by i. CRF is a ratio used to calculate the present value of a series of equal annual cash flows.

$$C_{NPC} = \frac{C_{Yearly,tot}}{CRN(i,N)} \quad (11)$$

$$CRF\ (i,N) = \frac{i(1+i)^N}{(1+i)^N-1} \quad (12)$$

3.4.2 Load Profiling of Water Irrigation Requirement

The total water consumption of one-hectare rice production was estimated to determine the annual energy input for the water pump. Estimation was performed using the CROPWAT software, a reliable and accurate tool in irrigation planning (Gabr & Fattouh, 2021). It was performed by considering the climatic conditions, soil composition, and the crop season of rice planting at the selected site (Gabr & Fattouh, 2021). The system design uses a 1.1-kW hollow tube well (STW) pump with a discharge capacity of 55 liters per minute and can handle a suction lift of 20 meters (Sarkar & Ghosh, 2017). The following equations were used to estimate daily load demand L_D.

$$ET_o = \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}U_2(e_a-e_d)}{\Delta+\gamma(1+0.34U_2)} \quad (13)$$

$$ET_a = ET_o * k_c \quad (14)$$

$$CWR = ET_a + S\&P_{field} \quad (15)$$

$$L_D = \frac{CWR}{30*(F_{p*60})} \quad (16)$$

Where: CWR is crop water requirement (L/month), ET_a actual evapotranspiration, ET_o reference evapotranspiration, k_c crop coefficient, $S\&P_{field}$ seepage and percolation in the field, L_D daily load demand (kWh), F_p=Flow rate of the pump (L/min)

Table 4
Technical parameters and cost used in the simulation

Parameter	Diesel Generator	Solar PV	Battery	System Converter
Initial capital (₱/Kw)	28,925	42866.85	15793.05	19437.60
Replacement cost (₱/Kw)	28,925	42866.85	15793.05	19437.60
O&M	57.85 ₱/op.hour	1446.25 ₱/yr.	344.79 ₱/yr	173.55 ₱/yr
Lifetime	15000 hours	25 years	5 years	10 years

Table 4 lists the technical elements along with unit costs used in the simulation. The cost of the components was based on (Malik et *al*., 2022) and (Javed *et al*., 2021).

3.4.3 Sensitivity Analysis

Sensitivity analysis was done to analyze how parameter uncertainty affects the performance of the SPIS. This is done to evaluate the impact of variations of factors that cannot be seen during the designing stage. Using a variety of input assumptions, this study assessed the effect of storage capacity, capital cost of PV, and fuel price on the overall cost of electricity.

3.5 SDG Impact Assessment

This study utilized the Sustainable Development Goals Impact Assessment Framework for Energy Projects (SDGs-IAE) developed by (Castor *et al*., 2020). The objective of this evaluation is to qualitatively assess the SPIS application for the province, to identify synergies and trade-offs among Sustainable Development Goal (SDG) targets within the context of SPIS applications, and to recommend possible actions to maximize the benefits of the technology for the local farmers. The subsequent questions were categorized into three areas to simplify the response process: (1) governance of the project, (2) technical aspect of the project, and (3) outcome of the project. The framework is a database accessible through a questionnaire that captures the interconnections between energy projects and the Sustainable Development Goals (SDGs) targets.

4. Results and Discussion

4.1 Geospatial Analysis

The land suitability map of Sorsogon province, as presented in Figure 3 below, was developed by applying constraints and criteria conditions. Based on the criteria evaluation through pairwise comparison using AHP, the scores for criteria weights directly indicate the significance of groundwater availability and solar insolation with 30.70% and 24.70% of weights, respectively. Groundwater availability represents a critical criterion for site selection since it will be the source of irrigation for non-irrigated areas. The groundwater availability map utilized in this study categorizes areas into high, moderate, and low water availability zones based on aquifer productivity. Solar insolation converted to electrical energy by PV systems varies based on geographical location and needs to be considered when evaluating potential sites. Proximity to open water sources (18.3%) and proximity to non-irrigated areas (14.7%) were also significant factors in evaluating optimal sites. Areas closer to the open water networks were regarded as more suitable than those situated at a greater distance from these sources. This study focused on prioritizing rice field areas that lack irrigation network access. These are rainfed areas with inadequate rainfall to supply the needed crop water requirement. In this regard, locations near the rainfed areas were priority sites for SPIS installation. Other parameters with a

