Unleashing a solar irrigation pump revolution for smallholder farmers in Myanmar

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Thesis to obtain the Master of Science degree in

Energy Engineering and Management

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January 2021

Acknowledgements

Throughout the writing of this dissertation, I have received a great deal of support and assistance along the way. First and foremost, I would first like to thank my supervisor, Dr. Rui Pedro da Costa Neto, whose expertise was invaluable to me in formulating the research questions and methodology. His insightful feedback motivated me to sharpen my thinking and brought my work to a higher level. I appreciated the enthusiasm and general interest Dr. Rui had with my project, and how he used his curiousity to push the envelope further than my initial expecations.

Also, I would like to thank my colleagues from my internship at Mandalay Yoma for the opportunities and understanding I received by working first hand with solar mini-grid projects in remote Myanmar villages. Without this experience I would not have honed in on this specific thesis topic, which has been extremely rewarding by merging both my engineering and humanitarian interests.

In addition, I would like to thank my classmates, roommates, friends, and family who provided me with consistent love and encouragement. Thank you all for listening, being a soundboard, having patience when I expressed frustration, and celebrating with me when I made progress. Special thanks to my grandmother, Mim, who passed away this year. Her love for education has shown through me, and I know that being the first in my family to obtain a graduate degree would make her very proud.

Lastly, I would like to thank InnoEnergy for giving me this wonderful gift to pursue my dreams. In the United States, renewable energy graduate programs are few and far between, so I am glad that Europe would welcome an American to learn from them. The past two years have been the best experience of my life, and I am beyond grateful for this program: the connections made, the lessons learned, and the doors it has opened for me.

Abstract

500 million smallholder farmers are responsible for producing 80% of the world's food. As the price of solar has decreased 96% over the past 12 years, farmers no longer have to waste money on expensive diesel pumps while only affording to irrigate half of their crops. 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, as is typical. 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 DC pump, 2.64 kW of solar PV, a 50,000 liter ferrocement elevated 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 mil 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

Resumo

500 milhões de pequenos agricultores são responsáveis pela produção de 80% dos alimentos do mundo. Como o preço da energia solar diminuiu 96% nos últimos 12 anos, os agricultores não precisam mais desperdiçar dinheiro com bombas a diesel caras, ao mesmo tempo em que conseguem irrigar metade de suas safras. Um sistema de irrigação de baixo custo movido a energia solar para uma propriedade agrícola de 0.81 hectares na Mianmar foi projetado para o cultivo de feijão mungo durante a estação seca e arroz de monção durante a estação chuvosa. Um NPV de $ 3.518 com uma taxa de desconto de 5% e LCOE de $ 0,11 / kWh (quantidade necessária) e $ 0,06 / kWh (total disponível) foi obtido para um sistema composto de uma bomba submersível DC de 2,2 kW, 2,64 kW de PV solar, um 50.000 um tanque de água elevado de cimento reforçado com capacidade de 50 000 litros e irrigação por gotejamento móvel para máxima eficiência. Uma TIR de 19% com um retorno de 5,5 anos foi encontrada para um custo total de vida de 20 anos do sistema de $ 3.235, 3,8x mais barato que o diesel. O custo total da água foi de $ 0,07 / kg de grama verde cultivada e 29 toneladas métricas de CO_2 são evitadas ao longo de 20 anos de vida para o projeto solar ou 10,8 milhões de toneladas métricas de CO_2 se todas as 370.000 bombas de irrigação a diesel em Mianmar fossem substituídas por solares.

Palavras-chave:

Bombeamento solar de água, Irrigação, Energia solar, Pequenos agricultores, Agricultura, Myanmar

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Abbreviations

5 P	Pro-Poor-Public-Private-Partnerships
AC	alternating current
BLDC	brushless direct current
CAPEX	capital expenditures
CDZ	Central Dry Zone
CE	Commodity Exchange
DC	direct current
DRD	Department of Rural Development
EDC	Energy Development Committee
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environmental Facility
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
HDPE	High-Density Polyethylene
iDE	International Development Enterprises
IDA	International Development Association
IRR	Internal Rate of Return
IRENA	International Renewable Energy Agency
IWMI	International Water Management Institute
LCOE	Levelized Cost of Energy
KSSI	Kenya Smallholder Solar Irrigation Project
MAB	Myanma Apex Bank
MADB	Myanmar Agricultural Development Bank
MAAS	Myanmar Aquaculture-Agriculture Survey
MES	Myanmar Engineering Society
MPPT	Maximum Power Point Tracking
NEMC	National Energy Management Committee
NGO	Non-Governmental Organization
NPV	Net Present Value

OEM	Original Equipment Manufacturer
OGS	Off-Grid Solar
OPIC	Overseas Private Investment Corporation
PAYG	Pay-as-you-go
PEU	Productive Energy User
PV	photovoltaic
RBF	Results-Based Financing
RCC	Reinforced Cement Concrete
SIDA	Swedish International Development Cooperation Agency
SoLAR IF	Solar Irrigation for Agricultural Resilience Innovation Fund
SPIS	Solar Powered Irrigation Systems
SWP	Solar Water Pump
TDH	Total Dynamic Head
UMFCCI	Union of Myanmar Federation of Commerce and Industry Chamber
UNDP	United Nations Development Programme
USAID	United States Agency for International Development

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.

Irrigation accounts for 70% of global water withdraws to provide 40% of the world's food across 300 million hectares. 61% of irrigated water is surface water (i.e. rivers, lakes, aquifers) and 39% groundwater extracted from a well [4]. Ten years ago, it was believed that investment into large-scale irrigation systems would have the highest impact; however, present-day research suggests that investing in small-scale irrigation will make a more powerful contribution for not only improving food security, nutrition, and farmers' income but also creating larger internal rates of return than a dam [5]. Currently, only 9% of the world's PV (photovoltaic) 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 [5].

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, globally [6] (Figure 1). This price decrease can best be explained by the exponential growth of installed PV capacity as it is now, as of 2019, 10.3% of total world renewable energy generation and over 2% of total global electricity production [7].

Figure 1: PV selling price decline, world [6]

The cheapest solar energy deal in the world was signed in April 2020 by Abu Dhabi at $0.0135/kWh, lower than the record-breaking bid set in 2019 for Portugal solar tender at $0.0164/kWh. Averaging about $0.05/kWh, the cost of generating solar electricity has reached lows that six years ago the International Energy Agency (IEA) did not expect to come into fruition until 2050. Solar electricity is now cheaper than coal at 2-6 Euro cents per kWh compared to brown coal at 6 Euro cents [8].

Most of the funding for solar irrigation pumps is focused on Africa, such as Powering Agriculture: An Energy Grand Challenge for Development [5] and a United Nations Development Programme (UNDP) initiative in Sudan to solarize 29 farms in the Sahara using a $4.4 mil grant from the Global Environmental Facility (GEF) [9]. Southeast Asian countries are another prospective area of focus as their population and standard of living has risen, energy demand has also grown by 60% over the past 15 years [10]. Also, in Asia, only 4% of land has valuable soil for cultivation (in comparison to Latin America with 12% and Africa 15%) due to excessive soil erosion and land degredation, so efficiency and sustainability in agriculture is paramount [11].

Myanmar (previously Burma) is a unique choice for a case study as the SouthEast Asian country of 51 million has experienced 50 years of isolation (a military dictatorship from 1962-2011), so the country is technologically behind and thus an ideal market for renewables and innovation. As with most developing countries, Myanmar’s workforce is mostly agrarian (64%), and the agriculture sector is responsible for 48% of the GDP [12]. As of 2015, only 40% of Myanmar’s 65,000 rural villages are electrified [13]. The country is about 15-20 years behind Thailand and Vietnam’s development as farm practices are still largely labor intensive, with only 1% of Myanmar farmers using combine harvesters and paddy threshers, compared to 100% of Thailand farmers [14].

Myanmar is number six in the world for rice production with eight million hectares of rice grown on 50% of the country’s arable land [11]. To harvest rice, one day of work in Myanmar yields a mere 23 kg of paddy, compared to 62 kg in Cambodia, 429 kg in Vietnam, and 547 kg in Thailand [15]. Consequently, Myanmar has the worst rice production profits with a 2014 net margin of $114/hectare for monsoon rice paddy compared to Indonesia and Thailand at around $1,500/ha. Due to these low profits, farmer wages in Myanmar are the lowest in Asia at about $2/day in 2014 (or $2.20 in 2020, accounting for inflation) [14] (Figure 2). With this low income small farmers are unable to escape poverty.

Figure 2: Myanmar farmer wages are the lowest in Asia [15]

The low yields are due to a number of reasons. For instance, the number of certified (quality) paddy seeds can only meet 1% of the demand, so farmers use their saved seeds, which result in low yields [16]. Another reason for low yields is the limited use of fertilizer due to lack of education and sufficient loans to pay for this enhancer. Lastly, and perhaps most important, is the country's lack of public irrigation systems. Myanmar's public irrigation system only covers 15% of their agricultural land compared to 70% in Vietnam, 50% in China, and 30% in Thailand and Indonesia.

Currently, Myanmar uses 370,000 decentralized diesel pumps for irrigation, but due to high diesel pump operation and maintenance costs, many farmers can only afford to irrigate half of their crops (i.e. if a crop requires water every day, the farmers could only afford to irrigate every other day) [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 [17] to ½ the cost over a 20 year life [18]. 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.

The 2019 Global LEAP Awards nicely summarized, "Situated at the heart of the water-food-energy nexus, solar water pumps can play an important role in delivering a sustainable water supply in an increasingly climate-sensitive world, all while reducing or preventing harmful greenhouse gas emissions and improving the incomes and resilience of rural households worldwide." [2]

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

2.1. History of solar powered irrigation systems (SPIS)

Solar pumps are not a new concept, nevertheless they are becoming more popular due to recent technological breakthroughs that have allowed for the pumps to be more efficient in terms of both energy and cost. Centrifugal solar pumps with 25-35% efficiency were first introduced in the 1970s but could only be used in shallow water applications and for low demand [18]. Second generation developed with positive displacement pumps achieving 70% hydraulic efficiency or vane efficiency, ηh, with low required PV power input and thus lower cost. Third generation now includes helical motor pumps that are submersible, long-lasting, and powered by the same motors as centrifugal pumps. There have also been advancements in controllers such as for maximum power point tracking (MPPT), pump speed, and monitoring storage.

Water-filled brushless DC motors are the latest trend for SPIS because they are maintenance free and not plagued by frequent starts/stops [4] (Figure 3). The rotor itself is a permanent magnet and the coils are fixed on the stator, so there is no need for brushes (which must be replaced every 2 years). Another key benefit is the high efficiency from always rotating at maximum torque, unlike brushed motors that only reach max torque at certain points of rotation. When paired with MPPT, BLDC motors have efficiencies as high as 85% [4]. The motors are also compact, controllable, less noisy, low power, and extremely durable to run all day for applications such as fans, air conditioners, and washing machines. The downside is that these motors are expensive since rare earth metals must be extracted for the permanent magnet.

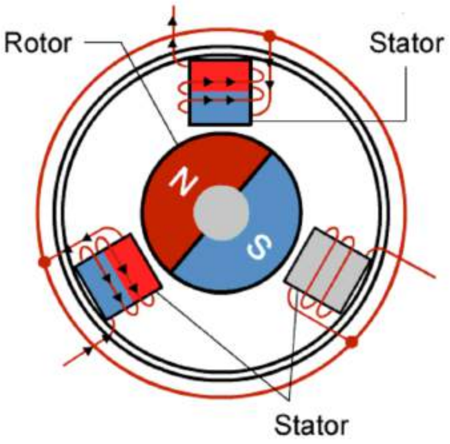


Figure 3: Brushless DC motor [19]

2.2. Potential market

There are 500 million smallholder farmers in the world and only a small fraction have access to SPIS. So far, 40% of the SPIS market share has been in Asia-Pacific, accounting for India, China, Bangladesh, Japan, and Pakistan due to government support with specific initiatives and also rapid increase in power consumption and demand due to rising population and increasing wealth [18]. For example, India aims to deploy 100,000 solar water pumps by 2020 and Bangladesh 50,000 by 2025.

For Myanmar in particular, there are 370,000 diesel-powered pumps used for irrigation, which each consume about 7.5 liters of diesel/day [3]. The cost of diesel is the main reason why farmers only irrigate their land half of the necessary days, 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 [20]. Understandably, the ideal solar irrigation system for this subset will be as cheap as possible.

2.3. Competition

While the market of using solar irrigation for smallholder farmers has only begun to emerge in the past 5 years or so, there are a few notable competitors whose products and services could be used (or are already actively in use) in Myanmar.

2.3.1. Proximity (Myanmar)

Proximity originally began selling manual treadle pumps ($25 to irrigate 0.2 ha in 4 hours) [21] but is now offering submersible centrifugal solar pumps as the farmers can free up their time and expend less energy [20]. The 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 brushless DC motor, submersible 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/day. The Lotus's low cost is comparable to diesel pumps and the system can pay for itself in 11 months, but since the pump was built for affordability and not durability, the pump is only expected to last 2 years. (Farmers in Myanmar already replace their diesel pumps every 2 years so they are accustomed to this expected equipment lifetime).

