Design and implementation of solar pump irrigation systems for the optimization of irrigation and increase of productivity

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Abstract. The irrigation solar water pump system is a technological innovation using water pumps that are more efficient and economical. The aims of this study are: (1) to design an efficient solar pump irrigation system for shallots and red chili, and (2) to measure the irrigation efficiency of the solar pump irrigation system. The configuration of the solar water pump irrigation system should be determined on the basis of (1) the pump performance curve, (2) the irrigation system performance curve and (3) the pump discharge and the operating pressure curve. Our results show that the operational duration of the pump for 7.59 hours/day in Playen Sub-District, Gunungkidul was able to irrigate 2,333 m$^2$, while in Imogiri Sub-District, Bantul a regime of 5.42 hours/day could irrigate 3,630 m$^2$. Irrigation techniques using Impact Sprinklers for shallots and Streamlines for red chili, when combined with mulch could increase the growth and yield of shallots and red chili crops compared to the patterns and methods practiced by farmers. The efficiency of the solar water pump irrigation system should be further improved by a more detailed calculation of water supply pumping power calculation in order to increase the planting capacity of farm.

1. Introduction

The main problem of agricultural development on dry land is the limited availability of water, especially in the dry season. One of the solutions to increase land productivity is by providing water for supplementary irrigation through optimizing the potential of existing water resources in the region. Farmers who are using water for supplementary irrigation often use pumps, both electric pumps and fuel pumps. The use of water pumps that are driven by electricity or fossil fuels results in environmental damage due to high carbon dioxide emissions, which significantly contribute to global warming [1]. When viewed from the financial side, both in the development and maintenance stages, this irrigation technology creates problems at the field level, especially for farmers and farmer groups, as they often face difficulties in operating and maintaining their irrigation facilities and infrastructure. Therefore, it is necessary to find and develop a model of irrigation technology that is both energy-efficient and water-efficient.

Since not all lands have electrical energy infrastructure due to remote location constraints and/or limited electricity supply and/or high fuel prices, solar energy can become the solution to drive pumps. Solar power pumps take advantage of free solar radiation as an energy source for irrigation [2]. According to BMKG data, the potential for solar radiation in Indonesia is quite large, with an average radiation intensity of 4.8 kWh/m$^2$/hour equivalent to 112,000 GWp (Giga Wattpeak) throughout the year. However, the utilization has only reached 5 MWp (Mega Wattpeak), so that it can be optimized for the supply of electricity for irrigation which is expected to be able to meet the needs for irrigation as solar power pumps have been developed [3].

Utilization of solar energy has various advantages, including: (1) this energy is available in large quantities in Indonesia, (2) it strongly supports national energy policies regarding energy savings,
diversification, and equity, (3) it can be installed in remote areas because it does not require energy transmission and transportation of energy sources [4]. Solar cells are an active element that converts sunlight into electrical energy. Solar cells generally have a minimum thickness of 0.3 mm, made of a slice of semiconductor material with a positive pole and a negative pole. The basic principle of solar cells is to take advantage of the photovoltaic effect, which can directly convert sunlight into electrical energy. This principle was first discovered by Bacquere, a French physicist in 1839. When a metal is exposed to light in the form of photons with a specific frequency, the kinetic energy of the photon will shoot at the metal atoms. The irradiated metal atoms will release electrons. These free electrons flow a certain amount of current. Solar cells are semiconductors in which solar radiation is converted directly into electrical energy.

Solar water pumps are easy to use, and provide a high efficiency, stable performance and can be used for a long time [2]. Solar power pumps are generally composed of several main lines, namely: solar cells as an absorber of solar energy that can be used as electrical energy, controlling storage and use of electrical power through a Solar Charge Controller, batteries to store electrical energy and supply electrical energy to loads, Inverters convert DC to AC currents [5]. Utilizing solar power to drive a water pump will reduce greenhouse gas emissions. Greenhouse gases from anthropogenic emissions come from several sources, including from the energy sector: excessive use of fossil fuels such as petroleum, coal, and gas in various activities is the leading cause of the release of greenhouse gas emissions into the atmosphere. Energy plays a critical role in people's lives because energy is an essential parameter for economic development and growth. Almost all sectors of life (industry, transportation, household, services, etc.) are inseparable from energy. In the household sector, energy is used for lighting, cooking, cooling, or heating as well as using vehicles for daily activities. Currently, more and more household appliances use energy for their utilization, thus increasing the emissions produced. In agriculture, the use of pumps for irrigation also uses premium types of fuel [6] and [7]. The purpose of this research is to design a Solar Pump Irrigation System (SIPTS) that should be able to save water and energy and to estimate the irrigation efficiency of SIPTS.

2. Materials and Methods

2.1. Materials and Tools
The materials used are (1) materials for the manufacture of solar-powered pumps (solar panels, Solar Charge Controller (SCC), Master Circuit Board (MCB), dry batteries, inverters, power dividers, lighting lamps, installed electric power used in the pump assembly solar power, (2) materials for irrigation installations to build irrigation networks that are directly connected to solar-powered pumps (PVC pipes, streamlined hoses, impact sprinkler heads, TLTOs, ball valves, vol sox, elbows, tees, water torn, water meters), (3) field experiments for planting shallots and red chilies used for field experiments on irrigation efficiency (seeds, fertilizers, pesticides, etc.).

We used (1) a set of tools for assembling a solar power pump in the form of an electronic control device, (2) a set of tools for measuring plants in the form of meters, plastics, scales, and calipers, (3) a set of tools for measuring soil in the form of a ring sampler, and (4) a computer set [8].

2.2. Methods
The stages of the activity are carried out as follows: (1) analysis and design of a Solar Pump Irrigation System (SIPTS), (2) installation of the irrigation system, and (3) analysis of irrigation efficiency for shallot and red chili plants.