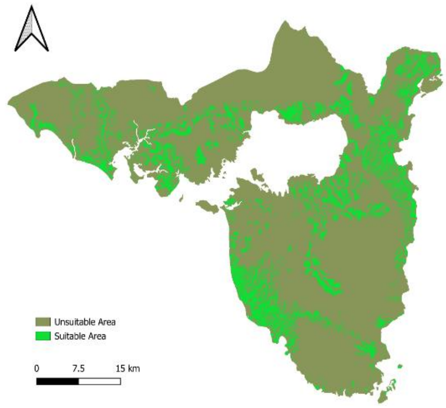


Fig. 3 Suitability Map of Sorsogon Province for SPIS Installation

lesser weight but still essential in identifying viable sites are Slope (3.60%), Elevation (3.60%), proximity to road networks (2.60%), and average annual temperature (1.90%). Since high-temperature exposure reduces the overall performance of the PV, this is also a factor in the evaluation. The slope is a crucial factor in irrigation planning; areas with steeper slopes are not advisable due to possible soil erosion. Accessible sites near access roads have lower installation costs and are prioritized to reduce equipment transport costs. These weights were used to formulate and obtain the overall land suitability score, which was overlayed on the final raster of the suitability map.

The geospatial analysis determined that municipalities with suitable locations are predominantly situated in the province's lowland regions. Non-agricultural land cover, such as forests, wetlands, and protected and urban areas, is not viable for installing SPIS. Other unsuitable areas are primarily covered in dense forests characterized by steep inclines and situated at elevations exceeding 2.2 km above sea level. Seventeen percent of the province's total land areas were identified as suitable for SPIS deployment. For the next phase, a site located in Lungib, Pilar, Sorsogon, with coordinates 123.75° longitude and 12.75° latitude evaluated to be suitable area for installing SPIS is considered in the techno-economic assessment.

4.2 Techno-Economic Assessment

4.2.1. Renewable Energy Resource Assessment

For non-irrigated crops of the site location, irrigation depends on the amount of rainfall and the water that SPIS can compensate for during insufficient rainfall. The performance of SPIS is heavily dependent on solar radiation. The Solar Energy potential of the site, as presented in Figure 4 from the NASA Prediction of Worldwide Energy Source (POWER) database, indicates a good solar irradiance, with an annual average of 5.49 kWh/m^2/day and a peak irradiance of 6.96 kWh/m^2/day during the month of April. The clearness index, which quantifies the level of visibility in the atmosphere, is 0.56, indicating good sunny conditions throughout the year.

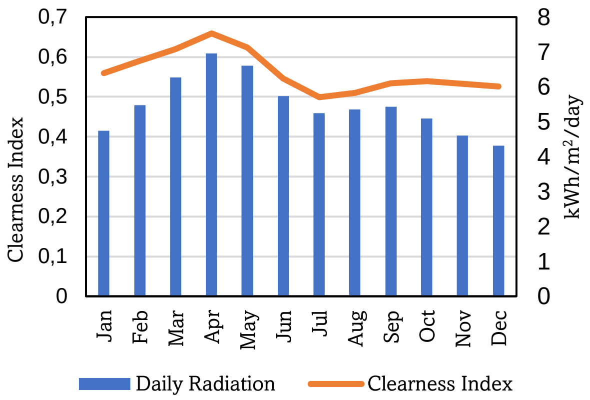


Fig. 4 Solar Energy Potential at the proposed site

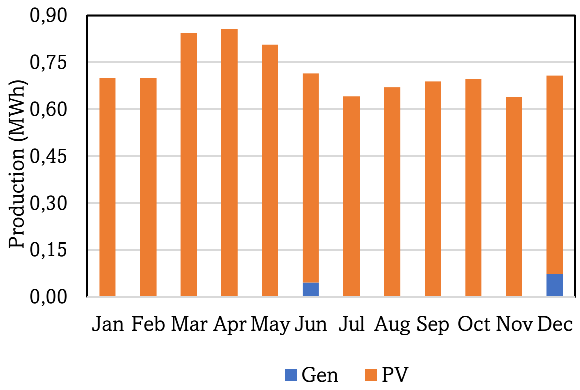


Fig. 5 Annual Energy production of System A

Rice needs to be fully irrigated in the dry season, while in the wet season, irrigation is applied supplementary to rainfall. The irrigation for rice planting in the province has two cropping seasons: the wet season, which runs from May to September, and the dry season, which spans from November to March (PRiSM, 2024). Due to the province's intermittent rainfall, an additional 0.5 kWh/day load was added for supplementary irrigation. The annual average required for irrigation is 3.86 kWh/day.

4.2.2 Technical Analysis

Using HOMER software, 1,167 solutions were simulated, 867 of which were feasible, and 300 were infeasible due to capacity shortage constraints. The water irrigation system for one hectare of the identified site is designed to have a 200 kWh water storage capacity, consumes 3.302 kWh of energy per day, and has a peak power of 1.1 kilowatts. The most efficient systems were selected after evaluating various feasible system configurations. The four best system configurations were considered in the discussion. These configurations provided cost-effective energy to meet the load demand of the irrigation pump. Based on the result shown in Table 5, the viable configurations are as follows: A—PV-Diesel Generator, B—PV-Diesel Generator-Battery, C—PV-Battery, D- Diesel Generator, and E- Diesel Generator- Battery. These configurations are ideal for locations with limited access to the power grid, which is more advantageous in rural areas of the province.