2.3.2. Futurepump (India and Kenya)

The SF1 surface piston pump by Futurepump is sponsored by USAID and was the winner of the 2017 Ashden Award for Sustainable Energy and Water (Figure 4). The pump can be used in rivers and 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 [22]. The system is transportable and also the only surface pump available with a 5 year warranty (warranties are usually 1-2 years for SPIS) [12]. The SF1 pump alone costs $539 and has an expected payback of 1-2 years [23]. 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 hectares at 3600 l/h, 15 m head retailing for $695.

Figure 4: Futurepump's piston surface pumps, SF1 (left) and SF2 (right) [23]

2.3.3. SunCulture (Kenya)

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) pipe, 4 sprinklers, necessary fittings, 4 LED light bulbs and USB charging ports [24] (Figure 5). This system can pump water from any water source (i.e. lake, river, well, or borehole) 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.

Figure 5: SunCulture's RainMaker2 solar pump kit [24]

2.3.4. Summary

Table 1 compares the current products on the market. Normalizing for a 20 year period of isolating the pump cost per hectare, SunCulture is the cheapest option at $1658/ha, without mentioning the added benefit of training and 1 year support. Proximity was the most expensive option at $6000/ha but also designed for the smallest farm size so was expected to have a higher price (although not over three times as much). Futurepump's 20 year cost is competitive with SunCulture at $1716/ha; however, since SunCulture provides an entire solar kit and not just a pump, the obvious choice is SunCulture. SunCulture's package system with drip irrigation will therefore be used as a model approach for the subsequent solar irrigation design.

Table 1: Comparison of available solar irrigation pumps for small farmers

Solar pump company	Proximity	Futurepump	SunCulture
Pump type	Submersible, Centrifugal	Surface, Piston	Submersible, Centrifugal
Solar power [W]	260 W	Not included	310 W
Additional components	n/a	n/a	ClimateSmart battery, drip irrigation (100 m) + 4 sprinklers, training, 1 yr support
Total Cost [$]	375	695	850
Pump Cost [$]	150	695	539

Farming size [ha]	0.25	0.81	0.65
Water pumped [l/day]	15,000	36,000	30,000
Payback [years]	0.92	1-2	n/a
Lifetime	2 years (pump), 10 years (panels)	5 year warranty	10 years (pump), 20 years (panels)
20 year cost ($/ha)	6000	1716	1658

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 [25]. DC motors have been the first preference for the vast majority of SPIS research studies showing the highest efficiencies (70-90%) [4] with about 10% of research focusing on AC motors, which have higher efficiencies than DC for high capacity use-cases over 7 kW [29]. 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 [27].

3.2. Positive displacement pump

3.2.1. 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 [28]. The flow rate and efficiency remain constant with a change in pressure and can handle high viscosity fluids, unlike centrifugal pumps which experience frictional losses [29]. Also, piston pumps have minimal maintenance and are simple to install.

3.2.2. 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 [4] (Figure 6). 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.

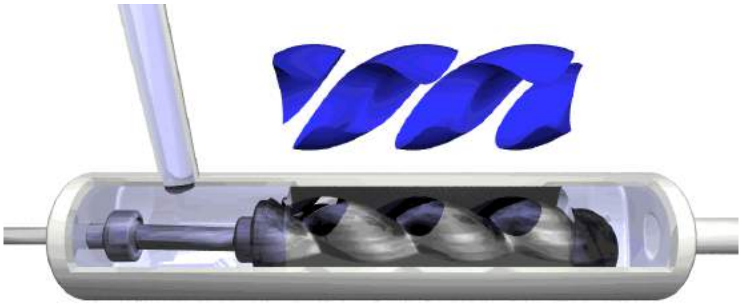


Figure 6: Helical pump animation [30]

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 its ability to operate with high efficiency and at very low speeds (similar to a vertical wind turbine).

3.3. Dynamic pump

3.3.1. 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 [31] (Figure 7). 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 [29].

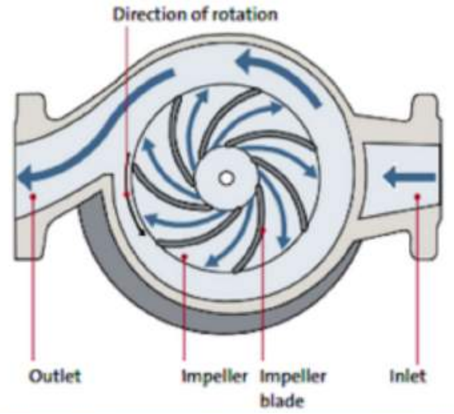


Figure 7: Centrifugal pump schematic [4]

3.4. Submersible pump

The most common SPIS design incorporates a submersible pump (with motor incorporated) in a borehole and pumping 10-120 meters to a reservoir a couple of meters above the crop's field [4]. 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.

3.5. Surface pump

The simplest SPIS configuration is using a surface pump in a reservoir or river (no deeper than 6 m due to atmospheric pressure) [2] (Figure 8). 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.

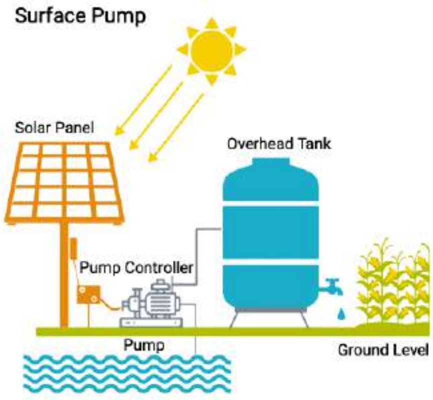


Figure 8: Surface pump [2]

3.6. Drip irrigation

With climate change, water scarcity will likely be amplified due to drought and wildfire coupled with increasing demand from the growing population and less available fresh water due to pollution contamination. Designing an efficient irrigation system is key to prevent overuse of a critical resource, with water efficieny defined as the beneficial use of water (i.e. not lost to evaporation, erosion, etc) per total irrigated water used (Figure 9).

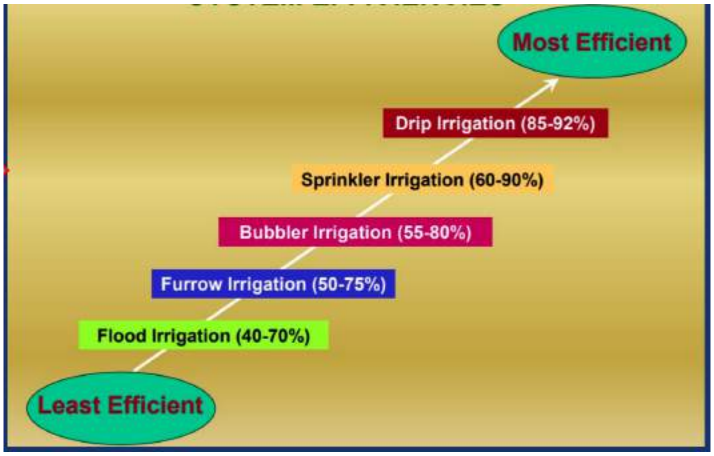


Figure 9: Efficiencies of irrigation methods [4]

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 [32] (Figure 10). 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 (see Appendix A, Table 15) [33], thus less than 1% of the world's irrigated land uses this method [34]. Drip irrigation is also vulnerable to clogging so requires a filtration system when the water quality is not good, which can be expensive.

Figure 10: Drip irrigation field in Kenya [4]

3.7. Water storage tank

Most SPIS include an elevated water tank in the design to act as a battery and free-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%, thus one day's worth of water should be stored to make up for the difference [2]. Another advantage is reducing evaporation losses by watering the crops during dawn/dusk or at night. If the tank is on level land (or distance traveled is too far), a surface booster pump and additional solar panels would be needed (Figure 11).

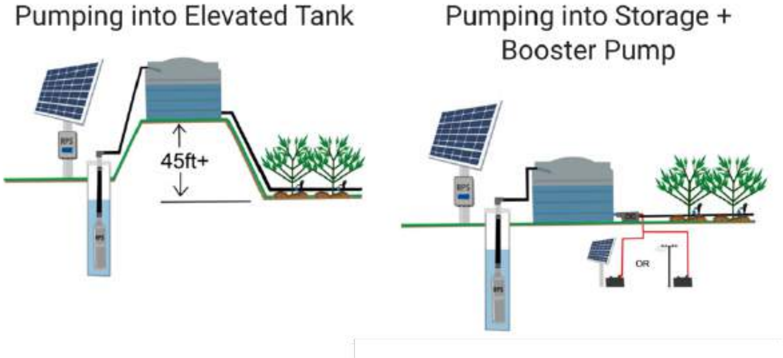
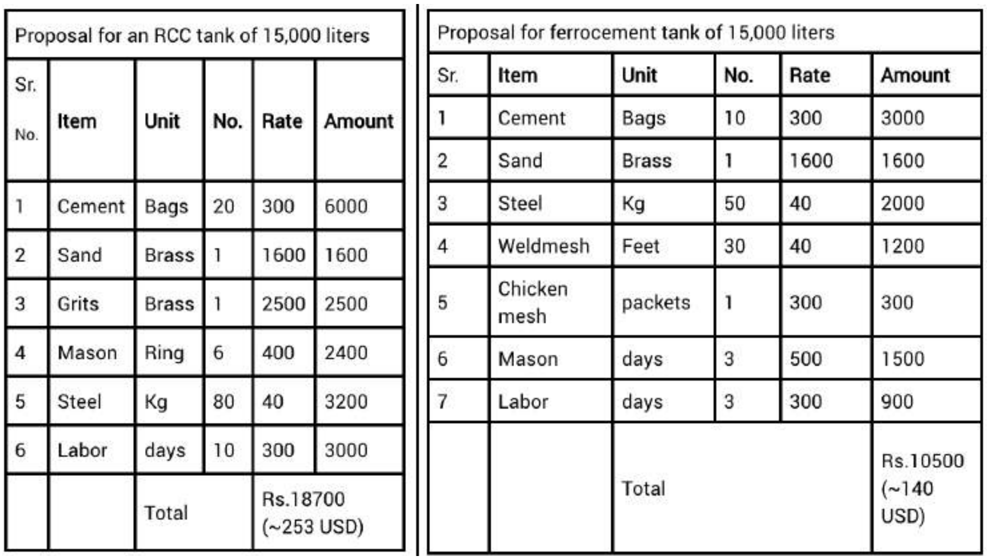


Figure 11: Water tank configurations [35]

Cost and access to remote locations for delivery are of course important factors to consider when choosing a water tank. Ready-to-use plastic tanks are easy to install, do not corrode like metal or cement tanks, but are more costly than if the farmers builds a tank him/herself [4]. Reinforced cement concrete (RCC) has a few downfalls as it needs to be waterproofed and develops cracks after a few months so must be repaired often [36]. 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 shown in Table 2 as \$253 and \$140, respectively. (In comparison, a 15,000 liter plastic tank would cost \$3,000-\$3,500 [37].)

Table 2: 15,000 liter cost estimate for RCC water tank (left) vs. ferrocement (right) [36]



Proposal for an RCC tank of 15,000 liters

Sr. No.	Item	Unit	No.	Rate	Amount
1	Cement	Bags	20	300	6000
2	Sand	Brass	1	1600	1600
3	Grits	Brass	1	2500	2500
4	Mason	Ring	6	400	2400
5	Steel	Kg	80	40	3200
6	Labor	days	10	300	3000
		Total		Rs.18700 (~253 USD)	

Proposal for ferrocement tank of 15,000 liters

Sr.	Item	Unit	No.	Rate	Amount
1	Cement	Bags	10	300	3000
2	Sand	Brass	1	1600	1600
3	Steel	Kg	50	40	2000
4	Weldmesh	Feet	30	40	1200
5	Chicken mesh	packets	1	300	300
6	Mason	days	3	500	1500
7	Labor	days	3	300	900
		Total			Rs.10500 (~140 USD)

Ferrocement requires less cement and steel so is more environmentally friendly than RCC and also less weight for the potential raised structure it will sit on (Figure 12). It is also better suited against natural disasters such as earthquakes and strong winds, not to mention it is much cheaper. An RCC tank can be easily constructed by farmers themselves with little required training. The only downside, in comparison to a plastic tank, is that it takes some time to build. The tank can also be left open to collect rain water (but is not recommended when paired with a drip line system as debris may get clogged).

Figure 12: Ferrocement water tank [36]

4. SPIS design

4.1. Introduction to the case study

Solar powered irrigation systems (SPIS) present some technical challenges since their performance is largely dependent on being properly designed and sized for a specific use-case/application as well as other environmental factors such as the amount of rainfall, sunshine, temperature, humidity, and quality of water (Figure 13). The capacity of a solar pumping system is a function of three main variables: pressure, flowrate, and solar power to pump the required irrigation water to a specific vertical feet (head) [17].