2.2.1. Analysis and design of SIPTS
A. Analysis of potential determination of SIPTS service area
Analysis for the determination of the potential area were implemented in two SIPTS locations, namely Playen District, Gunungkidul Regency, and Imogiri District, Bantul Regency, Yogyakarta Province. These were carried out by calculating the operational duration of the pump based on the solar power
pump based on: (1) specifications for solar panels, (2) specifications for dry batteries, (3) specifications for pumps, and (4) current consumption of pumps and inverters.

B. Design of various SIPTS models

The components of a solar water pump are divided into four, namely: (1) solar panels, (2) solar charge controllers, (3) inverters, (4) water pumps, and (5) water reservoirs [8]. To design a solar water pump, it is carried out through the following stages:

1. Electrical power requirements by calculating the following components:
   - Electric water pump voltage
   - Installed electric water pump power
   - The time the water pump runs
   - The volume of the water reservoir to be filled
   - The area to be irrigated
   - Electric power required by the water pump

2. The specifications for the solar panel electrical installation being installed require the following components:
   - Solar panels
   - Solar Charge Controller (SCC)
   - Master Circuit Board (PCB)
   - Dry battery
   - Sinusoidal inverter
   - Electric divider
   - Lighting
   - Installed power

3. Calculate power requirements

The need for electric power to start an electric pump is calculated using the following formula:

\[ LP = P \times V \times t \]  \hspace{1cm} (1)

where:
- \( LP \) : load pump electric power (watt)
- \( P \) : power (watt)
- \( V \) : voltage (volt)
- \( T \) : time of using the solar panel system (hour)

The total power required for pumps and other components, namely the solar charge controller and inverter, is added by about 20% of the power load so that the total power required is calculated using the following formula:

\[ TP = LP + (20\% \times LP) \]  \hspace{1cm} (2)

The calculation of the electric power installed in the field is calculated from the battery size (voltage and current) and the maximum duration of irradiation a day. The following is the formula for calculating the electrical power installed in the field:

\[ IP = A \times V \times LR \]  \hspace{1cm} (3)

where:
- \( IP \) : installed power (watt hour)
- \( A \) : battery current (Ampere hour)
- \( V \) : battery voltage (volt)
- \( LR \) : maximum length of radiation in a day (hour)

The time required for charging the battery from a solar panel installed with the effective time of solar radiation intensity is presented in the following formula:

\[ D_{in} = SP \times max Rad \]  \hspace{1cm} (4)

where:
- \( D_{in} \) : battery charge time (hour)
The time requirement to fill the water reservoir is calculated by observing the real time for filling the pump from the pump capacity (pump discharge) of the solar radiation pump, or by calculating the pump flowrate through the following equation:

\[ TP = \frac{WR}{Q_p} \]  

where:
- \( TP \): pump charge time (hours)
- \( WR \): water reservoir volume (liter)
- \( Q_p \): solar radiation pump discharge (liter/minute)

The total volume of water that can be lifted by the pump at the location, assuming the existing equipment can start the pump for 5 hours, can be calculated using the following equation:

\[ V_{wp} = WR \times PT \]  

where:
- \( V_{wp} \): the volume of water from the pump (liter)
- \( WR \): water reservoir volume (liter)
- \( PT \): intensity of water reservoirs filled during pump switching on (assuming 5 hours)

The time it takes to fill a water reservoir with a capacity of 20 liters per minute, it can be calculated the time (T) needed to fully fill the water reservoir.

\[ T = \frac{3000}{20} = 150 \text{ minute } = 2.5 \text{ hours} \]

2.2.2. Irrigation system installation

A. Installation of irrigation networks in the field

Field testing to test the ability of a solar water pump to function as a substitute for conventional energy for irrigation was carried out in the field at the 2 locations mentioned above. The irrigation network to be developed is adjusted to the needs of the crops to be planted.

For Imogiri District, an impact sprinkler was installed for irrigation of shallot plants, and for Playen District a streamlined drip irrigation hose was installed [9].

B. Observation of pump discharge

After installing the irrigation system connected to SIPTS, the discharge is observed. Observation of the discharge is carried out by turning on the pump in the normal battery position, counting from the water out until the water does not come out, then the water production time is calculated from starting to flow until it runs out.

Flow validation is done by measuring the flow directly by taking water from its source (rivers, wells, etc.) using a pump directly to the irrigation pipe without going through a reservoir. Furthermore, volume measurements were carried out at several points/holes in the irrigation pipe where water was discharged in several sample plots according to the set time target.

2.2.3. Implementation of solar water pumps for plant irrigation

A. Analysis of plant water requirements (irrigation dosage and interval)

The dose of plant irrigation needs was calculated based on the FAO Method [10]. This method calculates the water requirements of the plant by considering the physical characteristics of the soil and the depth of roots at each phase of plant growth.

The optimization of the irrigation interval was analyzed based on the comparison between the net irrigation need (NID) for each plant growth phase and the cumulative plant evapotranspiration.

Plant evapotranspiration is calculated based on the following equation:

\[ ET_c = K_c \times ET_o \]  

where:
- \( ET_c \): plant evapotranspiration (mm/day)
- \( ETo \): reference evapotranspiration (mm/day)
- \( Kc \): crop coefficient

To calculate plant evapotranspiration, we followed several stages:
• Identify the stage of plant growth, determine the length of each growth period and choose the \( K_c \) that corresponds to the growth period.
• Calculate \( K_c \) in the middle of the growth period based on daily climatic conditions using the following equation:

\[
K_{cmid} = K_{cmid(Tab)} + \left[ 0.04(U_2 - 2) - 0.004(RH_{min} - 45) \right] \left[ \frac{h}{3} \right]^{0.3}
\]

where,
- \( K_{cmid(Tab)} \): the value of \( K_c \) at the middle of the growth period is based on the table
- \( U_2 \): daily average wind speed during the middle of the plant growth period (m/s)
- \( RH_{min} \): daily average minimum relative humidity (%)
- \( h \): plant height during the middle of the plant growth period (m)
• Determine a crop coefficient curve that can determine the \( K_c \) value for each growing period.

