Unleashing a solar irrigation pump revolution for smallholder farmers in Myanmar

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Abstract

A low cost solar powered irrigation system for a 0.81 hectare farm in the Central Dry Zone of Myanmar was designed for growing green gram during the dry season and monsoon rice during the rainy season. A NPV of $3,518 with a 5% discount rate and LCOE of $0.11/kWh (required amount) and $0.06/kWh (total available) was discovered for a system comprised of a 2.2 kW submersible centrifugal DC pump, 2.64 kW of solar PV, a 50,000 liter ferrocement raised water tank, and movable drip line irrigation for maximum efficiency. An IRR of 19% with a payback of 5.5 years was found for a system's 20 year lifetime total cost of $3,235, 3.8 times cheaper than diesel. The total cost of water was $0.07/kg of green gram grown and 29 metric tonnes of CO_2 are avoided over 20 year life for the solar design or 10.8 million metric tonnes of CO_2 if all 370,000 diesel irrigation pumps in Myanmar were replaced with solar.

Keywords: solar water pumping, irrigation, solar energy, smallholder farmers, agriculture, Myanmar

1. Introduction

Agriculture is the world's largest employer, incorporating approximately 40% of the global population and 2 billion in the Asia-Pacific specifically [1]. An estimated 500 million smallholder farmers [2] produce 80% of the world's food [3]. Small farmers are predominately in poverty; however, irrigation can serve as the engine to increase their income by improving crop yields, ensuring more reliable harvests against unpredictable drought/rainfall patterns, and ultimately make use of the fuel savings to fund the transition to grow more high value crops. Currently, only 9% of the world's PV systems are used for small-scale agriculture, even though most countries in small scale agriculture receive 4-6 kWh/m²/day of solar energy year round. The cost of solar has come down significantly in the past 12 years - 96% to be exact from $4.12/W in 2008 to $0.17/W in 2020 [5]. This price drop can best be explained by the exponential growth of installed PV capacity which is 10% of total world renewable energy generation and over 2% of total global electricity production (2019) [6].

As with most developing countries, Myanmar's workforce is mostly agrarian (64%) and the agriculture sector responsible for 48% of their GDP [7]. As of 2015, only 40% of Myanmar's 65,000 rural villages are electrified [8]. Myanmar uses 370,000 diesel pumps for irrigation, but due to high operation and maintenance costs many farmers can only afford to irrigate half of their crops [3]. Low cost solar irrigation pumps can power this engine of economic growth of smallholder farmers as studies have found replacing diesel water pumps at ¼ [9] - ½ the cost over a 20 year life [10]. An affordable solar irrigation system is designed for a 0.81 hectare farm in the Central Dry Zone of Myanmar to increase the farmer's productivity/earnings and analyze the financial parameters of the system in comparison to diesel.

2. The state of the off-grid small farmer solar irrigation market

2.1. Potential market

There are 370,000 diesel-powered pumps used for irrigation in Myanmar, which each consume about 7.5 liters of diesel/day [3]. The cost of diesel is the main reason why farmers only irrigate half of their land, lowering their crop yields and profit. SPIS can alleviate energy poverty for Myanmar smallholder farmer by boosting their income and productivity. Small farmers in Myanmar make $1,000 - $3,000 per year so they only have a few hundred dollars to spare on farm equipment [11]. Understandably, the ideal solar irrigation system will be as cheap as possible for this subset.

2.2. Competition

Proximity's Lotus pump is designed specifically to fit Myanmar's small tube wells of 5 cm diameter. The $375 solar pump system has an impeller connected to a brushlessDC motor, submersible centrifugal pump, and two 130 W solar panels. The flow rates are ideal for farmers with ¼ hectare of land and require an average of 15,000 liters per day.

The SF1 surface pump by Futurepump can be used in river/ponds of shallow depths up to 6 meters. It uses a simple piston design with a rotating flywheel to draw water up so it can easily be maintained and repaired [12]. The system is transportable, costs $539 and has an expected payback of 1-2 years [13]. It is capable of irrigating an acre and 15 m of head with 0.5 l/s. There is also the SF2 pump designed for 0.81 ha at 3,600 l/h, 15 m head retailing for $695.