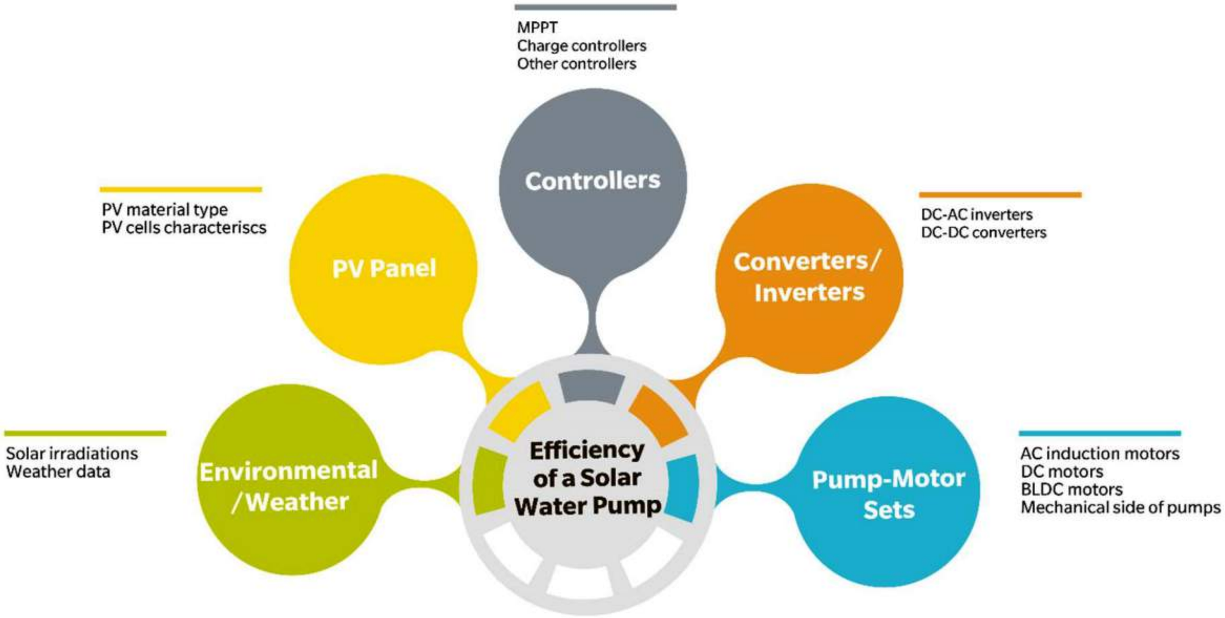
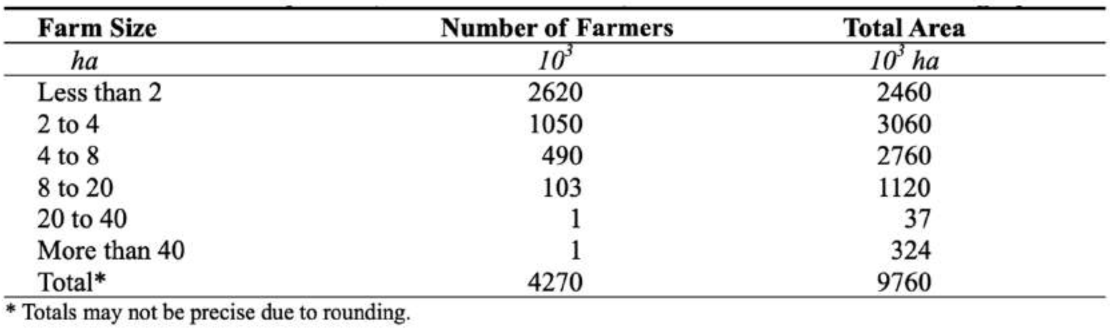


Figure 13: Key factors influencing the efficiency and performance of a solar water pump [18]

The Myanmar Aquaculture-Agriculture Survey (MAAS) conducted a survey of 329 agricultural households in Myanmar and found that 49% had farms less than 2 hectares [38]. 50% of farmers in the Ayeyarwady region (the nation's "rice bowl") are subsistence farmers, owning 1.2 hectares or less [39]. Below, in Table 3, is another study from the Institute of Agriculture in Myanmar and confirms the above study's findings with 61% of farmers owning less than 2 hectares [40].

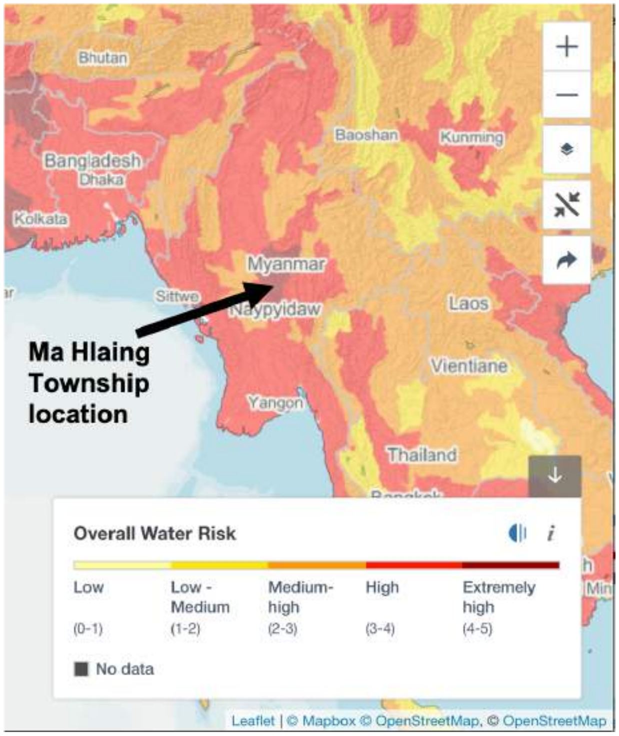
Table 3: Farm size in Myanmar, number of farmers, and total acreage [40]



Farm Size	Number of Farmers	Total Area
ha	*10^3*	*10^3 ha*
Less than 2	2620	2460
2 to 4	1050	3060
4 to 8	490	2760
8 to 20	103	1120
20 to 40	1	37
More than 40	1	324
Total*	4270	9760

* Totals may not be precise due to rounding.

The Central Dry Zone (CDZ) is responsible for 20% of Myanmar's rice production and 54% pulse production despite receiving the lowest amount of annual rainfall [41]. For the case study of this paper, a 0.81 ha farm in the CDZ of Mahaing is chosen to grow green gram during the dry season (Nov-Apr) and traditional paddy during the rainy season (May-Oct) (Figure 14).



Ma Hlaing Township location

Figure 14: Case study Ma Hlaing township location in the Central Dry Region [4]

In the chosen township of Ma Hlaing there are 72,812 hectares owned by 34,571 farmers; however, only 1,578 hectares are irrigated by 750 farmers, averaging about 2 hectares per farmer. Crops grown in this township include:

- Winter/dry season: green gram, groundnut, chili, onion
- Monsoon: paddy, sesame, groundnut, green gram, black gram, cotton

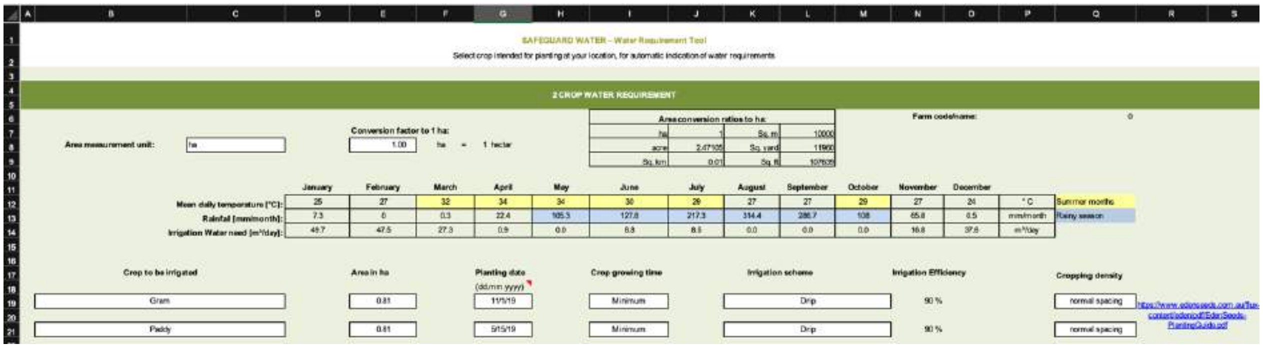
4.2. Water source

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.

It should be noted that unsustainable water use may pose as an issue since once the system is installed, there is no financial incentive for the farmer to save on fuel costs [17]. This is especially important as many solar irrigation projects are in areas with high water risk that may be exacerbated with climate change. Over-abstraction of the ground water beyond the designed intent may be for numerous reasons such as the farmer selling water to neighbors, growing more water intensive crops, or providing water for the livestock.

4.3. 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 [4] (Figure 15). 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 is divided into different growing stages: planting in the initial stage, crop development, flowering, grain setting, ripening, and harvest. Each of the stages require varying amounts of water, which is considered in the software.



SAFEGUARD WATER – Water Requirement Tool

Select crop intended for planting at your location, for automatic indication of water requirements.

2 CROP WATER REQUIREMENT

Area measurement unit: ha

Conversion factor to 1 ha: 1.00 ha = 1 hectar

Area conversion ratios to ha:			
ha	1	Sq. m	10000
acre	2.47105	Sq. yard	11960
Sq. km	0.01	Sq. ft	107639

Farm code/name: 0

	January	February	March	April	May	June	July	August	September	October	November	December		
Mean daily temperature [°C]:	25	27	32	34	34	30	29	27	27	29	27	24	° C	Summer months
Rainfall [mm/month]:	7.3	0	0.3	22.4	105.3	127.8	217.3	314.4	286.7	108	65.8	0.5	mm/month	Rainy season
Irrigation Water need [m³/day]:	49.7	47.5	27.3	0.9	0.0	8.8	8.5	0.0	0.0	0.0	16.8	37.6	m³/day	

Crop to be irrigated	Area in ha	Planting date (dd/mm yyyy)	Crop growing time	Irrigation scheme	Irrigation Efficiency	Cropping density	
Gram	0.81	11/1/19	Minimum	Drip	90 %	normal spacing	https://www.edenseeds.com.au/wp-content/edenpdf/EdenSeeds-PlantingGuide.pdf
Paddy	0.81	5/15/19	Minimum	Drip	90 %	normal spacing	

Figure 15: FAO Safeguard Water Tool [4]

4.3.1. Crop selection

Figure 16: Green gram sprouting [42]

The crop to irrigate during the dry season, green gram (or mung bean), was chosen based on it having the highest net margin of profits of popular pulses and oilseeds grown in Myanmar at $581/ha, Table 4 [16]. Green gram is notable for its nutritious properties of minerals, high protein, and fiber, and is an excellent crop to combat malnutrition, which is common in developing countries where rice is the main source of nutrition [43] (Figure 16).

Table 4: Net profits by crop type of pulses and oilseeds in Myanmar compared to paddy, 2014 [15]

	Net margin, $/ha	Labor productivity, $/day	Production costs, $/ha	Labor use, days/ha
Monsoon paddy	114	4.75	510	103
Dry season paddy	246	9.20	626	63
Black gram	267	9.29	237	45
Green gram	581	15.92	355	51
Chickpeas	141	6.85	266	42
Groundnuts	324	8.32	421	65
Sesame	202	8.54	217	44
Sunflower seeds	377	15.68	121	30

4.3.2. Calculating the rate of evapotranspiration

Evapotranspiration is the process of water evaporating from the soil and transpiration of plants back to the atmosphere. The reference rate of evapotranspiration (ETo) is found in FAO's Safeguard Water Tool using the Blaney-Criddle method (Equation 1):

$$\mathrm{ETo} = \mathrm{p} \times (0.46 \times \mathrm{T\_mean} + 8)\ [\mathrm{mm/month}] \tag{1}$$

Where *T* is the mean daily temperature and *p* is the mean daily percentage of annual daytime hours for different latitudes. The reference plant is well-watered green grass, 8 cm tall and completely shading the ground. This reference rate of evapotranspiration is then multiplied by the crop factor *Kc* which depends on the type of crop, growth stage of the crop, and climate. The crop's rate of evapotranspiration (*ETc*) is then found to be (Equation 2):

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc}\ [\mathrm{mm/month}] \tag{2}$$

This *ETc* can be supplied from a combination of rainwater and irrigated water. The effective rainfall, *P_e*, is then the water retained in the root zone and is equal to the total rainfall (*P*) minus the runoff, evaporation, and deep percolation (water moving through pores in rock/soil). The effective rainfall is determined by (Equation 3):

$$\begin{aligned} &\mathrm{P\_e}=0.8 \times \mathrm{P} - 25 \qquad \text{if } \mathrm{P}>75\ [\mathrm{mm/month}] \\ &\mathrm{P\_e}=0.6 \times \mathrm{P} - 10 \qquad \text{if } \mathrm{P}<75\ [\mathrm{mm/month}] \end{aligned} \tag{3}$$

4.3.3. Irrigation water required

The required irrigation water needed is then calculated as (Equation 4):

$$\text{Irrigation water need} = \text{ETc} - \text{P\_e} \ [\text{mm/month or m}^3\text{/day}] \tag{4}$$

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 of water per month. 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, Table 5.