The optimal irrigation interval is determined if the cumulative ETP of daily plants is less or equal to the net irrigation need.

B. Field test for irrigation efficiency
Field test in Bleberan village, Pluyen district, Gunung Kidul regency, Yogyakarta Special Region
Field testing was carried out to measure the performance of solar water pump technology of several types and component specifications for irrigation [9].

With the power of the solar panels that have been installed, the volume of water available per day is calculated, so the available water is used for crop irrigation. Irrigation volume and interval are adjusted to plant needs, as the treatment aims to determine the effect of water efficiency factors on the growth of red chili plants.

The experimental design was a two-factor randomized block design. The principle of factorial experiments in two-factor randomized block design is the same as a single-factor randomized design in terms of randomization and layout unless there is a combination of treatments. After the experimental units are grouped into a number of groups, the treatment combinations are then randomly assigned to the experimental units in each group.

For two-factor factorial experiments, A (4 levels) and M (2 levels) were experimented, each of which will form 8 treatment combinations.

In detail, the treatment applied consists of 2 factors, namely:
1) A: Irrigation consisting of conventional irrigation (A0) and recommended irrigation with 3 levels, namely 85% irrigation (A1), 70% irrigation (A2), and 55% irrigation (A3) of water requirements for chili plants according to FAO.
2) Mulch which consists of 2 levels, namely with mulch (A1) and without plastic mulch (A0)

The treatments combinations that were repeated 4 times were as follows:
1. A0M0 = conventional irrigation + without mulch
2. A0M1 = conventional irrigation + with mulch
3. A1M0 = Recommended 85% + irrigation without mulch
4. A1M1 = Recommended 85% + irrigation with mulch
5. A2M0 = Recommended irrigation 70% + without mulch
6. A2M1 = Irrigation recommendation 70% + with mulch
7. A3M0 = Irrigation recommendation 55% + without mulch
8. A3M1 = Irrigation recommendation 55% + with mulch

The provision of irrigation in accordance with the needs of the plants is calculated based on ETP data and groundwater results are available from soil physics analysis. At the level of 85%, it means that only 85% of water is supplied from the needs of plants, 70% irrigation means that only 70% of the water needs are added and 55% means that only 55% of water is added from the needs of plant water. To facilitate the provision of irrigation, this irrigation volume is then converted into units of time [9].

Field test in Kedungmiri village, Imogiri district, Bantul regency, Yogyakarta
With the power of the solar panels that have been installed, the volume of water available per day is calculated, so the available water is developed for crop irrigation. Irrigation volume and interval are adjusted to the needs of the plant, for the treatment applied aims to determine the effect of water efficiency and mulching on rainfed land [9].

The design used was a two-factor RAK factorial which was repeated 5 times, the combination of treatments:

1. A₀M₀ = conventional irrigation + without mulch
2. A₀M₁ = conventional irrigation + with mulch
3. A₁M₀ = Recommended 85% + irrigation without mulch
4. A₁M₁ = Recommended 85% + irrigation with mulch
5. A₂M₀ = Recommended irrigation 70% + without mulch
6. A₂M₁ = Irrigation recommendation 70% + with mulch
7. A₃M₀ = Irrigation recommendation 55% + without mulch
8. A₃M₁ = Irrigation recommendation 55% + with mulch

C. Observation of plant growth and yield
Observations of chili plant growth in Playen include (1) plant height, (2) canopy width, (3) number of flowers, (4) number of chilies carried out at the age of 4 to 10 weeks after planting (WAP). The harvest observations in Playen include the number and weight of chilies carried out 85 days after planting (DAP), 92 DAP, 99 DAP, 106 DAP, 113 DAP, and 120 DAP in Playen. As for the harvest in Purabaya 90 DAP and 100 DAP.

Observations of shallot plant growth include: (1) plant height, (2) number of tillers, (3) number of tubers, (4) tuber diameter carried out at 4-10 WAP. Meanwhile, harvest observations include tuber weight (wet weight and dry weight) carried out at 70 DAP [9].

D. Analysis of the effect of treatment on growth and yield
To determine the effect of irrigation and mulch treatments on growth and harvest parameters, analysis of variance was carried out using the F test. To find out the differences between treatments using the Tukey test at the 5% significance level.

3. Results and Discussion

3.1. Analysis and design of SIPTS

3.1.1. Determination of potential area of SIPTS services
Analysis was carried out by calculating the operational duration of the pump based on the PTS components installed, namely: (1) solar panel specifications, (2) dry battery specifications, (3) pump specifications, and (4) current consumption of pumps and inverters [9].

The locations of Imogiri District, Bantul Regency are presented in Tables 1 and 2, and for Playen District, Gunungkidul Regency, they are presented in Tables 3 and Table 4.

| Parameter                  | Unit  | Symbol | Value |
|----------------------------|-------|--------|-------|
| Solar Cell Specification   |       |        |       |
| Watt Peak (WP)             | Watt  | W      | 100   |