SunCulture's RainMaker2 can pump 3,000 l/h and up to 65 m head and for $850 includes a full kit: submersible centrifugal pump (with 10 year life), 50 m electric cable, ClimateSmart battery, 310 W solar panel, 100 m (25 mm) HDPE (high-density polyethylene) drip irrigtion pipe, 4 sprinklers, necessary fittings, 4 LEDs and USB charging ports [14]. This system can pump water from any water source and into a storage tank during the day to then be freely released by gravity at night or dawn/dusk to eliminating evaporation losses, and distributed by a drip irrigation system which delivers water efficiently and directly to the crop's roots. SunCulture reports 300% crop yield increases and includes in-person training to the farmers with soil analysis and a call center for year-round support.

3. SPIS technology literature review

3.1. Pumps

Solar pumps are typically direct current (DC) but also available as a more complex and higher-loss AC system, due to the necessary inverter and consequently advanced controls [15]. DC motors have been the first preference for the vast majority of SPIS research studies showing the highest efficiencies (70-90%) [16] with about 10% of research focusing on AC motors, which have higher efficiencies than DC for high capacity use-cases over 7 kW [17]. For shallow wells (10–20 m deep), AC motor pump systems showed similar water output levels when compared to DC systems; yet, at higher depths (30–50 m) DC motor systems produce higher flowrates. Positive displacement pumps, unlike centrifugal pumps, are used when the required flow rate is low and TDH (Total Dynamic Head, or vertical distance the water must be pumped) is high. In general, modern solar pumps last 5-10 years depending on the water quality and pump utilization rate [18].

3.1.1. Piston

A piston pump operates by forcing a fixed volume of water in a cavity from suction to discharge by creating a vacuum on the inlet side. The flow rate and efficiency remain constant with a change in pressure and can handle high viscosity fluids, unlike centrifugal pumps which experiences frictional losses [19]. Also, piston pumps have minimal maintenance and are simple to install.

3.1.2. Helical/Screw

A helical or screw pump is a cavity pump that creates a corkscrew-like motion and pulse-free flow in which valves are not required – the only parts are the stator and rotor [16]. These pumps are used in high head, low water demand applications. They can be used as either submersible or surface pumps depending on having a vertical or horizontal placement.

Some disadvantages include that helical rotors are only available in small sizes and are extremely sensitive to sand and pH. The main advantage is that this pump can work early in the day when the solar irradiation is low due to ability to operate with high efficiency at very low speeds (similar to a vertical wind turbine).

3.1.3. Centrifugal

A centrifugal pump, also referred to as a dynamic pump, is the preferred pump for irrigation systems as they work best for situations where the pumping head is low and water demand is high [20]. This pump works by rotating an impeller in the motor to move the fluid and create pressure, which can then be increased simply by adding more stages. The design is compact and simple as there are minimal valves and moving parts, so the required maintenance is very minimal [17].

3.1.4. Submersible

The most common SPIS design incorporates a submersible pump (with motor included) in a borehole and pumping 10-120 meters to a reservoir a couple of meters above the crop's field [16]. The water is then gravity released into a low-pressure drip irrigation system where the water can be filtered and mixed with fertilizer. Submersible pumps can last 7-10 years, but if sediment content is high, the hydraulic part of the pump will need to be replaced in about 2-3 years.

3.1.5. Surface

The simplest SPIS configuration is using a surface pump in a reservoir or river (no deeper than 6 m). The pump's flow rate then depends on the amount of solar irradiance which varies throughout the day. The main advantage of surface pumps is the easy installation and low costs. One drawback is needing to regularly check the priming behavior (when the pump first fills with water). This is not required for submersible pumps since they can operate in automatic mode with control switches.

3.2. Drip irrigation

Designing an efficient irrigation system is key to prevent overuse of a critical resource. For the past 30 years, drip irrigation has become very popular for its high efficiency of 85-92% by applying small amounts of water 1-3 times a day directly at the root through pin holes in plastic pipes [21]. This irrigation method allows for high levels of soil moisture, which is critical for many cash crops. Despite being the most efficient, it is cost prohibitive at $2,500/ha [22] thus less than 1% of the world's irrigated land uses this method [23]. It is also vulnerable to clogging and requires a filtration system when the water quality is not good, which can be expensive.