Table 5: Mean daily temp, rainfall, and irrigation water needed per month [4]

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Mean daily temp (°C)	25	27	32	34	34	30	29	27	27	29	27	24
Rainfall [mm/month]	7.3	0	0.3	22.4	105.3	127.8	217.3	314.4	286.7	108	65.8	0.5
Irrigation water needed [m^3/day]	49.7	47.5	27.3	0.9	3.6	19.3	17.3	0.0	0.0	0.0	16.8	37.6

The total required annual irrigation 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, Table 5. This is, however, for 24 hours of pumping per day whereas with solar would be utilized for about 10 hours per day. Therefore, a minimum flow rate of 4,970 l/h or 4.97 m^3/h is needed (Figure 17). 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. Also, crop harvest occurs during the months that irrigation is not needed, which is in April for green gram and October for monsoon rice.

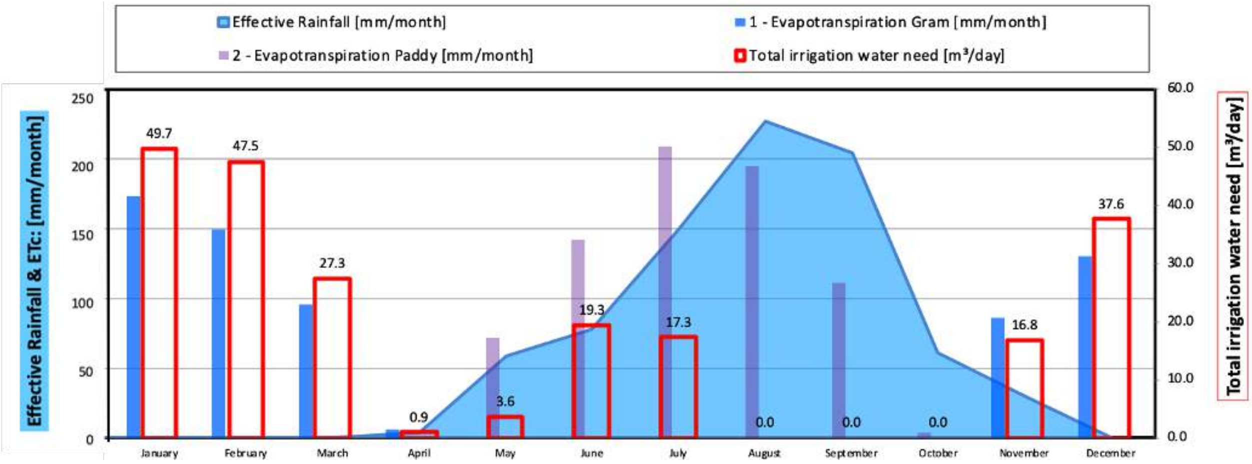


Figure 17: Irrigation water requirement for one year: green gram in dry season and monsoon paddy [4]

4.4. Drip irrigation design

The high cost of drip irrigation at $2500/ha makes the efficient system cost prohibitive for small farmers in developing countries [33]. One design by a non-profit, International Development Enterprises, reduces the drip irrigation cost 90% from to $250/ha by making the drip lines movable so that only three drip lines have to be used instead of 25 per hectare [34]. The system was tested in Nepal and India with great success of doubling farmers income by doubling their irrigated land, cutting labor costs in half with the low flow system vs. watering by hand with a hose, and reducing water consumption 40-60%. 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 of 20 liter containers with nylon cloth filters. The filter should be cleaned when clogged and has an estimated 3.5 m of maximum head loss [44].

The movable design of using one drip line instead of ten will be incorporated into the design for a total cost of $200 for the two acres. The farmer may also decide to pay for the full installation of drip lines as a later investment from the savings of the solar system, in which labor costs would then be further reduced as the irrigation system would be “automatic”.

4.5. 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 [27].

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 [36]. 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 of the well and also overflow protection for the water tank. Switches are small, long lasting, fast responding, and provide a high resistance to load input [8]. They can be purchased for as little as $1.50 each [45] and can cause a head loss of up to 1 m each [46].

4.6. 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 19). 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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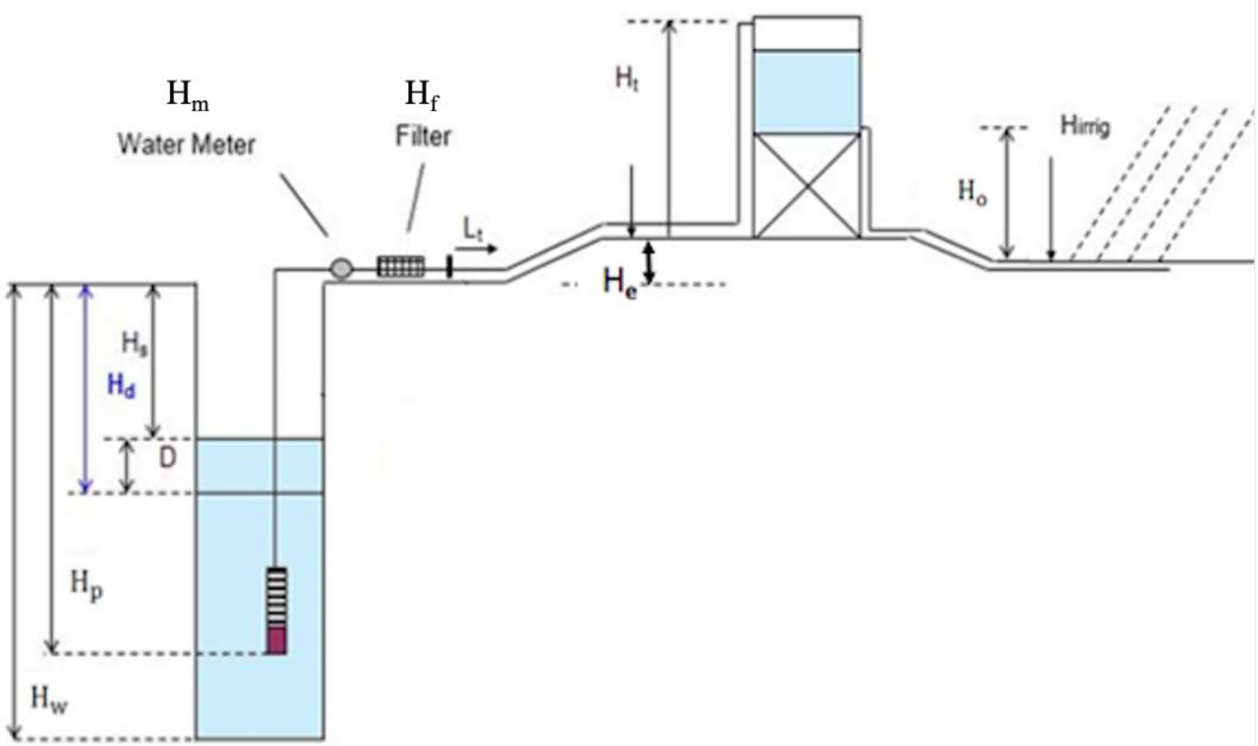


Figure 18: Storage tank system with head losses [4]

The TDH is then found to be (Equation 5):

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

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 Ma Hlaing 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 [35]. There are also friction losses in the pipes from elbows and bends as well as the total length of the pipe. Frictional losses, estimated from Grundfos (see Appendix B, Table 16), with a flow rate of 4.97 m^3/h and pipe diameter of 2 inches are 1.551 m per 100 m of straight pipes [47]. 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.

4.7. 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 pump is selected with a 10 cm diameter [48]. Below in Table 6 is an example of pump specs that fit the design requirements (full specs can be found in Appendix C, Table 17).

Table 6: Solar pump specs [48]

Make/model (Country)	Power [kW]	Max flowrate [m^3/h]	Max head [m]	Pump diameter [cm]	Outlet diameter [cm]	Cost [$]
GolPump ST 5509 (Taiwan)	2.2	18	76	10	5	787

To determine the flowrate for the desired head, the pump performance curves must be used (see Appendix C, Figure 32). 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.

4.8. Solar design

4.8.1. 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 daily temperatures that are typical in this tropical country. 2.64 kW are then required by the solar panel and can be accomplished by 330 W x 8 panels. The price of panels from a Chinese OEM has been found to be $0.18/W, which comes to $475 in total for the solar panels [49]. The solar cells have an efficiency of 17% with a maximum fuse rating of 20 A (see Appendix D, Table 18). The panels will be installed on flat land without recent flooding or nearby shading.

4.8.2. Mounting system

The solar panel dimensions are 1,960 x 992 x 40 mm, which need to be matched with the 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 [50], Figure 20. 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. Ideally, MPPT would be incorporated to achieve maximum power at all times; however, due to the cost constraints of designing for a small rural farmer, MPPT will not be included in the design.

Figure 19: Ground mounted frame [50]

4.8.3. Cabling

Prices for electric cables are estimated at \$5/m to run the pump from the well's depth (30 m) and distance to PV panels (estimated at 15 m) for a total of 45 m translating to \$225 [17]. Another study estimated costs for SPIS using specific pilot project examples in Kenya and Myanmar and can be found in Appendix E, Table 19.

4.8.4. 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 [34]. The advantages of DC-DC automatic voltage stabilizer power converter regulator include: short circuit protection, over-current protection, overheating protection, under-voltage protection with high conversion and stability, a maximum conversion rate of 97%, low heat, stable and reliable [51].

A 1200 W DC-DC buck converter is available for \$66.50 [52]. Connecting two in parallel would be suitable to run the 2.2 kW pump with 96% efficiency for a total cost of \$133.

4.8.5. Helioscope solar design output

Solar radiation varies from 2.3 to 3.2 kWh/m^2/day in the extreme northern and southern regions of Myanmar while the majority of the country, including the central region, have good solar radiation ranging from 3.6 to 5.2 kWh/m^2/day [53] with some areas having more than 270 sunshine days per year [13]. During the dry season, the average solar radiation is more than 5 kWh/m^2/day and available for 7–10 hours per day. During the rainy season, the weather is cloudier and the daily sunshine is only 3–4 hours a day. Satellite imagery of Myanmar's solar radiation (which is largely influenced by the country's topography and southwest monsoons) can be seen in Appendix F, Figure 33, showcasing that the CDZ has excellent solar radiation year round [54].

Helioscope solar design web software was used to simulate the energy production from the panels using weather data from the nearest city of Mandalay. 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 (Figure 20). The Helioscope design parameters can be found in Appendix G, Figure 34.

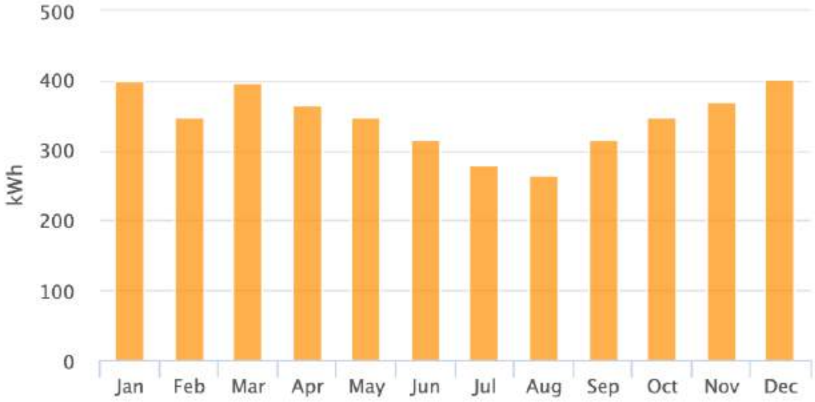


Figure 20: Helioscope monthly production of 2.64 kW PV system [55]

4.9. Final SPIS design

4.9.1. Schematic

A diagram of the solar powered irrigation system design can be seen below (Figure 21). The plants are spaced 30 cm between rows and 10 cm between rows, totaling 270,311 green gram plants across the 0.81 ha farm [43] (one plant in the schematic represents about 9,000 green gram plants). A 15 cm diameter well is assumed for the 10 cm submersible pump, and the TDH is 50.3 m from the frictional losses of the pipes, water switches, and filter, and the vertical distance from the minimum operating depth of the well to the top of the storage tank.