Table 1. Analysis of pump operational duration in Playen district, Gunungkidul regency, Yogyakarta
| Parameter                                      | Unit   | Symbol | Value |
|-----------------------------------------------|--------|--------|-------|
| Irrigation System                             |        |        |       |
| Type                                          |        |        | Streamline |
| Merk                                          |        |        | Netafim |
| Operational Pressure: Minimum                 | Bar    | b      | 1.7   |
| Operational pressure: Maximum                 | Bar    | b      | 4.1   |
| Distance Between Emitter Points               | meter  | m      | 0.2   |
| Discharge Capacity                            | liter per hour | l/h   | 1.00  |
| Rotation, Duration dan Effective Irrigation Area |        |        |       |
| Distance Between Planting Lines               | meter  | m      | 0.60  |
| Emitter Coverage Area                         | meter square | m²  | 0.12  |
| Emitter Discharge Capacity                    | liter per hour | l/h   | 1.00  |
| Pump Discharge Capacity                       | liter per second | l/s   | 0.45  |
| Number of Emitter Points per Irrigation Rotation |   point |        | 1,620.0 |
| Effective Irrigation Area per Irrigation Rotation | meter square | m²     | 194.4 |
| Peak Irrigation Dose                          | millimeter per day | mm/day | 5.02 |
| Water Requirements Volume per Irrigation Rotation | meter cubic | m³     | 0.98 |
| Irrigation Duration per Irrigation Rotation   | minute | min   | 36.1  |
| Maximum Pump Operation Duration               | hour   | J      | 7.6   |
| Total Number of Irrigation Rotations          | rotation | R     | 12    |
| Total Effective Irrigation Area               | meter square | m²     | 2,333 |

Table 2. Effective irrigation area in Playen district, Gunungkidul regency, Yogyakarta

| Parameter                                      | Unit   | Symbol | Value |
|-----------------------------------------------|--------|--------|-------|
| Pump Specification                            |        |        |       |
| Type                                          | -      | -      | Centrifugal |
| Merk                                          | -      | -      | Shimizu PS-230BIT |
| Voltage/Hz                                     | Volt/Hz | V/Hz | 220/50 |
| Motor Output Power                             | Watt   | W     | 200   |
| Head                                          | meter  | m     | 15    |
| Optimal Discharge                              | liter per second | l/s   | 0.45  |
| Pump and Inverter Current Consumption          | Watt   | Maximum | 200 |
| Inverter Internal Power Estimated              | Watt   | W     | 20    |
| Total System Power                             | Watt   | W     | 220   |
| Total current consumption of 12 V battery      | Ampere | A     | 18.33 |
| Optimal Pump Operation Duration                | Hour/Day | h/d  | 7.59  |

Table 3. Analysis of pump operational duration in Imogiri district, Bantul regency, Yogyakarta

| Parameter                                      | Unit   | Symbol | Value |
|-----------------------------------------------|--------|--------|-------|
| Solar Cell Specifcation                       |        |        |       |
| Watt Peak (WP)                                | Watt   | W     | 100   |
Electric Current at Maximum Power Ampere A 5.8
Optimal Radiation Duration for Battery Charging Hour h 3
Average Daily Capacity Amper Hour Ah 17.4
Number of Panel Unit 20
Current Capacity Total Ampere Hour Ah 348
Dry Battery Specification
Battery Current Ampere Hour Ah 100
Battery Power Volt DC VDC 12
Number of Battery Power Unit 10
Battery Capacity Total Ampere Hour Ah 1000

| Pump Specification |
|--------------------|
| Type               | -              | Submersible |
| Merk               | -              | Grundfos SP3A 12 |
| Voltage/Hz         | Volt/Hz        | 230/50 |
| Motor Output Power | Watt           | 750 |
| Head               | meter          | 50 |
| Optimal Discharge  | liter per second | 1.00 |

Pump and Inverter Current Consumption
Pump Power (input) Watt Maximum 750
Inverter Internal Power Estimated Watt W 20
Total System Power Watt W 770
Total current consumption of 12 V battery Ampere A 64.17

| Optimal Pump Operation Duration |
|--------------------------------|
| Hour/Day                       | h/d 5.42 |

Results from the analysis of the optimal duration of pump operation show that in Playen District, Gunungkidul Regency the operational duration is 7.59 hours/day with an effective irrigation area of 2,333 m², while in Imogiri District, Bantul Regency 5.42 hours/day with an effective irrigation area of 3,630 m² [9].

3.1.2. SIPTS various design

Figure 1 presents two models of solar pump irrigation systems installed in two locations, namely: (1) Bleberan village, Playen district, Gunungkidul regency, Yogyakarta Special Region, and (3) Kedungmiri hamlet, Sriharjo village, Imogiri district, Bantul regency, Special Region of Yogyakarta. Table 5 presents the design of the solar pump irrigation system with its specifications [8].

![Imogiri, Bantul, Yogya (4500 watt)](image1)
![Playen, Gunungkidul, Yogya (1500 watt)](image2)

**Figure 1.** Two design of solar pump irrigation systems at two locations

| Table 4. Effective irrigation area in Imogiri District, Bantul Regency, Yogyakarta |
|-----------------------------------------------|
| Parameter | Unit | Symbol | Value |
| Effective irrigation area | | | |
Irrigation System

| Type                          | Impact Sprinkler |
|------------------------------|-----------------|
| Inlet Pipe Diameter          | Rainbird 2045 PJ |
| Operational Pressure: Minimum| bar              |
| Operational pressure: Maximum| b               |
| Irrigation Coverage Diameter: Minimum| meter |
| Discharge Capacity: Minimum  | liter per second |
| Discharge Capacity: Maximum  | liter per second |

Rotation, Duration dan Effective Irrigation Area

| Sprinkler Irrigation Coverage Diameter | meter | m |
|----------------------------------------|-------|---|
| Sprinkler Effective Irrigation Area    | meter square | m² |
| One Unit Sprinkler Effective Irrigation Area | meter square | m² |
| Distance Between Sprinklers            | meter | m |
| Sprinkler Discharge Capacity            | liter per second | l/s |
| Pump Discharge Capacity                 | liter per second | l/s |
| Number of Sprinkler Units per Irrigation Rotation | unit |
| Effective Irrigation Area per Irrigation Rotation | meter square | m² |
| Peak Irrigation Dose                    | millimeter per day | mm/day |
| Water Requirement Volume per Irrigation Rotation | meter cubic | m³ |

Irrigation Duration per Irrigation Rotation

| Maximum Pump Operation Duration | hour | min |
|---------------------------------|------|-----|
| Total Number of Irrigation Rotations | rotation | Rot |
| Total Effective Irrigation Area  | meter square | m² |