Based on the optimization result, configuration A is the most cost-effective system in meeting the energy demand of the water pump. The energy production from this system is presented in Figure 5, which shows that the output from solar PV exhibits significant monthly variations attributed to fluctuations in weather conditions. The months with higher solar PV production also coincide with the periods of higher system demand, particularly during the dry season, when there is insufficient or no rainfall. The annual energy provided by Solar PV in this setup is 8,547 kWh and 119 kWh delivered by the diesel generator.

Table 5
Technical Attributes of the System Configurations

System Configuration	Energy Production (kWh/yr)	RE Frac (%)	Excess Elec (%)
A	8665.47	90.2	85.36
B	8637.48	90.71	85.3
C	11424.61	100	88.76
D	1210.4	0	0
E	1210.4	0.04	0

System configuration A has a diesel generator that compensates for the additional energy requirement for the months of June and December when the output power of the PV panels is inadequate to meet energy demand. Based on the computed energy requirement, these months have irrigation loads of 19.18 kWh and 18.58 kWh, respectively. Additional energy is used to offset the large energy requirement of paddy rice in preparation for the demand for cultivation. Configuration B generated an annual energy output of 8,511 kWh from solar PV, 126.48 kWh from the diesel generator, and a battery discharge of 8.82 kWh. Configuration C has an output of 11,424.61 kWh solely from solar PV and battery storage discharge energy of 94.4 kWh. B and C configurations are designed to store excess energy in batteries and discharge it when solar PV output is insufficient. This allows continuous operation when low solar irradiance and can supply energy when needed. However, in these cases, the battery cannot accommodate the significant excess electricity from solar PV generated throughout the year. As the frequency of charging and discharging cycles decreases, the overall capacity demand for the battery storage system may also decrease. Configuration C has a capacity shortage of 1.1 kWh, indicating that PV and battery only present in the system cannot feed the required load consistently, and no diesel generator will serve as a backup power source. In the case of configurations D and E, the water pump relies solely on a diesel generator with 1,210 kWh of energy output, consuming 353 liters of fuel annually. Configuration E has an additional expense because of the additional battery component, which only discharges 0.6 kWh of energy. These are the least cost-effective among the feasible configurations identified. Also, additional expenses are associated with the transportation of fuels, maintenance, and repairs for these systems if installed in rural areas. On the other hand, these setups ensure no excess electricity and unmet load. They can produce electricity only during irrigation demand, resulting in no surplus power. Since water irrigation is a deferrable load, it does not require a continuous and accurate timing of energy supply; the supply can be delayed until it becomes accessible, provided that the system has an adequate water storage tank. Water supply will only be needed during insufficient or no rainfall. On the contrary, solar PV is known to be a primary contributor to excess electricity in hybrid energy

Table 6
Cost details of the System configurations

Configuration	NPC (₱)	Capital Cost (₱)	Yearly O&M (₱/yr)	Yearly Fuel cost(₱/yr)	LCOE (₱/kWh)
A	1,079,642	270,024	14,822	2,087	18
B	1,136,790	284,994	14,960	1,990	19
C	2,092,618	610,202	15,968	0	35
D	4,655,347	23,140	70,022	21,197	77
E	4,731,249	39,743	70,374	21,197	78

systems because of its continuous power conversion of solar energy. As indicated in Table 5, while configurations A, B, and C, with solar PVs, have the highest renewable energy fraction, they are expected to generate a substantial surplus of electricity. Therefore, strategies for managing excess electricity are needed to improve the productive use of solar energy, which is practical from both economic and technical perspectives. Even though expanding the battery capacity is one solution to address the excess electricity of the SPIS application, the expansion cost must be weighed against its benefits since this will increase the life cycle cost of the system. A secondary application of energy can be a feasible solution to reduce the surplus power, but this will require proper planning and management on how energy will be used other than for irrigation purposes.

4.2.3 Economic Analysis

The HOMER software simulates different energy configurations and identifies the most feasible systems based on economic parameters. The optimization results in Table 6 indicate that configuration A is the most cost-effective system configuration. Although this setup has a high capital cost, it demonstrates the highest return on investment at 27%, the shortest payback period of 3.3 years, and the lowest levelized cost of electricity. This configuration exhibits lower capital cost than configurations B and C due to the absence of a battery system, which speeds up the return on investment and reduces the overall system cost.