3.3. Water storage tank

Most SPIS include an elevated water tank in the design to act as a battery and flows with gravity. The pressure of the irrigation system then depends on the height of water in the tank. A cloudy day can reduce the solar pump's performance by 87% so one day's worth of water should be stored to make up the difference [2]. Another advantage is reducing evaporation losses by watering the crops during dawn/dusk or at night.

Ready-to-use plastic tanks are easy to install, and do not corrode like metal or cement tanks, but are more costly than if the farmers builds a tank him/herself [16]. Reinforced cement concrete (RCC) has a few downfalls as it needs to be waterproofed and develops cracks after a few months so needs repairs often [24]. Ferrocement is a better alternative which does not need waterproofing or repairs and is expected to last at least 25 years. It is made from a thin layer of mortar cement that is reinforced by a cage made of steel bars (rebar) and chicken wire mesh, which helps withstand tension forces. The costs to build a 15,000 liter tank from RCC or Ferrocement in India are $253 and $140, respectively. (In comparison, a 15,000 liter plastic tank would cost $3,000-$3,500 [25].)

4. SPIS design

4.1. Introduction to the case study

For the case study of this paper, a 0.81 hectare farm in the Central Dry Zone village of Mahaing is chosen to grow green gram during the dry season (Nov-Apr) and traditional paddy during the rainy season (May-Oct). This profile fits the traditional Myanmar farmer as 50% are subsistence who own own less than 1.2 ha [26]. Although most farmers in Myanmar use 5 cm tube wells, it is not practical to have such a small pump for the necessary flow rate, so it will be suggested to use a 15 cm tube well. In Mahaing, 5 and 10 cm tube wells are used at 24-30 m depths.

4.2. Determination of irrigation water required

The Safeguard Water's "Water Requirement tool" (based on FAO, Food and Agriculture Organization of the United Nations, training manual no. 3: Irrigation Water Management: Irrigation Water Needs) was used to find the irrigation water needed based on the crop type, farm acreage, and chosen location's temperature, humidity, windspeed, solar irradiation, and rainfall [16]. The full hydrological cycle of the system is included for the surface water, groundwater, soil moisture, and evaporation. The growing period is also determined for the chosen crop with the plant's growth divided into different growing stages with each requiring varying amounts of water.

4.2.1. Crop selection

The chosen crop to irrigate during the dry season, green gram (or mung bean), was based on it having the highest net margin of profits of popular pulses and oilseeds grown in Myanmar at $581/ha [27]. Green gram is notable for its nutritious properties of minerals, high protein, and fiber, and is an excellent crop to combat malnutrition [28].

4.2.2. Irrigation water required

The selected area's rainfall (mm/month) and daily temperatures were inputted along with the chosen crop to find the annual irrigated water need. The ideal growing temperatures for green gram is 28-30 °C and with seasonal rainfall of 350-650 mm. For the chosen location, the rainfall during the dry growing season of November to March is only 73.9 mm, hence the need for an irrigation system. The average temperature during this season is 27 °C, only slightly less than ideal conditions for green gram.

The total required annual irrigation, Figure 1, was then found to be 7,513 m^3 with a pump utilization rate of 37%, which is directly related to the economic efficiency of the SWP (Solar Water Pump). The highest daily required irrigation water use is 49.7 m^3/day during January. This is however for 24 hours of pumping per day whereas with solar would be utilized about 10 hours per day. Therefore a minimum flow rate of 4,970 l/h or 4.97 m^3/h is needed. It should be noted that this is designed for the worst case if the farmer decides to irrigation during peak daylight with evapotranspiration losses, as opposed to using the water tank storage at dusk/dawn.

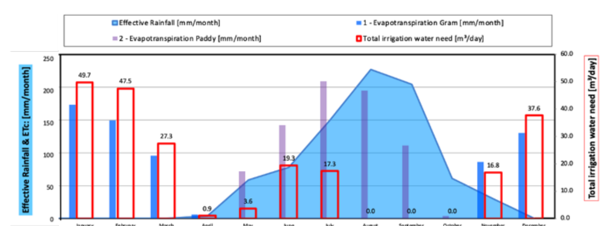

Figure 1: Irrigation water requirement for *1* year [4]

4.3. Drip irrigation design

The high cost of drip irrigation at $2,500/ha makes the efficient system cost prohibitive for small farmers in developing countries [22]. One design by a non-profit, International Development Enterprises, reduces the drip irrigation cost 90% from $2,500/ha to $250/ha by making the drip lines movable so that only three drip line has to be used instead of 25 per hectare [23]. Cost savings were also found by replacing hundreds of $0.25 plastic drip emitters with holes punched by a safety pin and using an inexpensive $3 filtration system consisting of20 liter containers with nylon cloth filters. The filter should be cleaned when clogged and has an estimated 3.5 m of maximum head loss [29].