Table 5. Design of a solar pump irrigation system with specifications of its constituent components

| No | Name                              | Playen, Gunung Kidul | Imogiri, Bantul |
|----|-----------------------------------|----------------------|-----------------|
| 1  | Installation Date                 | 26-7-2015            | 1-9-2015        |
| 2  | Solar panel (w/unit)              | 100/8                | 100/20          |
| 3  | Solar charge control/SCC (Amp/unit)| 20/1                 | 20/5            |
| 4  | Master Circuit Board/MB (Amp/unit)| 10-50/3              | 20-30/2         |
| 5  | Dry battery (Amp/volt DC/unit)    | 150/12/3, 200/12/1   | 100/12/10       |
| 6  | Inverter sinusoidal (vA/volt AC/unit)| 1500/220/1         | 6000/220/1      |
| 7  | Electric divider (unit)           | 1                    | 1               |
| 8  | Electric power required by the pump (watt) | 1500               | 4500            |
| 9  | Installed electric power (watt jam/Ah)| 7800/650          | 12.000/1.200    |
| 10 | The ability of the generator power to turn on the pump / long time the water pump is running (hour) | 10 | 6 |
| 11 | Potential area of irrigation targets alternately (ha) | 2-3 | 3-5 |
| 12 | Irrigation Design                 | Streamline           | Impact Sprinkler |

3.2. Installation of irrigation system

3.2.1. Installation of irrigation networks in the field

The irrigation network design installed in the field is adjusted to the commodity to be planted. For Imogiri Subdistrict, an impact sprinkler has been installed for irrigation of shallot plants, while for Playen District a streamlined hose is installed for drip irrigation for red chili plants.

In Figures 2 and 3, the design and installation of solar-powered pump irrigation with streamlined irrigation techniques for the development of red chili plants in Playen District, Gunungkidul Regency is presented. The design and installation of SIPTS with impact sprinkler irrigation techniques for the development of shallot plants in Imogiri District, Bantul Regency are presented in Figures 4 and 5 [9].
Figure 2. SIPTS design using streamlined irrigation technique in Playen district, Gunungkidul regency

Figure 3. SIPTS installation using streamlined irrigation technique in Playen district, Gunungkidul Regency

Figure 4. Design of SIPTS with impact sprinkler irrigation technique in Imogiri district, Bantul regency
3.2.2. Observation of pump discharge

Observation of the pump discharge is carried out by turning on the pump in the normal battery position, calculated from starting the water to come out until the water does not come out. In Table 6, the results of the optimal duration of the pump operation are presented [8].

| Number | Location                                      | The optimal duration of the pump operation (hours/day) |
|--------|-----------------------------------------------|------------------------------------------------------|
| 1      | Bleberan Village, Playen District, Gunungkidul Regency, Yogyakarta | 7.5                                                  |
| 2      | Sriharjo Village, Imogiri District, Bantul Regency, Yogyakarta       | 5.2                                                  |

3.3. Implementation of solar water pumps for plant irrigation

3.3.1. Field Test in Bleberan village, Playen district, Gunungkidul regency, Yogyakarta Special Region

The land area used was 1,800 m² recommended treatment and 600 m² farmer treatment, with TM 99 chili commodity with a total of 26 recommended treatment plots and 6 farmer treatment plots. Each plot measures 10 m x 6 m. Plant spacing 60 cm x 70 cm.

Results of analysis of irrigation needs for irrigation (dose and interval) of chili plants were carried out using the FAO equation [10] with available water input data calculated based on the results of analysis of soil physics samples at the research location in Bleberan Village, Playen District, Gunungkidul Regency, are presented in Tables 7 and 8. The calculation of the optimal total irrigation interval for chili cultivation is presented in Table 9.
Table 7. Soil physics analysis to calculate water available in Playen

| Growth Stage       | Length of Growing Phase (Day) | Period       | ETo (mm/day) | Kc  | ETc (mm/day) | Water Content (%) | Type Density (g/cm³) | Water available (%) |
|--------------------|--------------------------------|--------------|--------------|-----|--------------|-------------------|----------------------|---------------------|
| Initiation         | 30                             | 19-Jul-16    | 17-Aug-16    | 3.6 | 0.6          | 2.16              | 33.4                 | 20.3                | 1.27               | 16.6               |
| Vegetative         | 40                             | 18-Aug-16    | 26-Sep-16    | 3.9 | 0.9          | 3.32              | 67.6                 | 33.2                | 1.27               | 10.6               |
| Flowering          | 40                             | 27-Sep-16    | 5-Nov-16     | 3.9 | 0.4          | 4.68              | 33.4                 | 20.3                | 1.27               | 16.6               |
| Seed               | 25                             | 6-Nov-16     | 30-Nov-16    | 3.7 | 0.8          | 2.96              | 33.4                 | 20.3                | 1.27               | 16.6               |

Table 8. The calculation of irrigation water requirements of chili plants in Playen

| Growth Stage       | Length of Growing Phase (Day) | Period       | ETo (mm/day) | Water available (%) | Maximum Depth of Root (m) | Total Water available (%) | Groundwater Decrease Fraction (p) | Net Irrigation Requirement (mm) | Irrigation Interval (Day) |
|--------------------|--------------------------------|--------------|--------------|---------------------|--------------------------|---------------------------|----------------------------------|---------------------------------|--------------------------|
| Initiation         | 30                             | 19-Jul-16    | 17-Aug-16    | 3.6                 | 0.35                     | 58                        | 23                               | 11                             |
| Vegetative         | 40                             | 18-Aug-16    | 26-Sep-16    | 3.9                 | 0.45                     | 74                        | 30                               | 9                              |
| Flowering          | 40                             | 27-Sep-16    | 5-Nov-16     | 3.9                 | 0.55                     | 91                        | 36                               | 8                              |
| Seed               | 25                             | 6-Nov-16     | 30-Nov-16    | 3.7                 | 0.7                      | 116                       | 46                               | 16                             |