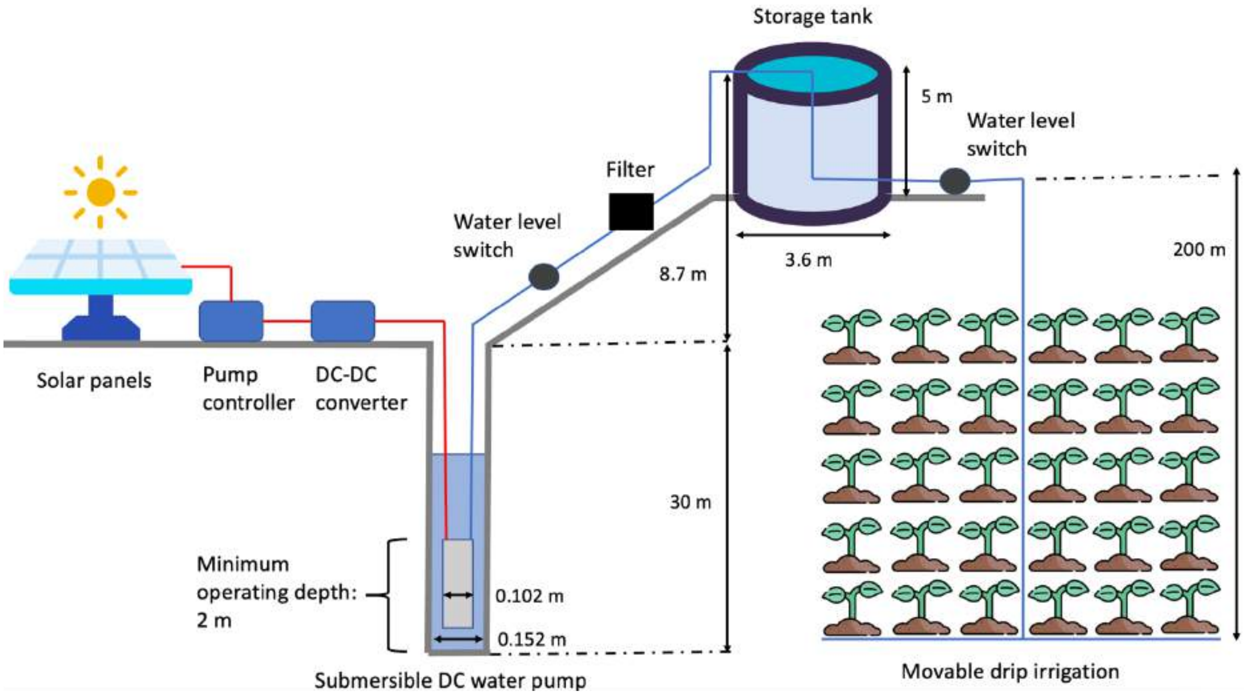


Figure 21: Schematic of design for 0.81 hectare farm in Mahaing

4.9.2. Project costing

The total upfront cost for the solar powered irrigation system is $2,457. The solar panels are assumed to last for 20 years and the pump 10 years. This CAPEX will be later used in the financial analysis of the system to compare against business-as-usual diesel. The 20 year cost is $3,244, which normalizing per hectare is $4,005/ha.

Table 7: Project costing, CAPEX

Item	Cost [USD]
2.2 kW submersible centrifugal 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	$3
Total upfront cost [$]	**2,457**
20 year cost [$]	**3,244**
20 year cost per hectare [$/ha]	**4,005**

4.9.3. 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. As illustrated in Figure 22, the SPIS can pump 87% less water on a cloudy day than a sunny day due to the low solar irradiance.

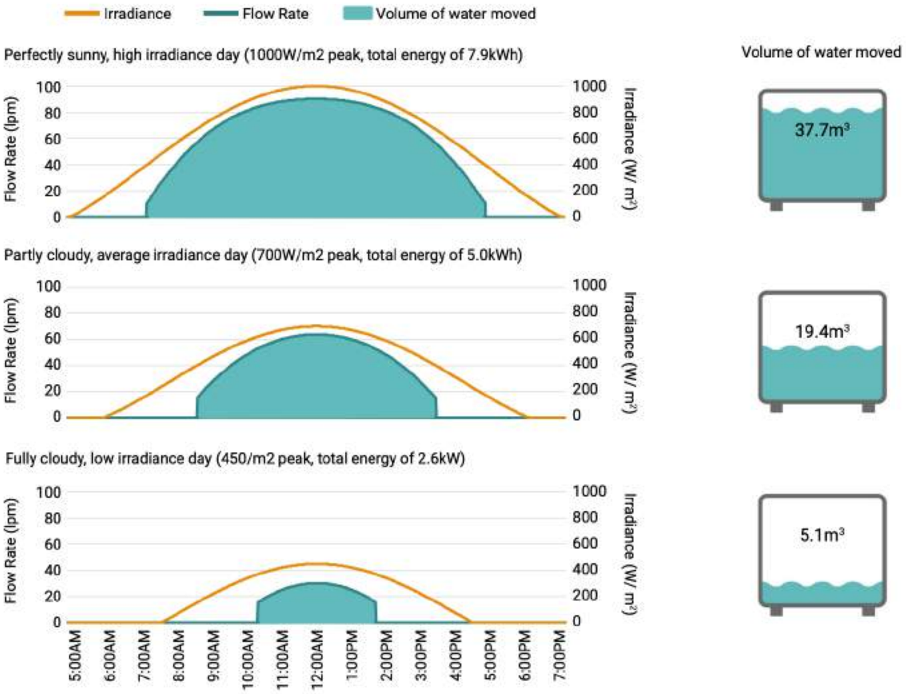


Figure 22: Indicative pump performance on different solar days [2]

The solar weather data was obtained from Helioscope's Meteonorm source and a frequency analysis was done to determine the number of days per year with peak irradiance in various buckets. Below in Table 8 are the average peak irradiance (W/m^2) for each month.

Table 8: Peak and average daily solar irradiance by month [55]

Month	Max global irradiance [W/m^2]	Average peak irradiance [W/m^2]
January	842	714
February	930	750
March	973	836
April	1012	834
May	1028	811
June	1016	817
July	1039	705
August	1064	622
September	1012	699
October	942	712
November	927	730
December	828	714
Total	**1064**	**745**

Using similar metrics as Figure 22 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 a generic solar pump value of 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 2,221.36 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, in Equation 6:

$$P = P\_hyd / \eta = \rho g H Q / \eta \tag{6}$$

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 November-March (Figure 23). During all required months of irrigation the water needs are met by the solar pumping system. The solar irrigation system 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 (if desired) and also the water can also be useful for community water, livestock, or sold as passive income.

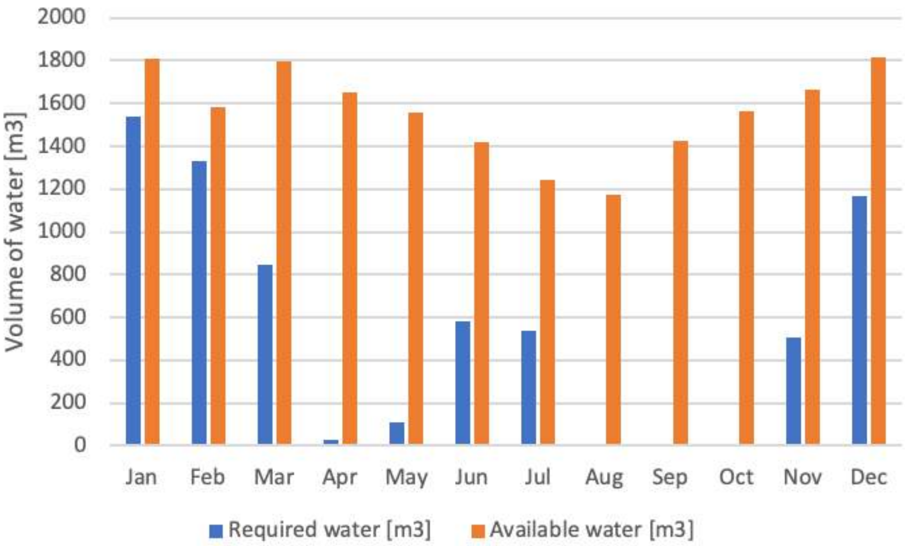


Figure 23: Required irrigation water vs. potential available pumped water [m^3]

The pump's performance based on weather (sunny, partly cloudy, cloudy) was analyzed by selecting three days that matched the above characteristics of peak irradiance mentioned in Figure 24. As can be seen below in Figure 26, on a cloudy day the pump's max flow rate is about 3.5 m^3/h. Surprisingly, the pump's flowrates are very comparable for sunny and partly cloudy days; the only difference being that on sunny days the pump operates for 2 extra hours. This phenomenon can best be explained by the summation of diffuse radiation from the clouds, paired with direct sunlight.

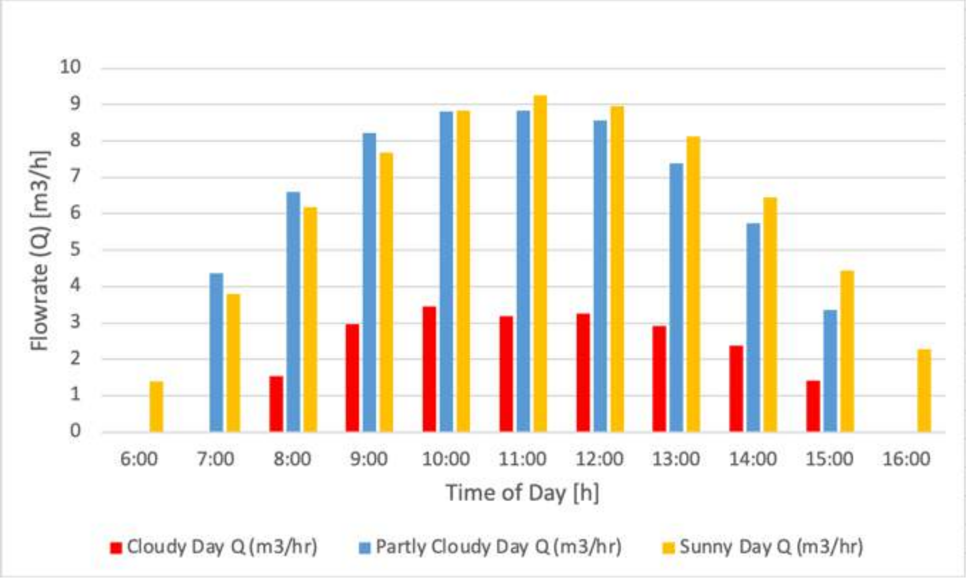


Figure 24: Flowrate based on the weather (i.e. sunny/cloudy/partly cloudy)

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 9. The highest irrigation requirement is 50,000 liters/day in January, which happens to be the chosen cloudy day example. This highlights the importance of the water tank storage to compensate for the loss in available water.

Table 9: Solar pump performance based on the weather

Weather	Peak irradiance [W/m^2]	Total irradiance [W/m^2]	Hours of pump operation [h]	Grid power [W]	Water pumped [m^3]
Sunny	1,014	7,734	11	14801	67.42
Partly Cloudy	745	4,882	9	13596	61.93
Cloudy	325	2,173	8	4636	21.12

The pump's performance decreased 69% on a cloudy day in comparison to a sunny day. This is less than is shown in Figure 24 at 87%, but that reference may have used a more extreme weather example [2]. 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

5.1. Introduction to diesel: advantages and disadvantages

There are 370,000 diesel pumps in Myanmar for irrigation with efficiencies of 20-35% [56]. Diesel pumps cost \$200-\$500 plus about \$100/season for fuel [57] (with diesel prices in Myanmar currently at lows of \$0.47/l in November 2020 compared to double that in 2019 due to the coronavirus lockdowns) [58]. 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, according to Agrosolar [3].

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 [15]. The solar pump has a slower flowrate than the diesel which takes getting used to for the farmers but is also advantageous to limit soil erosion. Despite solar water pumps needing significantly less maintenance compared to diesel pumps (washing the panels of dust and debris once or twice a year), solar water pumps have the downfall of requiring service professionals for installation and service, which is seldom available in rural areas [18]. If the solar system is not installed or designed properly, the farmers will revert back to using the diesel pumps which are familiar and user friendly.

5.2. 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. Therefore, 552.7 liters of diesel are required annually at a present 2020 cost of \$0.47/liter which 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) [60], Table 10. The maintenance cost has been estimated as \$150/year [58]. The capital cost of a 3.73 kW diesel pump to irrigate 0.81 hectares of vegetables costs \$350 but only has a 2 year life compared to the solar pump lasting 5-10 years [18].

Table 10: Solar vs. diesel total life cycle cost, 20 years (Note: Installation cost not included)

Parameters	**Diesel**	**Solar**	
Capital cost	$350	2.2 kW submersible pump	$787
		Solar panels x 8 (330 W)	$475
		Mounting system	$158
		Ferrocement water tank (50,000	$467
		Movable drip irrigation	$200
		Electric cable (45 m)	$225
		DC-DC converter	$133
		Water level switches	$3
Maintenance cost	$3,000		$0
Equipment replacement cost	$3,150		$787
Fuel cost	$5,720	n/a	$0
Life of system	2 years	Solar panels	20 years
		Pump + controller	10 years
Total Life Cycle Cost (20 years)	**$12,220**		**$3,235**

Solar irrigation was found to be 3.8 times cheaper than diesel over the course of 20 years (Figure 25). This is a higher benefit than another study which found solar irrigation to be 2.8 times cheaper than diesel; 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% [18]. Other research confirmed these findings with diesel being 2 to 4 times the cost of solar [17], 3 times [18], or up to 4 times the cost of solar [17].

The low cost of these findings were particular for the ferrocement tank design, low cost drip irrigation, and reduced price of solar. The maintenance cost for solar is recorded as zero as the farmer can clean the panels himself as well as well as check the water flow for any blockages in the filter or drip lines.