4.4. Water tank sizing

For simplicity, an elevated water tank will be chosen. The tank can also be used to water at dusk/dawn to eliminate evapotranspiration losses. For the drip lines, 13.7 m of head is required, therefore the top of the tank will be raised 13.7 m above the crops [18].

By ratio comparison of the 15,000 liter ferrocement tank mentioned earlier, a 50,000 liter tank needed to cover the maximum daily water usage to accommodate for cloudy days would cost $467 [24]. The cylindrical tank's size would be 3.6 m diameter and 5 m height and would then be placed on an artificial hill of 8.7 m height.

Water level switches will be added for both dry run protection for the well and also overflow protection for the water tank. Switches are small, long lasting, provide fast response and a high resistance to load input [30]. They can be purchased for as little as $1.50 each [31] and can cause head loss of up to 1 m each [32].

4.5. Calculating the total dynamic head

The Total Dynamic Head (TDH) is the vertical distance the water must be pumped while also overcoming frictional losses in the pipes and bends as well as any filters or water meters. When the pump starts, the water level in the well will drop a distance referred to in the figure below as *D* (drawdown), Figure 2. The water will then be pumped up to the top of the storage tank and gravity fed to the crops below.

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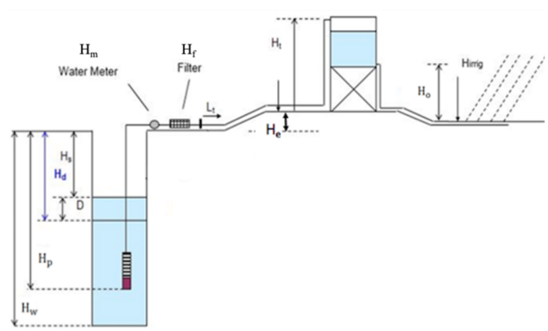

Figure 2: Storage tank system with head losses [16]

$$TDH = H_s + D + H_e + H_t + H_m + H_f + H_l \text{ [m]} \quad (5)$$

Where *H_s* is the static water level, *H_e* is the elevation distance from the well to the tank stand, *H_t* is the height of the tank, *H_m* is the head loss in the water meter, *H_f* is the head loss of the filter, and *H_l* is the head loss is the pipeline.

In the village, 24-30 m wells are typical so the design will account for the deepest well of 30 m and assume the water level is at least 2 m from the bottom for *D* + *H_s* to equal 28 m. For drip lines at least 20 psi are required to operate, which translates to 13.7 m of tank elevation [33]. There are also friction losses in the pipes from elbows and bends as well as the total length of the pipe. Friction losses can be estimated from Grundfos with a flow rate of 4.97 m^3/h and pipe diameter of 2 inches, the head loss is 1.551 m per 100 m of straight pipes [34]. An acre is 4047 m^2 which is about 64 m x 64 m. For the distance from the well to the farthest point of two acres, a distance of 200 m is assumed for a total frictional head loss of 3.1 m. The head loss of the filter is assumed to be 3.5 m and the head loss of the two water switches are 2 m in total. The TDH is then 28 m + 13.7 m + 3.1 m + 3.5 m + 2 m = 50.3 m.

4.6. Pump selection

The pump sizing will depend on the acreage and solar irradiation. Using the minimum required flowrate of 4.97 m^3/h, a 2.2 kW submersible centrifugal GolPump ST 5509 (Taiwan) is selected with a 10 cm diameter and max flow rate of 18 m^3/h for $787 [35].

To determine the flowrate for the desired head, the pump performance curves must be used. At 50 m of head, the pump has a maximum flow rate of 180 l/min or 10.3 m^3/h and operates with about 62% efficiency at its rated power of 2.2 kW. The control panel is included and provides protection from high or low voltage, a drop in water level, and rapid cycling.