Table 9. Calculation of total irrigation dose and average irrigation interval of chili cultivation in Playen

| Growth Period  | Days after Planting | Irrigation Dose (mm) | Average Irrigation Volume (m³) |
|----------------|--------------------|----------------------|-------------------------------|
| Planting       | 0                  | 2,107                | 0.253                         |
| Vegetative-1   | 1-30               | 63,205               | 0.253                         |
| Vegetative-2   | 31-70              | 141,535              | 0.404                         |
| Flowering      | 71-110             | 182,092              | 0.546                         |
| Seed Formation | 111-135            | 72,423               | 0.348                         |
| Total Average  |                    | 461,362              | 0.361                         |

The results of the analysis of the dose and irrigation interval using the FAO method show that the total need for irrigation in the land is 461,362 mm in the irrigation interval every one day with an average of 2.1-4.6 mm [9].

The results of research [11] indicate that the application of drip irrigation systems in dry margin land in Bekasi area, where environmental factors are considered as limiting factor for chili cultivation, the result shows that the two-day water supply interval is the recommended water supply interval to be applied in areas with limited water sources. However, this location still has land potential that can be developed for chili cultivation.

A. The effect of irrigation and mulch levels on the growth of chili plants
During the growth period of chilies, the height of the chilies did not show a significant difference at 4 weeks after planting (WAP) and 7 WAP in both the irrigation and mulching treatment levels. Differences
in plant height began to appear at 10 WAP along with flowering time and early fruit formation, though. Plant height in general is not significantly different. The highest plants were found in the 85% irrigation treatment with mulching and significantly different from other treatments (Table 10). This condition indicates that the growth of chilies will be better if it is given adequate irrigation and mulching so that the provision of water as much as 85% of available water is reached [9].

Table 10. The effect of irrigation and mulch treatment on the height of chili plants at 4, 7, and 10 WAP in Bleberan Village, Playen District, Gunungkidul Regency

| Treatment     | Plant height I (4 WAP) | Plant height II (7 WAP) | Plant height III (10 WAP) |
|---------------|------------------------|-------------------------|---------------------------|
|               | cm                     | cm                      | cm                        |
| A0M0          | 31.0 A                 | 50.5 A                  | 76.5 B                    |
| A1M1          | 31.0 A                 | 52.6 A                  | 80.6 AB                   |
| A1M0          | 35.7 A                 | 55.4 A                  | 70.8 B                    |
| A1M1          | 35.3 A                 | 60.9 A                  | 89.6 A                    |
| A2M0          | 34.5 A                 | 52.6 A                  | 74.7 B                    |
| A2M1          | 34.4 A                 | 53.6 A                  | 76.3 B                    |
| A3M0          | 33.9 A                 | 51.8 A                  | 71.6 B                    |
| A3M1          | 33.6 A                 | 50.3 A                  | 73.7 B                    |

Note:
A0M0 = farmer irrigation without mulch
A0M1 = farmer irrigation without mulch
A1M0 = 85% irrigation without mulch
A1M1 = 85% irrigation with mulch
A2M0 = 70% irrigation without mulch
A2M1 = 70% irrigation with mulch
A3M0 = 55% irrigation without mulch
A3M1 = 55% irrigation with mulch

In general, in Figure 6 it can be seen that mulching has no effect on plant height at the age of 4 to 7 WAP, the height difference only occurs at the age of 10 WAP.

Figure 6. Trend of chili plant height in irrigation and mulching treatment in Playen District, Gunungkidul Regency

B. Effect of irrigation and mulch levels on flowering and formation of chili fruit
The irrigation treatment at 47 DAP did not show any difference, but at 70 DAP there was a significant difference. It can be seen that mulching is very effective for flower formation, it is shown in each treatment of mulching which has a relatively higher number of flowers than without mulch at various
levels of irrigation. The highest interest was found in the 85% irrigation treatment with mulching (Table 11). Thus providing irrigation at a level of 85% is efficient when combined with mulching.

**Table 11.** Effect of irrigation and mulch treatment on the number of flowers of chili plants at 7 and 10 MST in Bleberan Village, Playen District, Gunungkidul Regency

| Treatment | Flowering I | Flowering II |
|-----------|-------------|-------------|
|           | 7 WAP       | 10 WAP      |
| A0M0      | 8 A         | 43 ABCD     |
| A0M1      | 9 A         | 50 A        |
| A1M0      | 11 A        | 33 D        |
| A1M1      | 15 A        | 53 A        |
| A2M0      | 13 A        | 38 BCD      |
| A2M1      | 14 A        | 45 ABC      |
| A3M0      | 9 A         | 36 CD       |
| A3M1      | 12 A        | 48 AB       |

Note: The numbers followed by the same uppercase or lowercase letters in the same column do not differ at the 5% level according to the DMRT test.

The number of chilies at 7 WAP has shown a difference, giving 85% irrigation can trigger chilies growth that is more optimal than other treatments, even if the irrigation is combined with mulching it will show better results [9].

C. Effect of irrigation and mulch treatment on chili yield

Chili yields are presented by observing chili weight. Harvesting is effective 6 times. The analysis showed that the harvest at 12 and 13 MST still did not show any real results. The significant difference in yield was shown after the chilies were 14 WAP. Starting at the age of 14 MST until the 6th harvest at 17 MST, mulching can give better results than without mulching although it does not show a significant difference. This is indicated by the higher number and weight of chilies compared to the treatment without mulch (Table 12). Based on the overall yields, it shows that 85% of irrigation with mulching shows the best results. Thus, providing water for chilies will be more efficient if it is given as much as 85% of the available water by applying mulch [9].