Figure 25: Pump cost comparison, 20 year life cycle

5.3. LCOE

The Levelized Cost of Energy (LCOE) was determined using the solar electrical power 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 24. The LCOE is then calculated (Equation 7) where P_e is the power produced by the solar panels and η is the efficiency of the pump.

$$LCOE = \frac{NPV}{P_{\_e} * \eta} \text{ [\$/kWh]} \quad (7)$$

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 [17], however the price of solar in 2013 was 3.5 times higher than in 2020 [6].

5.4. NPV

A 2014 agricultural survey in Myanmar found that green gram had a net profit of $581/ha [16]. Adjusting for inflation of 10%, the net profit becomes $639/ha which is then $517 for a 0.81 hectare farm [59]. According to many real-world case studies, by switching from diesel to solar irrigation smallholder farmers increased their profits 2 times due to decreased labor costs for running the pump, fuel costs, maintenance, increased yield of at least 50% [41] up to 300% [24] 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 [61]. Another useful outcome of switching to solar irrigation was that farmers had more time and money to potentially start another business. "Solar energy has really made our lives easier, we used to buy a lot of gasoline and spare parts for the pumps and bring it over using small canoes. Now, we come over only to see how far the plants have grown, we really have less things to worry about now," [9].

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 [62]. A large and positive NPV indicates that the project is viable as it is the future cash flow minus the initial investment.

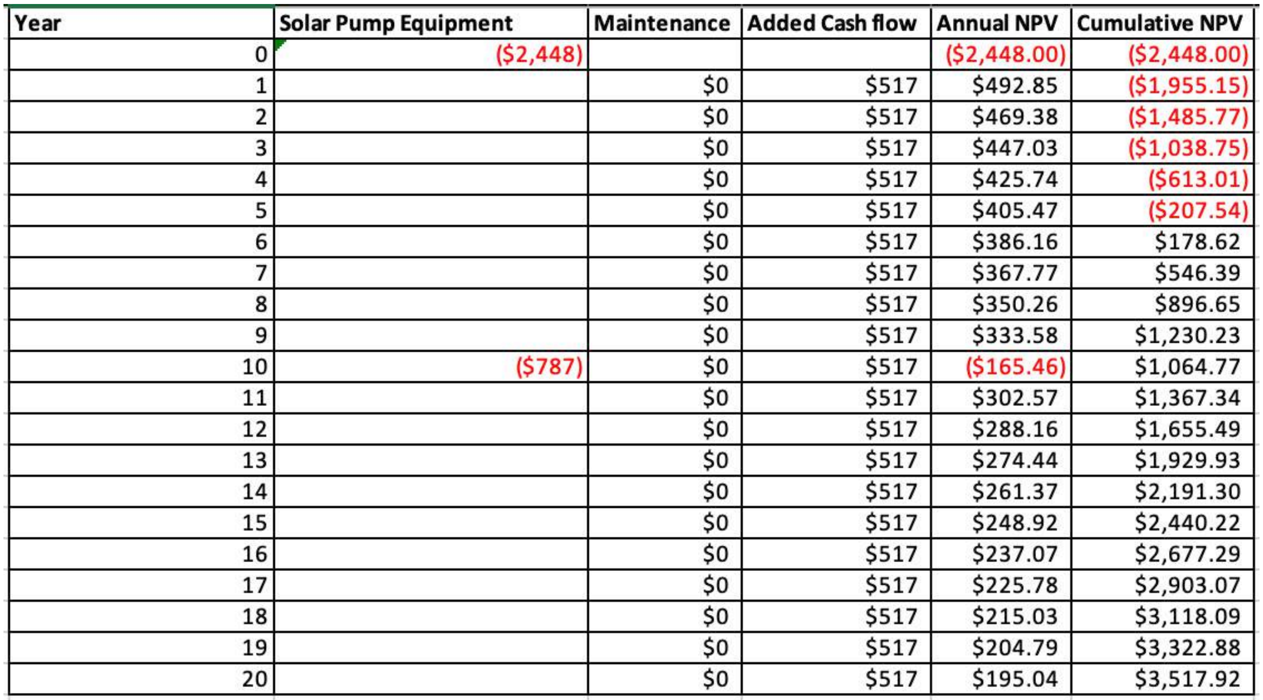
The NPV is calculated by the following (Equation 8):

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{8}$$

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% increase, seen in “Added Cash flow” column) due to the solar irrigation system cost benefits mentioned above and a 5% discount rate, a cumulative NPV of $3,518 was obtained (see Table 11).

Table 11: NPV of 20 year life of SPIS



Year	Solar Pump Equipment	Maintenance	Added Cash flow	Annual NPV	Cumulative NPV
0	($2,448)			($2,448.00)	($2,448.00)
1		$0	$517	$492.85	($1,955.15)
2		$0	$517	$469.38	($1,485.77)
3		$0	$517	$447.03	($1,038.75)
4		$0	$517	$425.74	($613.01)
5		$0	$517	$405.47	($207.54)
6		$0	$517	$386.16	$178.62
7		$0	$517	$367.77	$546.39
8		$0	$517	$350.26	$896.65
9		$0	$517	$333.58	$1,230.23
10	($787)	$0	$517	($165.46)	$1,064.77
11		$0	$517	$302.57	$1,367.34
12		$0	$517	$288.16	$1,655.49
13		$0	$517	$274.44	$1,929.93
14		$0	$517	$261.37	$2,191.30
15		$0	$517	$248.92	$2,440.22
16		$0	$517	$237.07	$2,677.29
17		$0	$517	$225.78	$2,903.07
18		$0	$517	$215.03	$3,118.09
19		$0	$517	$204.79	$3,322.88
20		$0	$517	$195.04	$3,517.92

5.5. 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 8) 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.

5.6. 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 (Table 11). This is comparable to other studies conducted in 2017 of 6-10 years (see Appendix H, Table 20) [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 [19] and up to 4-6 years for medium size [63]. 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 rate of the pump [59].

5.7. 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, Table 12. 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 [64]. This water cost amounts to \$0.07/kg of green gram which is 7% of its \$1 selling price to wholesalers/supermarkets [65].

Table 12: Cost of irrigated water per kg of green gram

Pumped water (total, 20 yr) [m^3]	374,040
Pumped water (required, 20 yr) [m^3]	132,820
Cost of water (total) [\$/m^3]	0.0086
Cost of water (required) [\$/m^3]	0.0244
Yield potential [t of green gram/ha]	2.75
Yield potential [kg of green gram]	2,227
Water required [m^3/kg of green gram]	2.98
Cost of water [\$/kg of green gram]	0.07

5.8. Summary of financial parameters

Below in Table 13 is a summary of the LCOE, NPV, IRR, payback, and cost of water to grow 1 kg of gram.

Table 13: Financial parameters of the solar irrigation system

Energy produced (total) [kWh]	2,577
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

5.9. Avoided CO_2 emissions

Perhaps the government of Myanmar could provide financial incentives for the avoided CO_2 emissions to reduce the investment burden on the farmers and accelerate the technological adoption. Cradle-to-grave life cycle assessments have found that SPIS have 97-98% less CO_2-eq/kWh compared to diesel [17]. Another example cited in India found if 5 million solar pumps are deployed, 26 million tonnes of CO_2 will be reduced or 10 billion liters of diesel [18].

The CO_2 avoided emissions of the designed SPIS were calculated as 29.183 metric tonnes of CO_2 avoided over the 20 year life of the design, Table 14. 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 [66].

Table 14: 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. Business model frameworks

6.1. Value chain

To understand how the food value chain works in Myanmar, in the Central region all farmers (large and small) sell their product to market traders who then sell to retailers, pulse mills, or the Mandalay large terminal market traders [67]. These traders then sell to China or Yangon traders, who then sell to Singapore exporters, Europe, or SE Asia. Finally the Singapore exporters sell to India and Europe (Figure 26).

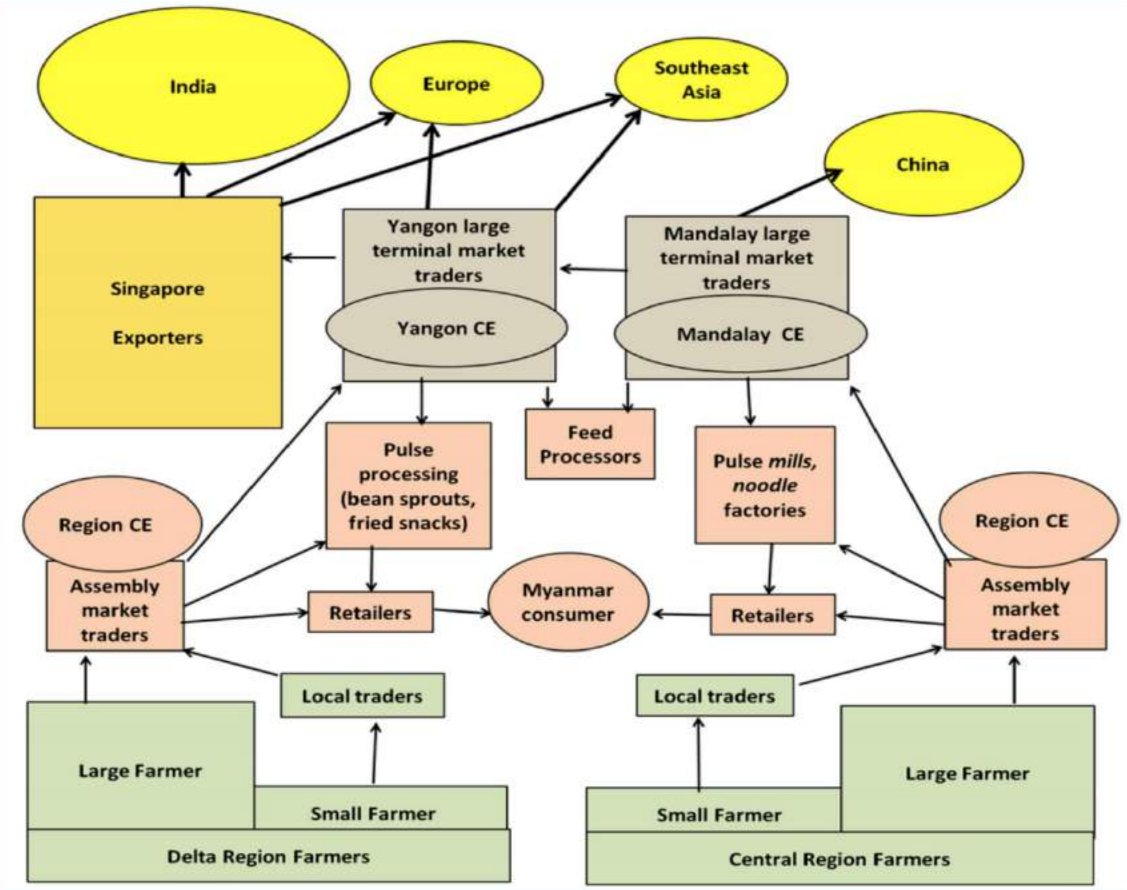


Figure 26: Commodity exchange (CE) value chain at Myanmar [67]

For vegetables and fruits, the marketing channel is simplified with less middlemen as there is no processing and the food is perishable (the primitive markets do not have storage facilities, or recordkeeping for that matter). Farmers sell their produce to truck drivers who then sell to wholesalers in Yangon or Mandalay who sell to retailers or consumers directly. The truck drivers then collect the money from the wholesalers and return it to the farmer (Figure 27).

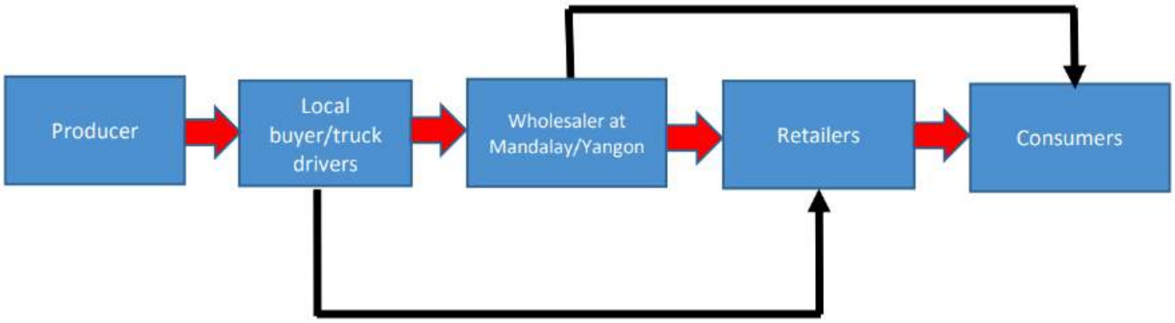


Figure 27: Major vegetable/fruits marketing channel [67]

6.2. Market trends: switching to high value crops

Paddy is the main crop grown comprising 40% of all cultivated land in Myanmar [68], with sugar cane and dry beans being the next most popular [69] (Figure 28). Other notable crops include: fresh vegetables, maize, groundnuts, fresh fruit, plantains, dry onions, sesame seed, pigeon peas, coconut, potato, and chick pea. Most small farms produce paddy during monsoon season and pulses, oilseeds, and corn during the dry months. Cash crops (rubber, tea, coffee, cotton) are beginning to be adopted but are only a small portion of total crops grown currently. Below the breakdown of crops grown based on cultivated land is shown with cereals (rice and maize) representing the majority at 44% and pulses (green gram and chick peas) coming in second at 25%.