Configuration A has the lowest net present cost, with a breakdown of cost components presented in Figure 6. It is associated with the initial capital cost of the system components such as solar PV, converter, and diesel generator. Solar PV has the most significant portion of the system's capital cost among the components. While diesel generator contributes only a small portion of the capital cost, it has the highest operating and maintenance costs, requiring regular servicing, parts replacement, and attention to ensure reliable performance. Furthermore, the cost of fuel contributes substantially to the overall net present cost, making it a critical factor in the economic feasibility of the system. During simulation, Homer software assumes a linear component decline in the value of system components proportional to their remaining life. Based on the result, the diesel generator has a negative salvage value of ₱ 58,117.19, and the system converter with ₱ 24,660.62 through its lifetime.

System configurations B and C are equipped with batteries, contributing to their high capital cost. This further highlights the significant impact of batteries on overall expenses. Configuration C has the highest capital cost primarily due to the substantial upfront costs of PV and costs associated with the initial purchase and replacement of batteries. Lastly, configurations D and E, which use purely diesel generators as a source of energy, have the lowest initial investment costs. However, they incur higher operating, maintenance, and fuel expenses throughout their operational lifetime.

4.2.4 Environmental Analysis

The CO_2 emissions were estimated during the simulation to assess the system configuration's environmental impact. Figure 7 represents the number of pollutants released by the systems, highlighting the environmental effects of the energy production approaches. The existence of non-renewable sources in the system leads to more significant carbon emissions, which are a direct result of the combustion of diesel generators. The emission reduction of Configuration A is 90.15 %, while Configuration B achieves a reduction of 90.61%. Configuration C has a 100% RE fraction among the feasible energy systems, produces zero CO_2 emissions.

Configurations A and B have produced emissions from diesel generators, which is due to periods with higher demand filling in the insufficient supply of solar PV. Systems A produces energy from diesel generators, demonstrating 91.05 kg/yr of CO_2 emission, consuming 34.8 liters of fuel annually.

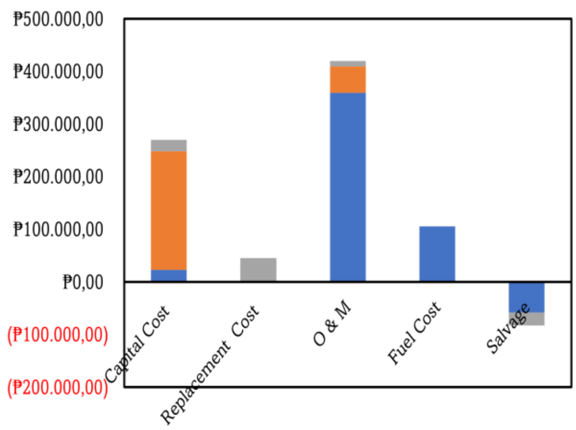


Fig. 6 Net present cost breakdown of System A

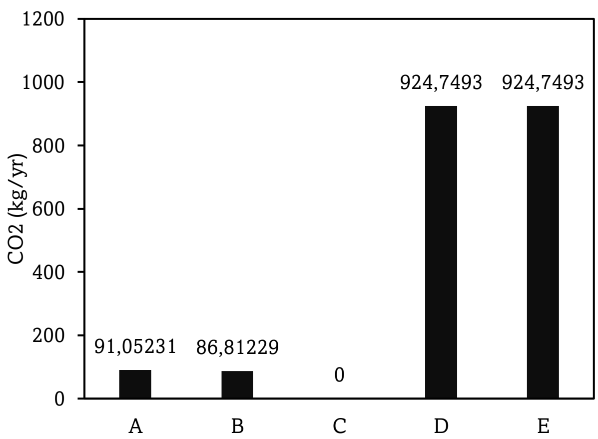
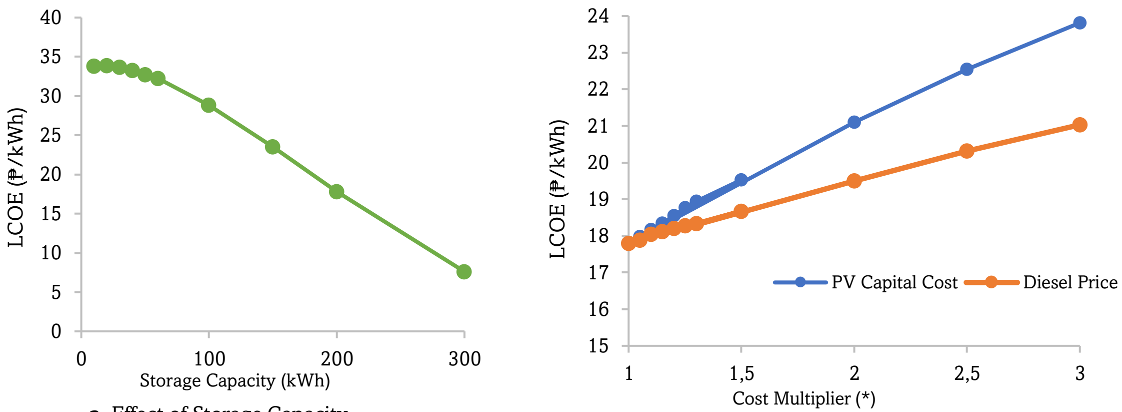