4.7. Solar design

4.7.1. Panels

For the 2.2 kW requirement of the pump, the solar system will be oversized by 20% for when the weather is not ideal (i.e. cloudy) and to account for efficiency losses from the high temperature in this tropical country. 2.64 kW are then required by the solar panels which comes to 330 W x 8 panels. The price of panels from a Chinese OEM with 17% efficiency has been found to be $0.18/W, which comes to $475 in total for the solar panels [36].

4.7.2. Mounting system

The price of an aluminum, ground and fixed mounting system has been found to be $0.06/W from another Chinese manufacturer, arriving at $158 [37]. The mounting system comes with a 10 year warranty but the structure is expected to last up to 30 years. A concrete base with stainless steel fastening will be angled at a fixed 21 degrees, matching the chosen location's latitude to maximize the solar power generated.

4.7.3. Cabling

Prices for electric cables are estimated at $5/m to run the pump well depth (30 m) and distance to PV panels (estimated at 15 m) for a total of 45 m translating to $225 [9].

4.7.4. DC-DC converter

A DC-DC converter is needed for PV systems to boost efficiency due to intermittent sunlight, causing power instability from varying amounts of fluctuating solar irradiance [33]. The advantages of DC-DC automatic voltage stabilizer power converter regulator include: short circuit protection, over current protection, over heating protection, under voltage protection with high conversion and stability, maximum conversion rate of 97%, low heat, stable and reliable [38]. A 1200 W DC-DC buck converter is available for $66.50 [39]. Connecting two in parallel would be suitable to run the 2.2 kW pump with 96% efficiency for a total cost of $133.

4.7.5. Helioscope solar design output

Satellite imagery of Myanmar's solar radiation showcase that the CDZ has excellent solar radiation year round [40]. Helioscope solar design web software was used to simulate the energy production from the panels. The solar production is assumed to be in use year round with a full potential of 4.156 MWh from the 2.64 kW system.

4.8. Final SPIS design

A diagram of the solar powered irrigation system design can be seen in Figure 3. The plants are spaced 30 cm between rows and 10 cm between rows, totaling 270,311 green gram plants across the 0.81 hectare farm [28]. (One plant in the schematic represents about 9,000 green gram plants.) A 6 inch diameter well is assumed for the 4 inch submersible pump, and the TDH is 50.3 m.

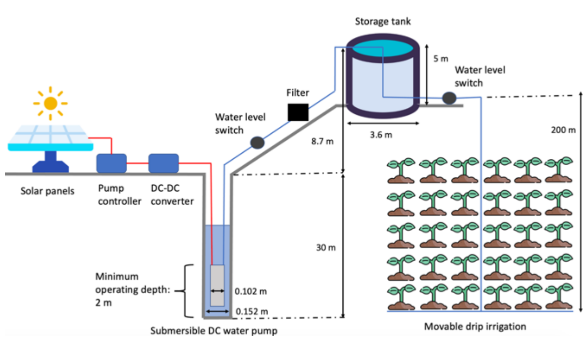

Figure 3: Schematic of design for 2 acre farm in Mahaing

4.8.1. Project costing

The total upfront cost for the solar powered irrigation system is $2,457, Table 1. The solar panels are assumed to last for 20 years and the pump 10 years. The 20 year cost is $3,244, which normalizing per hectare is $4,005/ha.

Table 1: Project costing, CAPEX

Item	Cost [USD]
3 hp submersible DC pump and controller	$787
330 watts x 8 solar PV panels	$475
Mounting system	$158
50,000 liter ferrocement water tank	$476
Movable drip irrigation + filter	$200
45 m of electric cable	$225
DC-DC converter x2	$133
Water level switches x2	$3
Total	$2,457
20 year pump cost/ha	$1,943
20 year kit cost/ha	$4,005
20 year kit cost	$3,244

4.8.2. System performance

The peak daily solar irradiance (W/m^2) was used to determine the number of cloudy, partly cloudy, and sunny days throughout the year in order to estimate the pump's flow rate performance. The solar weather data was obtained from Helioscope and a frequency analysis was done to determine the number of days per year with peak irradiance in various buckets.