**Table 12.** The weight of chilies in the 1st to 6th harvest (12, 13, 14, 15, 16, 17 MST) in Bleberan Village, Playen District, Gunungkidul Regency

| Treatment | Weight I | Weight II | Weight III | Weight IV | Weight V | Weight VI |
|-----------|----------|-----------|------------|-----------|----------|-----------|
|           | 12 WAP   | 13 WAP    | 14 WAP     | 15 WAP    | 16 WAP   | 17 WAP    |
| A0M0      | 2.6 A    | 14.5 A    | 30.7 B     | 44.5 B    | 42.8 B   | 73.0 ABC  |
| A0M1      | 4.7 A    | 22.8 A    | 52.8 AB    | 85.6 AB   | 97.8 A   | 73.0 A    |
| A1M0      | 1.7 A    | 18.5 A    | 30.0 B     | 41.8 B    | 34.2 B   | 17.1 C    |
| A1M1      | 5.5 A    | 26.8 A    | 64.7 A     | 130.6 A   | 103.8 A  | 67.4 AB   |
| A2M0      | 3.1 A    | 19.7 A    | 32.8 B     | 36.7 B    | 31.4 B   | 26.2 C    |
| A2M1      | 5.4 A    | 19.9 A    | 47.4 AB    | 70.3 AB   | 59.4 AB  | 24.4 C    |
| A3M0      | 4.6 A    | 16.5 A    | 24.9 B     | 55.6 B    | 29.1 B   | 22.5 C    |
| A3M1      | 5.9 A    | 19.7 A    | 38.5 AB    | 59.7 AB   | 67.6 AB  | 31.2 BC   |

Note: The numbers followed by the same uppercase or lowercase letters in the same column do not differ at the 5% level according to the DMRT test.

3.3.2. Field test in Sriharjo village, Imogiri district, Bantul regency, Yogyakarta Special Region

The land area used was 3,800 m² of experimental treatment and 700 m² of farmer treatment, with the commodity Tajuk variety of shallots with a total of 30 recommended treatment plots and 6 farmer
treatment plots. Each plot measures 11 m x 11 m. Plant spacing 20 cm x 20 cm. The field trial plot layout is presented in Figure 7.

The results of the analysis of irrigation needs for irrigation (dose and interval) of shallot plants were carried out using the FAO equation [10] with available water input data calculated based on the results of the analysis of soil physics samples at the research location in Sriharjo Village, Imogiri District, Regency, Bantul. The results of the analysis are presented in Tables 13 and 14. The calculation of irrigation dose and the average irrigation interval for shallot cultivation is presented in Table 15.

**Table 13.** Soil physics analysis to calculate water available at Imogiri

| Growth Stage | Length of Growing Phase (Day) | Period | ETo (mm/day) | Kc | ETc (mm/day) | Water Content (%) | Type Density (g/cm³) | Water available (%) |
|--------------|--------------------------------|--------|--------------|----|-------------|-------------------|---------------------|-------------------|
| Initiation   | 10                             | 25-May-16 | 3-Jun-16     | 3.2| 0.7         | 2.3               | 35.4                | 23.7              |
| Vegetative   | 20                             | 4-Jun-16  | 23-Jun-16    | 3.3| 0.9         | 2.9               | 146.7               | 29.3              |
| Tuber Formation Ripening | 15                        | 24-Jun-16 | 8-Jul-16     | 3.1| 1.2         | 3.7               | 35.4                | 23.7              |
| Harvesting   | 5                              | 9-Jul-16  | 18-Jul-16    | 3.2| 1.2         | 3.7               | 35.4                | 23.7              |
|              |                                | 19-Jul-16 | 23-Jul-16    | 3.3| 0.5         | 1.7               | 35.4                | 23.7              |

**Table 14.** The calculation of irrigation water requirements for shallot plants in Imogiri

| Growth Stage | Length of Growing Phase (Day) | Period | ETo (mm/day) | Water available (%) | Maximum Depth of Root (m) | Total Water available (%) | Groundwater Decrease Fraction (p) | Net Irrigation Requirement (mm) | Irrigation Interval (Day) |
|--------------|--------------------------------|--------|--------------|---------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|---------------------------|
| Initiation   | 10                             | 25-May-16 | 3-Jun-16     | 0.10                | 14.7                       | 4                          | 2                             | 35.4                         | 2                        |
| Vegetative   | 20                             | 4-Jun-16  | 23-Jun-16    | 0.10                | 14.7                       | 4                          | 2                             | 35.4                         | 2                        |
| Tuber Formation Ripening | 15                        | 24-Jun-16 | 8-Jul-16     | 0.20                | 29.3                       | 0.3                        | 9                             | 35.4                         | 2                        |
| Harvesting   | 5                              | 9-Jul-16  | 18-Jul-16    | 0.20                | 29.3                       | 9                          | 3                             | 35.4                         | 2                        |
|              |                                | 19-Jul-16 | 23-Jul-16    | 0.20                | 29.3                       | 9                          | 3                             | 35.4                         | 2                        |

**Table 15.** Calculation of total irrigation dose and average irrigation interval for shallot cultivation in Imogiri

| Growth Period | Days after Planting | Irrigation Dose (mm) | Average Irrigation Volume (m³) |
|---------------|---------------------|----------------------|-------------------------------|
| Planting      | 0                   | 2.201                | 0.424                         |
| Vegetative-1  | 1-15                | 33.017               | 0.424                         |
| Vegetative-2  | 16-35               | 73.371               | 0.706                         |
| Flowering     | 36-45               | 33.017               | 0.636                         |
| Tuber Formation | 46-70         | 64.200               | 0.494                         |
| Total         | 205,807             |                      | 0.537                         |

The results of the analysis of the dose and irrigation interval using the FAO method show that the total need for irrigation in the land is 205,807 mm in two daily irrigation intervals with an average of 2.2 - 3.7 mm [9].