Fig. 7 Yearly emission of CO2



a. Effect of Storage Capacity

b. Effect of Capital Cost of PV and Diesel Price

Fig. 8 Effect on Levelized Cost of Electricity

Meanwhile, system B produces 86.8 kg/yr of CO_2 from the 33.7 L fuel consumption of diesel generators. On the other hand, systems D and E only have a diesel generator to run the water pump, producing 924.75 kg/yr of CO_2 from consuming 353 liters of fuel annually. Solar PV applications enhance environmental sustainability by significantly reducing the quantities of greenhouse gases produced by fuel-based generators. Since Diesel fuel has a substantial impact on atmospheric contamination, the application of solar PV significantly reduces emissions decreasing dependency on diesel engines.

4.2.5 Sensitivity Analysis

Figure 8.a shows the effect of increasing the capacity of the storage tank on the overall cost of electricity. The tank can be filled using excess electricity from solar PV, which can help optimize energy usage. Increasing the capacity of the water tank will reduce the overall cost of electricity by utilizing more of the surplus power. However, managing the tank's capacity carefully is needed to avoid excessive water extraction if it exceeds the irrigation needs. The storage tank is designed to meet water demand during times when solar PV energy is either unavailable or insufficient to supply the required load.

Despite the high initial expenses, the long-term cost savings potential of solar PV installation, with its low maintenance cost, highlights the financial benefits of this technology. Based on the sensitivity analysis result shown in Figure 8.b, the increase in the cost of PV arrays will significantly increase the cost of electricity. For configurations that use a large portion of energy output coming from PV, increasing the capital cost of PV will have a more significant impact than increasing diesel price. However, for configurations that use diesel generators as a backup energy supply when solar PV does not meet the load demand, the increase in diesel price will also influence the overall cost of electricity. In the case of relying solely on a diesel generator, the increase in fuel cost will significantly impact the overall cost of rice production.

4.3 SDG Impact Assessment

Based on the assessment result, the SPIS project was identified to have twenty-seven possible synergies and three tradeoffs, as presented in Figure 9. With respect to GHG emissions, the reduction of reliance on diesel generators means disassociating economic growth from environmental degradation through the process of reducing climate change caused by CO2 emissions. Upgrading to a more cost-effective and environmentally

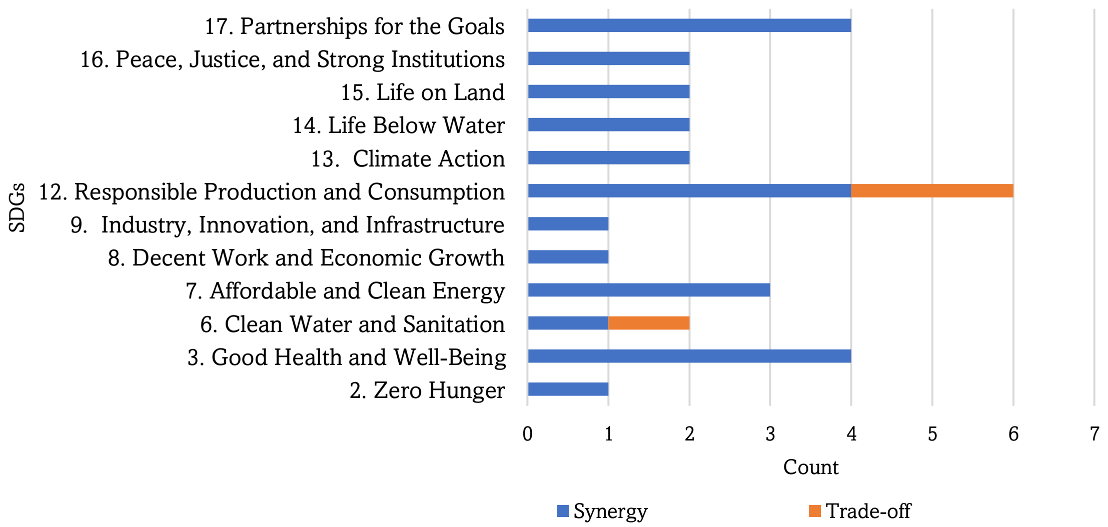


Fig.9 Impact Assessment result

friendly process of using groundwater and surface water for irrigation, the application of SPIS is a synergy of improving the current practice of traditional water pumps. A possible tradeoff with sustainable use of natural resources could happen without proper water withdrawal management. Continuous extraction of groundwater and surface water will affect the natural ecosystem. Addressing this challenge, excess electricity can be used for other agricultural tasks, like powering farm equipment. In addition, it can be used to supply electricity to nearby communities for their daily energy needs. A proper management plan is needed to decommission project wastes at the end of their lifespan. LGU needs a proper management plan for dealing with possible waste from this technology. The participation of stakeholders, along with local farmers, in the discussion of adapting SPIS projects will help ensure the sustainability of the application and acceptance of the technology. Furthermore, project transparency and information will enhance its success.