Using metrics of peak irradiation below 500 W/m^2 as cloudy, below 800 W/m^2 as partly cloudy and above 800 W/m^2 as sunny, the frequency analysis resulted in annually cloudy days represented 13% of total days, 40% partly cloudy, and 47% sunny. For the green gram dry growing season of November-March, the majority of days are partly cloudy at 55% vs. sunny at 39% and cloudy at a mere 6%.

The hours of pump operation were determined by assuming at least 100 W/m^2 of solar irradiance is required for the pump to start [2]. Solar power values lower than this were removed from the analysis for total pump power produced. It is also noted that the maximum power supplied to the pump (including losses) is 2,221 W which is only slightly above the pump's rated power of 2.2 kW meaning the solar system is properly sized for the pump. This brings the total annual solar power sent to the pump at 4,106 kW or 1,901 kW for the dry season growing months of November-March.

The electrical power is then translated to the pumped power by solving for the flow rate, Q.

$$P = P\_hyd / \eta = \rho g H Q / \eta \qquad (1)$$

Where *Phyd* is hydraulic power (kW), *ρ* is water density (1000 kg/m^3), g is the gravitational constant (9.81 m/s^2), H is the total dynamic head (m), Q is the flow rate (m^3/s), P is shaft power (kW), and η is pump efficiency (62%).

The total required irrigation water is 7,513 m^3 and the total available pumped water is 18,702 m^3 (annually) and 8,661 m^3 for the green gram months of Nov-Mar. During all required months of irrigation the water needs are met by the solar pumping system, Figure 4. The SPIS is oversized by 30% for a 1.3 hectare farm instead of 0.81 hectare farm. This oversize may not be the case in real-world application as head loss may be higher, pump and solar efficiency lower, or water quality worse. Having a safety factor is acceptable as the farmer can grow more water intensive crops in the future and also the water can also be useful for community water, livestock, or passive income.

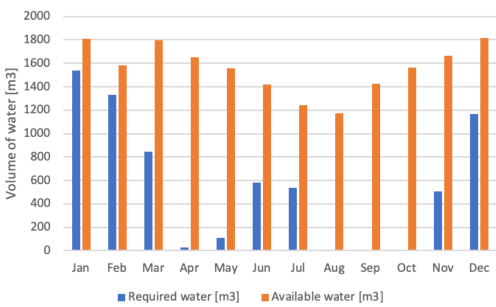

Figure 4: Required vs. available irrigation water [m^3]

The performance of the pump based on the weather can be seen in Figure 5, with the pump's max flow rate on a cloudy day at about 3.5 m^3/h. Surprisingly, the pump's flowrate's are very comparable for sunny and partly cloudy days; the only difference is that on sunny days the pump operates for an extra 2 hours. This phenomenon can best be explained by the summation of diffuse radiation from the clouds, paired with direct sunlight.

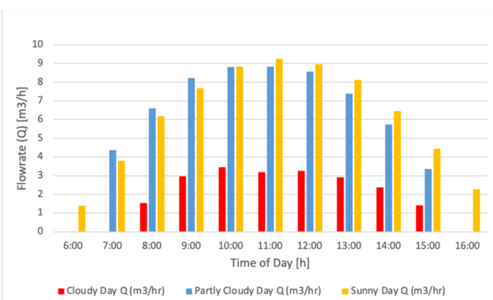

Figure 5: Flowrate based on the weather

On a sunny day, the system can pump 67,000 liters of water/day compared to only 21,000 liters on a cloudy day and 62,000 on a partly cloudy day, Table 2. The highest irrigation requirement is 50,000 liters/day in January, which would not be possible on a cloudy day. This highlights the importance of the water tank storage to compensate for the loss in available water.

Table 2: Solar pump performance based on weather

Weather	Peak irradiance [W/m^2]	Total irradiance [W/m^2]	Pump operation [h]	Grid power [W]	Water pumped [m^3]
Sunny	1014	7734	11	14801	67.42
Partly Cloudy	745	4882	9	13596	61.93
Cloudy	325	2173	8	4636	21.12

The pump's performance decreased 69% on a cloudy day in comparison to a sunny day. The difference between a partly cloudy day and sunny day was only 8% less pumped water volume. Since the solar pump will be mostly used during November to March, these months have an average irradiance of 749 W/m^2, which is similar to the partly cloudy example day chosen. Although assuming on a partly cloudy day the system is oversized 24% compared to the max need of 50,000 liters/day, a safety factor is comfortable as the performance can vary drastically with the unpredictable weather.