The critical period of shallots due to lack of water occurs during tuber formation [12], with risks of reduced production. To overcome this problem, it is necessary to adjust the level of the groundwater level (especially in former rice fields) and the frequency of water supply.
Research results [13] show that the provision of irrigation water with a height of 7.5 - 15 mm with a frequency of once a day on average produces the highest weight of shallot tubers.

A. The effect of irrigation and mulch levels on the growth of shallots

The differences in the irrigation level of 55, 70, and 85% of the water requirements of shallot plants show different effects on plant height (Table 16 and Figure 7). At the age of 4, 6, and 10 WAP, the plant height in the irrigation treatment was 55, 70, and 85% higher than the farmer irrigation treatment. The highest plant height was achieved at an irrigation rate of 85% with mulch and the lowest was at plants treated with farmer irrigation without mulch.

The height of shallot plants in the land that was given mulch was higher than in the land that did not use mulch.

Table 16. The effect of irrigation and mulch levels on the height and diameter of shallot plants in Sriharjo Village, Imogiri District, Bantul Regency, Yogyakarta Special Region

| Treatment | Plant height at 4 WAP (cm) | Plant height at 6 WAP (cm) | Plant height at 10 WAP (cm) |
|-----------|---------------------------|---------------------------|-----------------------------|
| A0M0      | 12.19 B                   | 17.76 C                   | 18.81 B                     |
| A0M1      | 13.68 AB                  | 17.97 BC                  | 17.91 B                     |
| A1M0      | 17.41 A                   | 26.36 A                   | 27.27 A                     |
| A1M1      | 17.91 A                   | 27.64 A                   | 31.54 A                     |
| A2M0      | 18.16 A                   | 26.69 A                   | 27.89 A                     |
| A2M1      | 14.56 AB                  | 21.28 ABC                 | 24.22 AB                    |
| A3M0      | 17.07 A                   | 25.28 ABC                 | 27.08 A                     |
| A3M1      | 17.39 A                   | 25.96 AB                  | 29.56 A                     |

Note: Numbers followed by the same uppercase or lowercase letters in the same column do not differ at the 5% level according to the DMRT test.

In general, in Figure 7 it can be seen that the application of straw mulch has an effect on plant height when the plants are 4, 6, to 10 WAP. The results of research [14] showed that rice straw mulch gave a better growth response and yield of shallot plants, with greater average value at plant height of 25.68 cm, leaf area of 386.14 cm², and plant fresh weight of 74.04 g. compared to silver black plastic mulch and coconut husk mulch.

Figure 7. The trend of shallot plant height in irrigation and mulching treatment in Sriharjo Village, Imogiri District, Bantul Regency, Yogyakarta Special Region
B. Effect of irrigation and mulch levels on shallot yield
The differences in the irrigation level of 55, 70, and 85% of the water needs of the plants showed that different effects on shallot bulb weight were higher than the treatment of farmers (Table 17). Likewise, mulching affects tuber weight. The highest weight was achieved in 85% irrigation treatment with mulch. The treatment of mulching had a significant effect compared without mulching. This is in line with research results [15] which states that mulching with either straw, litter, or plastic is beneficial for plants because it can inhibit radiation reaching the soil, thereby reducing weed growth and showing a higher number of fruits through more efficient use of water and soil nutrients.

Table 17. Effect of irrigation and mulch levels on the number and weight of chilies in Sriharjo Village, Imogiri District, Bantul Regency, Yogyakarta Special Region

| Treatment | Shallot Bulbs Weight |
|-----------|----------------------|
|           | Wet Weight | Dry Weight |
|           | gram       | gram       |
| A0M0      | 38.43      | C          |
| A0M1      | 47.57      | BC         |
| A1M0      | 49.54      | BC         |
| A1M1      | 66.29      | A          |
| A2M0      | 40.76      | BC         |
| A2M1      | 44.67      | BC         |
| A3M0      | 43.96      | BC         |
| A3M1      | 54.16      | AB         |

Note: Numbers followed by the same uppercase or lowercase letters in the same column, do not differ at the 5% level according to the DMRT test

Cultivating shallots in a good rainy season requires water or spraying water every morning before field conditions are hot/dry. This is intended to sweep or wash the sprinkling of soil caused by rain on plant leaves or to remove powdery mildew that sticks to the tips of plant leaves. Meanwhile, shallot cultivation in dry land should use plastic mulch to control weeds [16].

Furthermore, the advantage of using mulch in agriculture, especially vegetable crops, is that it can increase and improve the quality of the yield, allow planting outside the season (off-season) and improve cultivation techniques [17]. Mulching the soil surface can minimize losses due to solar radiation hitting the soil surface. According to [18], mulch greatly affects soil temperature, because soil temperature is very dependent on the heat exchange process between the soil and its environment. This process occurs due to solar radiation and its flow into the soil through conduction. The existence of mulch will cause less heat to flow into the soil than without mulch.

4. Conclusions
The SIPTS design has been determined based on the pump performance curve, the irrigation system performance curve, the pump operating pressure, and the discharge relationship curve. Irrigation analysis and design are determined based on the analysis of the area of potential services, analysis of plant water requirements, and SIPTS designs of various types. The analysis of pump operational duration provided information on the calculation of the capacity of solar pumps for water supply, while the analysis of effective irrigation area provided information on the broad potential of pump services required for the development of agricultural commodities in accordance with their water potential.

The results of the analysis of operational duration in Playen district, Gunungkidul regency showed that a pump operating duration of 7.59 hours/day was able to irrigate an area of 2,333 m². Furthermore, in Imogiri district, Bantul regency, a pump operating for 5.42 hours/day could irrigate an area of 3,630 m².

The irrigation technique that is suitable for shallot plants is the impact sprinkler, while for chilies it is streamlined. Provision of water for chili plants is better and more efficient when given as much as...
85% of available water by providing mulch for both the growth and yield components, while the growth of shallot plants as measured by plant height in both irrigation and mulch treatment was found to be higher than irrigation with farmers’ patterns.

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