5. Conclusion

The implementation of SPIS can significantly impact non-irrigated regions of the province during times when rainfall is insufficient. A suitability map was developed using geospatial analysis, identifying seventeen percent of the province's total land area suitable for SPIS deployment. These areas are predominantly situated in the lowland regions. A techno-economic assessment was conducted to determine economic viability and find the best and most cost-effective energy systems. The viable configurations include PV-Diesel Generator, B—PV-Diesel Generator-Battery, C—PV-Battery, D-Diesel Generator-Battery, and E- Diesel Generator. Assessing the economic viability, solar PV with a small amount of energy from a Diesel Generator system is the most economical and optimal choice, with ₱ 17.79/kWh and ₱ 1,079,642 of levelized cost of electricity (LCOE) and net present cost (NPC), respectively. However, systems with Solar PVs have the highest excess electricity due to the continuous supply of energy, even in times when the rice fields do not need irrigation. This excess electricity can be diverted to other agricultural applications, such as running agricultural equipment. It can also be used for alternative purposes, such as providing it to neighboring residents to fulfill their daily energy consumption. An assessment was conducted for the SPIS project to identify the broadest impact of its application towards achieving SDGs. The assessment identified twenty-seven possible synergies and three tradeoffs. A possible tradeoff with sustainable use of natural resources could happen without proper water withdrawal management. Continuous groundwater and surface water extraction will affect the natural ecosystem in the long run. The participation of stakeholders, along with local farmers, in the discussion of adapting SPIS projects will help ensure the sustainability of the application and the acceptance of the technology.

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References

Al-Shetwi, A. Q., Atawi, I. E., Abuelrub, A., & Hannan, M. A. (2023). Techno-economic assessment and optimal design of hybrid power generation-based renewable energy systems. *Technology in Society*, 75. https://doi.org/10.1016/j.techsoc.2023.102352

Ashrafi Goudarzi, S., Fazelpour, F., B. Gharehpetian, G., & Rosen, M. A. (2019). Techno-economic assessment of hybrid renewable resources for a residential building in tehran. *Environmental Progress and Sustainable Energy*, 38(5). https://doi.org/10.1002/ep.13209

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities. In *Advances in Agronomy*, 94, 55–133. https://doi.org/10.1016/S0065-2113(06)94002-4

Bisaga, I., Parikh, P., Tomei, J., & To, L. S. (2021). Mapping synergies and trade-offs between energy and the sustainable development goals: A case study of off-grid solar energy in Rwanda. *Energy Policy,* 149. https://doi.org/10.1016/j.enpol.2020.112028

Castor, J., Bacha, K., & Fuso Nerini, F. (2020). SDGs in action: A novel framework for assessing energy projects against the sustainable development goals. *Energy Research and Social Science*, 68. https://doi.org/10.1016/j.erss.2020.101556

Chandel, S. S., Nagaraju Naik, M., & Chandel, R. (2015). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. In Renewable and *Sustainable Energy Reviews,* 49, 1084–1099. Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.04.083

Cogay, S. C., Bayron, R. R., Cantones, R. V, Cogay, S. C., & Amplayo, I. P. (2020). GIS-Based Land Suitability Analysis for Solar Powered Irrigation System in Non-Irrigated Rice Production Areas of Davao Del Norte. *Southeastern Philippines Journal of Research and Development,* 47. https://doi.org/10.53899/spjrd.v25i1.45

Commer Soc Sci, P. J., Tariq Majeed, M., & Luni, T. (2019). Standard-Nutzungsbedingungen: Renewable Energy, Water, and Environmental Degradation: A Global Panel Data Approach. *Pakistan Journal of Commerce and Social Sciences*, 13(3). https://hdl.handle.net/10419/205276

Dadak, A., Mousavi, S. A., Mehrpooya, M., & Kasaeian, A. (2022). Techno-economic investigation and dual-objective optimization of a stand-alone combined configuration for the generation and storage of electricity and hydrogen applying hybrid renewable system. *Renewable Energy*, 201, 1–20. https://doi.org/10.1016/j.renene.2022.10.085

Dehghan, H., Pourfayaz, F., & Shahsavari, A. (2022). Multicriteria decision and Geographic Information System-based locational analysis and techno-economic assessment of a hybrid energy system. *Renewable Energy*, 198, 189–199. https://doi.org/10.1016/j.renene.2022.07.147