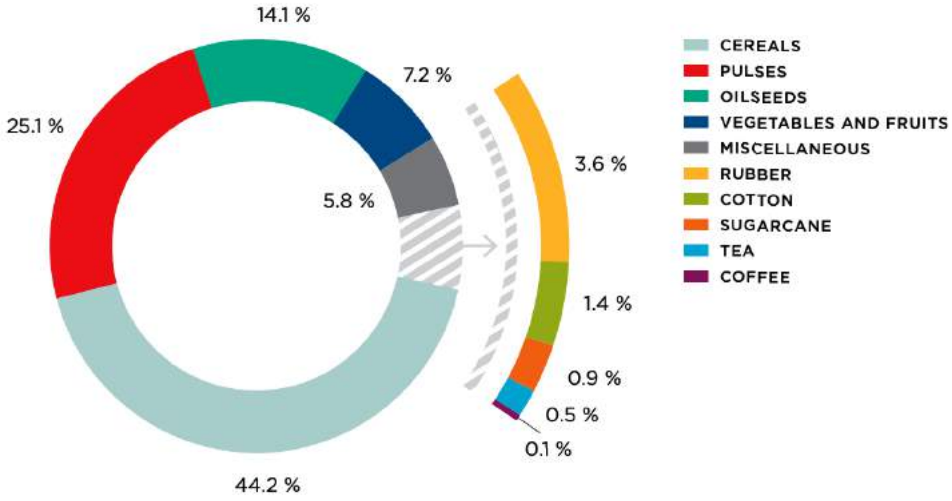


Figure 28: Cultivation area of principal commodity categories, in acres, 2017 [68]

The main export of Myanmar are pulses which are 74% of total agricultural export value. One pulse, green gram, is the most profitable pulse grown in Myanmar and also less water intensive than paddy [17]. That is the reason green gram was chosen as the traditional crop for farmers to grow during the dry season in the case study.

One issue is that the government of Myanmar has only focused on production-oriented crops for efficiency and ease instead of market-oriented to follow current trends, according to the director general of the Department of Agriculture [70]. This has led to large farms only producing paddy instead of more high value crops and according to Farmland Law, the farmer must get official approval from the government to stop growing rice. This is typically too large of a risk for farmers to take so they choose stability and steady profit, even if that means less potential profit. The small farmers that are being targeted for the purpose of this dissertation tend to be the more diversified and include vegetables and livestock compared to large farms which focus solely on paddy [38]. This insinuates that switching to high value and more water intensive crops (if an environmental study allows it due to exhibiting a low enough level of water risk) such as tomato, kale, and watermelon will be easier to convince to the target audience as a practical possibility than large farmers [22].

A market trend example is palm oil which has become a huge import for Myanmar. This could potentially be replaced by other oil-based crops such as peanuts, sesame, and sunflower seeds. Currently, melons are Myanmar’s highest value fruit export (30 times more than their second most valuable - mangos), selling $50 million annually to China alone, which represents 88% of Myanmar’s melon exports [71]. 150,000 farmers in Myanmar grow melons, 80% of those being smallholder farmers, and average net profits of $4,840/hectare. Other high value crops include: legumes, chili, potato, garlic, ginger, tomato, cucumber, avocado, tea, coffee, and bamboo shoots.

6.3. 5 P model: Pro-Poor-Public-Private-Partnerships

In 2019, the OGS (off grid solar) sector received $ 1.5 billion in investment, with growth in the early years mostly driven by equity, followed by debt in present-day [72]. This investment, although substantial, is not enough to meet the available market opportunity. This lack of capital is due to various reasons such as:

- Very few new equity investors are entering into the OGS
- Lack of exits prevent investors from liquidating to reinvest and discourages potential new investors
- Commercial investors are required to place large investments in companies with enough scale
- Investors are requiring near-term signals of profitability and positive cash flows

In reality, the demand for irrigation to improve productivity varies by crop type, access to market, quality of seed, and other non-energy-related aspects. In addition, demand is influenced by farmers' ability to pay and SWPs' affordability. This combines to create risk that many investors perceive as too high. It is therefore recommended that these small-scale solar irrigation projects have non-profits, NGOs or social enterprises to create programs that work on the ground level with farmers to consult and aid them along the way (similar to how Agrosolar and Proximity are operating in Myanmar).

The 5 P model (Pro-Poor-Public-Private-Partnerships) views the poor not only as consumers, but also as business partners [12] (Figure 29). These inclusive partnerships (unlike PPP) are participatory and cooperative instead of competitive and profit driven. A community-based approach allows for a strong feedback loop to improve the design, performance, and quality of life of the farmer with increased income. This will also ensure a long lasting success of the 20 year life of the system with continued involvement.

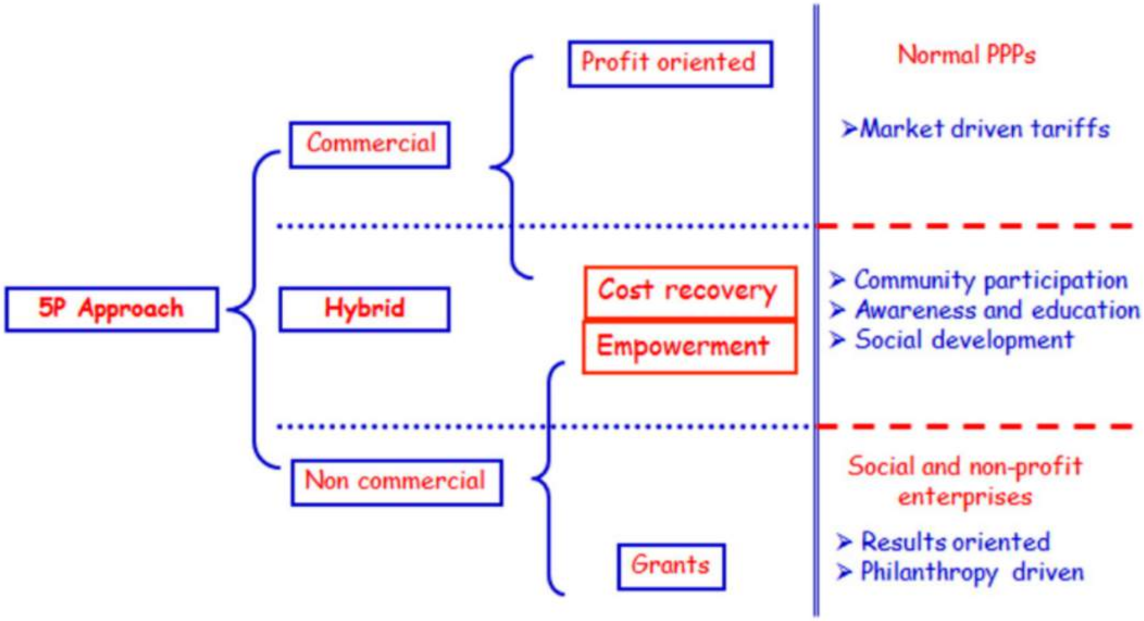


Figure 29: Key institutional innovations of the 5P approach [12]

The goal of the 5P approach is for the business model to be replicable and sustainable. By increasing productive energy users (PEU) with irrigation for agriculture, one potential business partner could be solar mini-grid developers, electrifying villages who do not have the in-house expertise, to design a solar irrigation system, with a business plan for the farmers to grow high value crops. The system could also be included in the mini-grid design to help recoup their mini-grid investment as well by increasing electricity use. Another mutually-beneficial collaboration would be with a pump manufacturer (such as Grundfos) to provide discounted equipment to a mission-driven organization to accelerate the solar pump market while also providing farmers with project, financial, and technical assistance.

6.4. Pay-as-you-grow: harvest cycle financing (PAYG)

PAYG business models allow for the consumer to make a down payment with follow up regular payments until full ownership is given. For example, Futurepump requires an initial down payment of $200 and then $25/month so that the pump is owned outright in 2 years [22]. These payments are typically with mobile money (such as Wave Money or KBZ Pay, popular in Myanmar) but can also be paid for in cash. PAYG is used in 76% of solar home system sales and 14% of pico solar sales [72]. PAYG contracts can also include covered maintenance until ownership transfer since expert technicians are difficult to find in rural areas and this concern may make farmers less willing to invest.

The PAYG model can then be adapted to farmers for Pay-as-you-grow or harvest cycle financing in which the farmers only make payments after recouping their costs post-harvest (as their cash flow greatly varies month to month). Having only two collections per year will also be more feasible for cash collection in rural areas if mobile money is not an option.

6.5. Results-based financing

Results-based financing (RBF) provides financial incentives to the private sector to overcome typical, but temporary, market development risks [73]. RBF is different from traditional grants because payment is given upon delivery of validated results. Private companies take on the full risk until the contracted results – in this case the successful sale of solar irrigation systems to rural customers – have been achieved. Companies, therefore, must have independent financing to cover the initial costs prior to payment. Funds are then dispersed after independent verification of results, which typically includes photographs of the customer with their system, proof of sale, contact info of the customer, and a small percentage of in-person verifications/audits.

RBF can combine PAYG elements in the business model and an example is seen below which incorporates the Department of Rural Development (DRD), World Bank, Ministry of Finance, independent verification agent, technical committee, and the proposed contracted solar company (Figure 30).

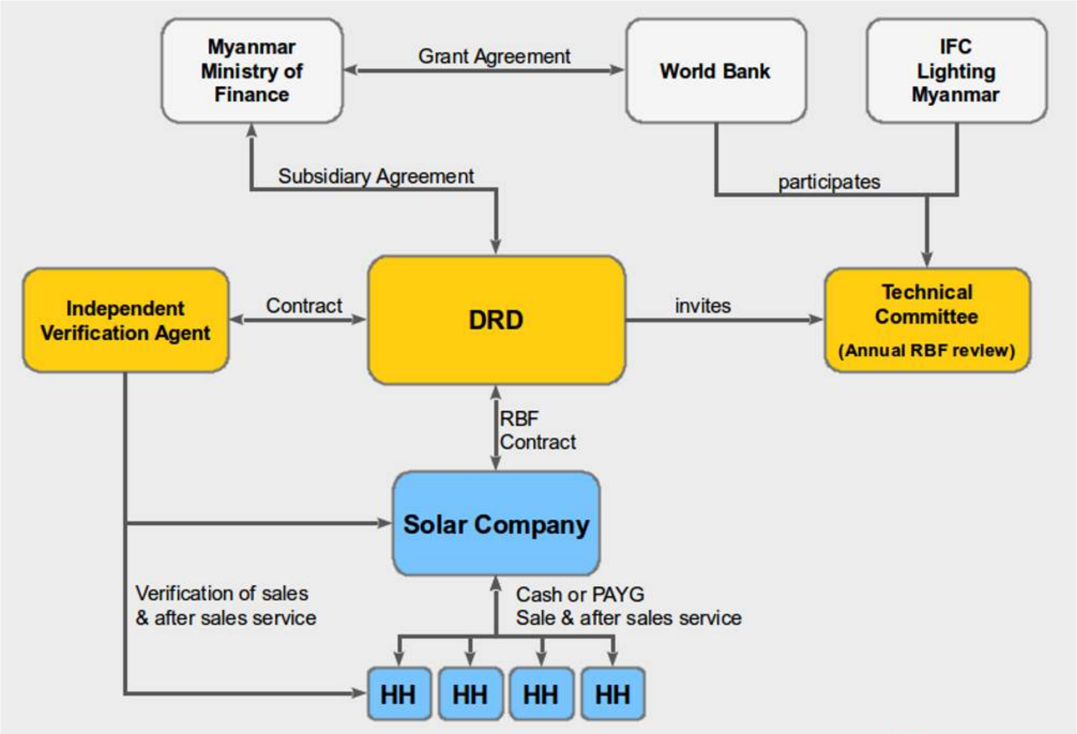


Figure 30: Organization of a RBF project [73]

6.6. Myanmar loans

According to the 2017 Global Findex, Myanmar has some of the lowest financial inclusion in Southeast Asia with only 26% of adults over the age of 15 having a bank account or mobile money. Rural areas are mostly underserved by banks, so agrarian families typically borrow money from friends, family, and money lenders with 10-15% monthly interest.

The Myanmar parliament is using legislation to promote and incentivize private sector involvement in agriculture; however, there is still a severe shortage of capital for farmers to invest in producing higher yields [11]. The state-owned Myanmar Agricultural Development Bank (MADB) offers small loans, but it is only for 22 different types of crops, with 90% of all loans being offered for paddy [68]. Seasonal loans are offered up to $126/ha for paddy and $84/ha for other crops, for a maximum of 4 hectares. The annual interest rate is only 8% since it is subsidized by the government.