5. Financial analysis of SPIS vs. diesel

There are 370,000 diesel pumps in Myanmar for irrigation with efficiencies of 20-35% [41]. Diesel pumps cost $200-$500 plus about $100/season for fuel [42] (with diesel prices in Myanmar currently at lows of $0.47/l in November 2020 compared to double in 2019 due to the coronavirus lockdowns) [43]. The pumps tend to last only 2-3 years and then need to be replaced. The diesel pumps also require frequent maintenance (such as replacing oil, filters, coolant, and refueling) which results in crop failure during the downtime. Some farmers rent the diesel pumps as needed during the dry season through a shared system. Affordability remains one of the greatest challenges to growing the market for solar water pumps, with a small solar pump costing the equivalent of about 8–10 months of income ($600$800) for a typical Myanmar farming household of $78 monthly income [44].

5.1. Cost benefit analysis

Diesel pump usage is assumed at 0.07357 l/m^3. For the case study, the total yearly irrigation needed is 7,513 m^3, which translates to about 73 ac-in. Therefore, 552.7 liters of diesel are required annually at a present 2020 cost of $0.47/liter comes out to $260 per year spent on the fuel itself (not including transportation costs, assumed to be 10% of total fuel costs, or $26 annually) [45]. The maintenance cost has been estimated as $150/year [43]. The capital cost of a 3.73 kW pump to irrigate 2 acres of vegetables costs $350 but only has a 2 year life compared to the solar pump lasting 5-10 years [10].

Solar irrigation was found to be 3.8 times cheaper than diesel over the course of 20 years (Figure 6). This is a higher benefit than another study which found solar irrigation to be 2.8 times cheaper than of diesel cost; however this study was conducted in 2013 and the price of solar was $1.33/W as opposed to $0.18/W, a percentage decrease of 86.5%. Other research confirmed these findings with diesel being 2-4 times cost of solar [9] or 3 times [10] or up to 4 times the cost of solar [9].

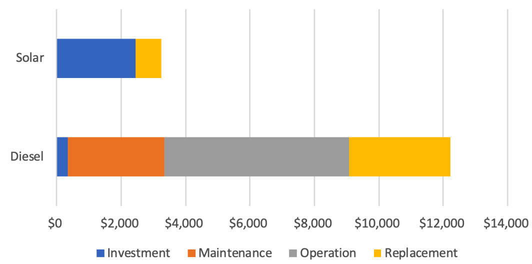

Figure 6: Pump cost comparison, 20 year life cycle

5.2. LCOE

The Levelized Cost of Energy (LCOE) was determined using the solar outputs from Helioscope combined with the pump's 62% efficiency at 50 m of head for a flow rate fluctuating with the solar irradiance as seen in Figure 5. The total required irrigation water is 7,513 m^3 and the total available pumped water is 18,702 m^3 (annually) and 8,661 m^3 for the green gram months of November-March. The energy was analyzed for both the entire year at $0.06/kWh and for only the required amount at $0.11/kWh. A 2013 study by GIZ in India found an LCOE of $0.141 for solar pumping compared to $0.228 for diesel [9], however the price of solar in 2013 was 3.5 times higher than in 2020 [5].

5.3. NPV

A 2014 agricultural survey in Myanmar found that green gram had a net profit of 581 $/ha [27]. Adjusting for inflation of 10%, the net profit becomes $639.10/ha which is then $517.49 for a 0.81 hectare farm [46]. According to many real-world case studies, by switching from diesel to solar irrigation smallholder farmers increased their profits 100% due to decreased labor costs for running the pump, fuel costs, maintenance, increased yield of at least 50% [47] up to 300% [14] by being able to afford to irrigate their crops fully (as most can only afford half of what their crops require) and potentially using gravity-fed storage at dusk/dawn to eliminate evapotranspiration losses, along with reduced loss of downtime when the diesel pump required maintenance [48]. Another useful outcome of switching to solar irrigation was that farmers had more time and money to potentially start another business.