El Hassani, S., Oueslati, F., Horma, O., Santana, D., Moussaoui, M. A., & Mezrhab, A. (2023). Techno-economic feasibility and performance analysis of an islanded hybrid renewable energy system with hydrogen storage in Morocco. *Journal of Energy Storage*, 68. https://doi.org/10.1016/j.est.2023.107853

Elnozahy, A., Abdel-Salam, M., & Abo-Elyousr, F. K. (2024). Optimal techno-economic energy coordination of solar PV water pumping irrigation systems. *Energy,* 288. https://doi.org/10.1016/j.energy.2023.129817
Gabr, M. E., & Fattouh, E. M. (2021). Assessment of irrigation management practices using FAO-CROPWAT 8, case studies: Tina Plain and East South El-Kantara, Sinai, Egypt. *Ain Shams Engineering Journal,* 12(2), 1623–1636. https://doi.org/10.1016/j.asej.2020.09.017
Gbadamosi, S. L., Ogunje, F. S., Wara, S. T., & Nwulu, N. I. (2022). Techno-Economic Evaluation of a Hybrid Energy System for an Educational Institution: A Case Study. *Energies,* 15(15). https://doi.org/10.3390/en15155606
Havrysh, V., Kalinichenko, A., Szafranek, E., & Hruban, V. (2022). Agricultural Land: Crop Production or Photovoltaic Power Plants. *Sustainability (Switzerland),* 14(9). https://doi.org/10.3390/su14095099
Hossain, M. A., Hassan, M. S., Mottalib, M. A., & Hossain, M. (2015). Feasibility of solar pump for sustainable irrigation in Bangladesh. International *Journal of Energy and Environmental Engineering*, 6(2), 147–155. https://doi.org/10.1007/s40095-015-0162-4
Hossein Jahangir, M., Bazdar, E., & Kargarzadeh, A. (2022). Techno-economic and environmental assessment of low carbon hybrid renewable electric systems for urban energy planning: Tehran-Iran. *City and Environment Interactions*, 16. https://doi.org/10.1016/j.cacint.2022.100085
Javed, M. S., Ma, T., Jurasz, J., & Mikulik, J. (2021). A hybrid method for scenario-based techno-economic-environmental analysis of off-grid renewable energy systems. *Renewable and Sustainable Energy Reviews,* 139. https://doi.org/10.1016/j.rser.2021.110725
Katche, M. L., Makokha, A. B., Zachary, S. O., & Adaramola, M. S. (2024). Techno-Economic Assessment of Solar–Grid–Battery Hybrid Energy Systems for Grid-Connected University Campuses in Kenya. *Electricity,* 5(1), 61–74. https://doi.org/10.3390/electricity5010004
Khan, F. A., Pal, N., Saeed, S. H., & Yadav, A. (2022). Modelling and techno-economic analysis of standalone SPV/Wind hybrid renewable energy system with lead-acid battery technology for rural applications. *Journal of Energy Storage*, 55. https://doi.org/10.1016/j.est.2022.105742
Khattak, S., Yousif, M., Hassan, S. U., Hassan, M., & Alghamdi, T. A. H. (2024). Techno-economic and environmental analysis of renewable energy integration in irrigation systems: A comparative study of standalone and grid-connected PV/diesel generator systems in Khyber Pakhtunkhwa. *Heliyon,* 10(10). https://doi.org/10.1016/j.heliyon.2024.e31025
Kumar, A., Kumar, K., Kaushik, N., Sharma, S., & Mishra, S. (2010). Renewable energy in India: Current status and future potentials. *Renewable and Sustainable Energy Reviews*,14(8), 2434–2442). https://doi.org/10.1016/j.rser.2010.04.003
Lozano, L., Querikiol, E. M., Abundo, M. L. S., & Bellotindos, L. M. (2019). Techno-economic analysis of a cost-effective power generation system for off-grid island communities: A case study of Gilutongan Island, Cordova, Cebu, Philippines. *Renewable Energy,* 140, 905–911. https://doi.org/10.1016/j.renene.2019.03.124
Luyun, R. A., & Elazegui, D. D. (2019). Issues on communal irrigation systems in the Philippines. 2019–2026. https://pidswebs.pids.gov.ph/CDN/PUBLICATIONS/pidspn1907.pdf
Mainali, B., Luukkanen, J., Silveira, S., & Kaivo-Oja, J. (2018). Evaluating synergies and trade-offs among Sustainable Development Goals (SDGs): Explorative analyses of development paths in South Asia and Sub-Saharan Africa. *Sustainability (Switzerland),* 10(3). https://doi.org/10.3390/su10030815
Malik, P., Awasthi, M., & Sinha, S. (2022). A techno-economic investigation of grid integrated hybrid renewable energy systems. *Sustainable Energy Technologies and Assessments,* 51. https://doi.org/10.1016/j.seta.2022.101976
Mohammed Wazed, S., Hughes, B. R., O'Connor, D., & Kaiser Calautit, J. (2018). A review of sustainable solar irrigation systems for Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews,* 81, 1206–1225. https://doi.org/10.1016/j.rser.2017.08.039
Paul, M., Negahban-Azar, M., Shirmohammadi, A., & Montas, H. (2020). Assessment of agricultural land suitability for irrigation with reclaimed water using geospatial multi-criteria decision analysis. *Agricultural Water Management*, 231. https://doi.org/10.1016/j.agwat.2019.105987
Petrollese, M., & Cocco, D. (2020). Techno-economic assessment of hybrid CSP-biogas power plants. *Renewable Energy*, 155, 420–431. https://doi.org/10.1016/j.renene.2020.03.106
Philippine Rice Information System (PRiSM), https://prism.philrice.gov.ph/dataproducts/. (accessed April 20, 2024)
Pojadas, D. J., & Abundo, M. L. S. (2022). A spatial cost-benefit-externality modelling framework for siting of variable renewable energy farms: A case in Bohol, Philippines. *Renewable Energy,* 181, 1177–1187. https://doi.org/10.1016/j.renene.2021.09.114
Regalado, M. J. C., Yadav, S., Samoy-Pascual, K., De Dios, J. L., Evangelista, G. K., Rafael, M. L., Dorado, J., & Cabangon, R. J. (2019). Irrigation advisory service: A comprehensive solution toward sustainable water management for rice production in the Philippines. *2019 ASABE Annual International Meeting*. https://doi.org/10.13031/aim.201900677
Rezk, H., Abdelkareem, M. A., & Ghenai, C. (2019). Performance evaluation and optimal design of stand-alone solar PV-battery system for irrigation in isolated regions: A case study in Al Minya (Egypt). *Sustainable Energy Technologies and Assessments*, 36. https://doi.org/10.1016/j.seta.2019.100556
Rios, R., & Duarte, S. (2021). Selection of ideal sites for the development of large-scale solar photovoltaic projects through Analytical Hierarchical Process – Geographic information systems (AHP-GIS) in Peru. *Renewable and Sustainable Energy Reviews,* 149. https://doi.org/10.1016/j.rser.2021.111310
Saheli, M. A., Lari, K., Salehi, G., & Azad, M. T. (2022). Techno-economic assessment of a hybrid on grid PV-wave system: A case study in Caspian Sea. Renewable Energy, 186, 596–608. https://doi.org/10.1016/j.renene.2021.12.146
Sarkar, M. N. I., & Ghosh, H. R. (2017). Techno-economic analysis and challenges of solar powered pumps dissemination in Bangladesh. *Sustainable Energy Technologies and Assessments,* 20, 33–46. https://doi.org/10.1016/j.seta.2017.02.013
Schmitter, P., Kibret, K. S., Lefore, N., & Barron, J. (2018a). Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa. *Applied Geography*, 94, 41–57. https://doi.org/10.1016/j.apgeog.2018.02.008
Shahbandeh, M., "Leading countries based on the production of milled rice in 2022/2023." Statista. https://www.statista.com/statistics/255945/top-countries-of-destination-for-us-rice-exports-2011/ (accessed April 20, 2024)
Stuecker, M. F., Tigchelaar, M., & Kantar, M. B. (2018). Climate variability impacts on rice production in the Philippines. *PLoS ONE*, 13(8). https://doi.org/10.1371/journal.pone.0201426
Supapo, K. R. M., Lozano, L., & Querikiol, E. M. (2024). Performance Evaluation of an Existing Renewable Energy System at Gilutongan Island, Cebu, Philippines. *Journal of Engineering*, 2024, 1–19. https://doi.org/10.1155/2024/3131377
Supapo, K. R. M., Lozano, L., Tabañag, I. D. F., & Querikiol, E. M. (2021). A geospatial approach to energy planning in aid of just energy transition in small island communities in the Philippines. *Applied Sciences (Switzerland),* 11(24). https://doi.org/10.3390/app112411955
Wamalwa, F., Maqelepo, L., & Williams, N. (2023). Unlocking the nexus potential: A techno-economic analysis of joint deployment of minigrids with smallholder irrigation. *Energy for Sustainable Development*, 77. https://doi.org/10.1016/j.esd.2023.101345
Xie, H., You, L., Wielgosz, B., & Ringler, C. (2014). Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management,* 131, 183–193. https://doi.org/10.1016/j.agwat.2013.08.011
Yan, Y., Wang, Y., Yan, J., Liu, Z., Liao, Q., & Wang, B. (2023). Tech-economic modeling and analysis of agricultural photovoltaic-water systems for irrigation in arid areas. *Journal of*

Environmental Management, 338. https://doi.org/10.1016/j.jenvman.2023.117858