The Net Present Value (NPV) is the amount of return/profitability the investment will accrue during its lifetime, taking into account the present time value of money using discounted future cash flows [49]. A large and positive NPV indicates that the project is viable as it is the future cash flow minus the initial investment.

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{2}$$

Where *C_t* is the net cashflow during period *t*, *C_0* is the initial investment costs, and *IRR* is the chosen discount rate of 5%. By inputting the resulting increase in profits (100%) due to the solar irrigation system cost benefits mentioned above and a 5% discount rate, a NPV of $3,518 was obtained.

5.4. IRR

The Internal Rate of Return (IRR) is the annual growth rate an investment is expected to generate. The IRR is the discount rate (or rate of return) which sets the NPV to zero (Equation 7) and is obtained using Excel's Goalseek. The IRR was found to be 19%, which is favorable considering the higher the rate of return the more potential of profitability the investment has.

5.5. Payback

The payback is then the number of years for the sum of NPV to break even with the initial investment and is found to be 5.5 years. This is comparable to other studies conducted in 2017 of 6-10 years [1]. Another study found SPIS for medium-sized systems have paybacks of about 2-3 years with small systems in as little as 18 months [50] and up to 4-6 years for medium size [51]. For high-value crops, the upfront cost of a solar water pump is recovered within 12–18 months through increased yields, and the solar water pump can break even financially with the diesel pump within two years depending on fuel prices and utilization of the pump [44].

5.6. Cost of water

Similar to the LCOE, the cost of water was determined using year-round use at $0.0134/$m^3$ and only during the dry months for the crop's required amount at $0.0244/$m^3$. Using a potential crop yield of 2.75 t/ha of green gram, it was found that 2.98 m^3 of water is needed to grow 1 kg of the crop [52]. This water cost amounts to $0.07/kg of green gram which is 7% of its $1 selling price to wholesalers and supermarkets [53].

5.7. Summary of financial parameters

Below is a summary of the LCOE, NPV, IRR, payback, and cost of water to grow 1 kg of green gram (Table 3).

Table 3: Financial parameters of the solar irrigation system

Energy Produced (total) [kWh]	2577
Energy Produced (required) [kWh]	1415
LCOE (total) [$/kWh]	0.06
LCOE (required) [kWh]	0.11
NPV [$]	3,518
IRR [%]	19
Payback [yrs]	5.5
Cost of water [$/kg of green gram]	0.07

5.8. Avoided CO_2 emissions

Cradle-to-grave life cycle assessments have found that SPIS have 97-98% less CO_2-eq/kWh compared to diesel [54]. The CO_2 avoided emissions of the designed SPIS were calculated as 29.183 metric tonnes of CO_2 avoided over 20 year life for the design (Table 4). If all 370,000 diesel irrigation pumps in Myanmar were replaced, that would amount to 10.8 mil metric tonnes of CO_2 over 20 years. This is equivalent to planting 10.8 million hardwood trees to sequester 1 ton of CO_2 across the timespan of 40 years. Also for perspective, this amount of avoided CO_2 emissions to replace all of Myanmar's diesel irrigation pumps is 1.12% of Myanmar's total carbon emissions in 20 years, estimated as 966 Mt [55].

Table 4: CO_2 avoided emissions

Diesel fuel (20 years) [l]	11054
Diesel emissions [CO_2 kg/liter of diesel]	2.64
CO_2 emissions avoided with SPIS [CO_2 t]	29.18
CO_2 emissions avoided for 370,000 diesel pumps [CO_2 Mt]	10.80

6. Conclusion

Now more than ever with the coronavirus lockdowns, smallholder farmers are being disproportionately affected as demand for fruit and vegetables has dropped from closed restaurants, labor shortages from migrant workers unable to cross the border, and reduced trade causing product prices to drop as high as 90% [3]. Harnessing the freely available sunlight, abundant in Myanmar, farmers can save four times on irrigation costs by switching from diesel pumps to solar. After the 5.5 year payback, the farmers can use their savings of switching to solar to invest in more high value crops such as melons, mangos, or chili. A consultant is needed to work with the farmer for the design work of the desired crops to grow, understanding the water requirement for pump and storage tank sizing, solar design, and obtaining financing.

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