These loans are small - so small that a paddy grower can only afford ¼ bag of fertilizer per acre whereas 2 bags/acre are recommended for optimal yield [70]. One main reason why the loans are so minuscule is that agricultural land in Myanmar is not able to be used as collateral for a loan [74]. (This is due to a 2013 law that was intended to protect farmers from having their land seized by banks. It would also not be seen favorably if banks confiscated farmers land and would give the bank a bad image and reputation). Another issue is that if larger loans were offered, banks would distrust farmers assuming they are borrowing for things unrelated to farming. Banks also have a difficult time assessing credit risk of potential rural borrowers as well as poor internal risk management systems due to Myanmar not having a credit bureau to track past repayment performance.

Even private banks such as Yoma Bank or MAB in Myanmar do not have products tailored specifically to farmers. The government has capped the interest at 13% for collateral loans and 16% for unsecured, so these low interest rates do not justify the risk for banks [68]. Private banks also do not have knowledge and tools to understand farmer's value chain activities. With the low loan amounts and lack of tailored products, it is therefore advisable to look outside of Myanmar for loans or grants (Figure 31).

LOAN PRODUCT NAME	LOAN DESCRIPTION	AVERAGE LOAN VALUE IN MMK (USD)
Crop loan	Seasonal loan that covers input costs, such as seeds and fertiliser, hired labour, tools, and harvesting equipment	MMK 250,000-600,000 (USD 170-408)
Livestock loan	Input finance for purchasing livestock and farm materials	MMK 200,000 (USD 136)

Figure 31: Credit products for Myanmar farmers offered by MFI Proximity Finance [68]

This problem of lack of available loans for smallholder farmers is not unique to Myanmar. For example, in 2015 the Kenya Smallholder Solar Irrigation Project (KSSI) could only find one financial institution with a suitable loan [18]. The majority of applications for this loan were rejected due to high perceived credit risk and inability to qualify. 22% annual interest is typical along with a 20-30% down payment, as well as additional crop and credit insurance.

6.7. International grants

6.7.1. Solar Irrigation for Agricultural Resilience Innovation Fund

The Solar Irrigation for Agricultural Resilience Innovation Fund (SoLAR IF) Grant is provided by the International Water Management Institute (IWMI), a non-profit, scientific research organization aiming to improve sustainable water and land use in developing countries [74]. The grant is specifically for solar irrigation projects in South Asia to work closely with the government to create scalable solutions and changes in policy. The projects will serve to develop and test technological, financial, and institutional innovations. The objectives of the IF are to:

- Bridge the gap to scale solar irrigation pumps in South Asia
- Reduce barriers for small, marginal, and women farmers
- Sustainable use of groundwater
- Enhance livelihood of small, marginal, and women farmers

The grant has $210,755 to divide between 8-10 real-world and testable projects over a 2 year period starting in March 2021. Universities, research institutes, nongovernmental organizations, public and private sector enterprises, research laboratories, and governmental agencies are all welcome to apply.

6.7.2. Powering Agriculture: an Energy Grand Challenge for Development Initiative

Powering Agriculture: an Energy Grand Challenge for Development Initiative (2012-2020) supports innovators to develop and deploy clean energy solutions in developing countries' agriculture sector [75]. The goals are to increase farmer's income, reduce reliance on fossil fuels, and enhance global food security. This was a partnership between the United States Agency for International Development (USAID), the Swedish International Development Cooperation Agency (Sida), the Government of Germany (BMZ), Duke Energy Corporation, and the Overseas Private Investment Corporation (OPIC).

24 innovators were chosen to receive grants of $500,000 - $2,000,000 to design, pilot, and deploy clean energy solutions in developing countries [76]. Private sector funds were leveraged for direct debt and equity investments though the Powering Agriculture Investment Alliance. Also, 10 pilot projects were supported by GIZ for research and development of solar irrigation systems in India and Egypt in addition to solar cooling and solar processing methods. GIZ partnered with the Food and Agriculture Organization of the United Nations to pilot a solar-powered irrigation toolbox (which was used for this dissertation's analysis).

Below are some examples of funded projects (in which SunCulture, Futurepump, and Claro were mentioned in earlier section):

- Claro Energy: pay-per-use irrigation service benefiting 1,500 farmers in India with 50 portable solar pump systems and 5 fixed PV systems (2015-2019, $500,000);
- The Earth Institute at Columbia University: three shared solar irrigation systems for 21 cooperative farms in Senegal (2013-2016, $1.1 mil);
- International Development Enterprises (iDE): installed 339 solar irrigation pumps in Honduras, Nepal, and Zambia (2013-2017, $1.5 mil);

- Futurepump**:** 1,750 deployed simple piston pumps in Kenya with 5 year warranty and pay-as-you-go financing pilot with Angaza and Green Light Planet. Future pump works with Equity Bank, SolarNow, and KuKuja Pamoja for product financing. (2015-2021, $2 mil);
- Institute for University Cooperation: 10 solar drip irrigation systems in Jordan and Lebanon (2018);
- KickStart International: 119 systems tested using foldable, flat pack solar irrigation pump that is easy for farmers in Kenya to install with average income increase of 400%. The pay-as-you-go software is paired with the pump for two different types - Angaza and Encap - and has been trialed for charging based on calendar days, pump runtime, and a hybrid of both. (2015-2019, $500,000);
- SunCulture: Complete solar irrigation kits (solar-powered pump, tank, and hoses) along with in-person agronomic advice to increase production and incomes in Kenya, Tanzania, Uganda, and Zambia. (2015-2019, $2,000,000);

6.7.3. World Bank

The World Bank provides one of the largest source of funding for developing countries with the goal of ending extreme poverty by 2030 [77]. The World Bank has funded numerous solar irrigation projects in the past including:

- $10 mil grant (for a total project cost of $24.5 mil) with the Government of Bangladesh and financing by Bangladesh Climate Resilience Fund to provide 1,300 solar irrigation for farmers to save $3.2 mil annually in diesel costs and 10,000 tons of CO_2/yr (2013) [78];
- $4.8 mil grant for Accelerating Solar Water Pumping via Innovative Financing in 165 villages across Tanzania (2017) [79];
- $80 mil grant from International Development Association (IDA, World Bank's fund for the poorest) for 2,629 irrigation systems as part of larger goals to increase agricultural productivity and market access to smallholder farmers in Ethiopia (2020) [77];

6.8. Barriers to adoption

The major obstacle faced in implementing renewable energy is affordability (cost and access to finance), accessibility (distribution to remote locations) and awareness (lack of education) [10]. Building consumer confidence in OGS products is essential— especially in younger markets—and governments play a key role in protecting consumers from exposure to low quality products or excessive financial risks by providing subsidies. Raising awareness of the benefits of OGS products is critical for drumming up demand among new potential customers. Lack of awareness among consumers is the most common reason for their lack of uptake, ranking even above affordability [72].

The Myanmar government has established an Energy Development Committee (EDC) and the National Energy Management Committee (NEMC) to oversee all activities carried out on the use and development of renewable energy under one umbrella. Several activities related to renewable energy for rural power generation are being undertaken by several organizations including the Union of Myanmar Federation of Commerce and Industry Chamber (UMFCCI) and Myanmar Engineering Society (MES) to address the shortage of the electricity in the region.

7. Conclusions and future work

"Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive."

UN Secretary General Ban Ki-moon [80]

7.1. Conclusions

The solar powered irrigation system (SPIS) design for a 0.81 hectare farm in the Central Dry Region of Myanmar to grow green gram in the dry season and monsoon rice consisted of a 2.2 kW submersible centrigual DC pump, 2.64 kW of solar PV, a 50,000 liter ferrocement elevated water tank, and movable drip line irrigation for maximum water efficiency. A financial analysis of the solar irrigation system's 20 year life resulted in a NPV of $3,518 with a 5% discount rate, IRR of 19%, and LCOE of $0.11/kWh (required irrigation amount) and $0.06/kWh (total available irrigation). The total cost of water was $0.07/kg of green gram grown and 29 metric tonnes of CO_2 avoided over its 20 year life or 10.8 mil metric tonnes of CO_2 (1.12% of Myanmar's total carbon emissions in 20 year) if all 370,000 diesel irrigation pumps in Myanmar were replaced with solar.

By analyzing for performance, on a sunny day the system can pump 67,000 liters of water per day compared to 62,000 on a partly cloudy day and only 21,000 liters on a cloudy day. Although assuming on a partly cloudy day the system is oversized 24% compared to the maximum irrigation need of 50,000 liters/day, a safety factor is comfortable as the performance can vary drastically with the unpredictable conditions. These results also confirm the need for the water tank as storage is essential for the practicality and reliability of the solar irrigation system. During all months of the year, the irrigation water needs are met by the SPIS.

Expertise is a barrier to SPIS projects as specialists are required for both installation and service, which is near impossible to find in rural areas. Also for the design, most farmers lack the knowledge required to select the pump type, size, and water requirements. 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 (which will be problematic as both the customer and project are seen as risky and largely unproven).

The main lessons learned from this work include the lack of available agriculture information such as water intensity of crops, profit margins, and selling price. Accounting for the full hydrological cycle, plant's growing stages, and seasonal rainfall, the FAO Safeguard Water Requirement tool allowed for this analysis to be completed; however, only a handful of sample crops are included so further work is needed to expand upon this software. Also, solar pump specs, pump curves, and prices were difficult to find as the market is relatively new and emerging.

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 solar savings to invest in more high value crops such as melons, mangos, or chili.

7.2. Future work

The next step of this dissertation would be to implement a real-world pilot project and track the performance of the system in comparison with the theoretical results to better fine-tune the design of future systems, ideally with free, quick, easy-to-use, open source software. Theoretical versus real world results for various crop types would then be tested for at least one year to better understand how the farmers actually utilize the system, as opposed to planned use. Grants such as the Solar Irrigation for Agricultural Resilience Innovation Fund (SoLAR IF) can potentially fund a project like this, which focuses specifically on bridging the gap to scale solar irrigation pumps for small, marginal farmers in South Asia.

The end goal would be to create inclusive partnerships with pump manufacturers, local mini-grid developers, established engineering conglomerates (for initial funding and in-house design expertise), local agriculture cooperatives (for networking and customer acquisiton) and local government policy makers (for quality assurance and incentives) to implement a scalable, affordable, and sustainable RBF and PAYG business model for smallholder farmers in Myanmar and beyond.

8. References

[1] Hartung, Hans, and Lucie Pluschke. “The Benefits and Risks of Solar-Powered Irrigation - a Global Overview.” *Food and Agriculture Organization of the United Nations*, GIZ, USaid, Duke Energy, OPIC, 2018, www.fao.org/3/i9047en/I9047EN.pdf.

[2] “2019 Buyer's Guide for Solar Water Pumps.” *Global LEAP Awards*, UKaid, Power Africa, 2019, storage.googleapis.com/e4a-website-assets/2019-Global-LEAP-SWP-Buyers-Guide_final.pdf.

[3] “Solar-Powered Irrigation.” *Agrosolar*, 2020, agrossolar.com/ (accessed May 15, 2020).

[4] “Solar Powered Irrigation Systems e-Learning Course.” *Powering Agriculture* , GIZ, OSTFALIA University of Applied Sciences , 2020, www.dis-course.net/courses/solar-powered-irrigation-systems/classroom.html (accessed June 17, 2020).

[5] Otoo, Miriam, et al. “Business Model Scenarios and Suitability: Smallholder Solar Pump-Based Irrigation in Ethiopia.” *IWMI Research Report 172: Agriculture Water Management, Making a Business Case for Smallholders*, International Water Management Institute, IFAD, CGIAR, 2018, www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub172/rr172.pdf.

[6] “Module Price Decline 2008-2020.” PV Magazine, Oct. 2020, doi:https://www.pv-magazine.com/issue/10-2020/ (accessed Nov 3, 2020).

[7] Ritchie, Hannah, and Max Roser. “Renewable Energy.” *Our World in Data*, 17 Dec. 2017, ourworldindata.org/renewable-energy (accessed June 2, 2020).

[8] “Plunging Solar Energy Prices Spell Bright Future For Clean Electricity.” *Lethal Heating*, 30 May 2020, lethalheating.blogspot.com/2020/05/plunging-solar-energy-prices-spell.html (accessed June 27, 2020).

[9] Seal, Will. “Solar for Agriculture: Empowering Farmers in Sudan.” *ESI AFRICA*, UNDP Sudan, 19 June 2020, www.esi-africa.com/industry-sectors/generation/solar/solar-for-agriculture-empowering-farmers-in-sudan/ (accessed July 5, 2020).

[10] Erdiwansyah, R., et al. “Renewable Energy in Southeast Asia: Policies and Recommendations.” *Science of The Total Environment*, vol. 670, pp. 1095-1102, 20 Mar. 2019, www.sciencedirect.com/science/article/pii/S0048969719312653.

[11] Puka-Beals, Jesse. “Upgrading Agricultural Systems: Opportunities and Challenges for Myanmar.” *The Cornell Policy Review*, 31 Aug. 2018, www.cornellpolicyreview.com/upgrading-agriculture-myanmar/ (accessed July 13, 2020).

[12] Sovacool, Benjamin K. “Confronting Energy Poverty behind the Bamboo Curtain: A Review of Challenges and Solutions for Myanmar (Burma).” *Energy for Sustainable Development*, vol. 17, no. 4, pp. 305-314, 4 May 2013, www.sciencedirect.com/science/article/pii/S0973082613000306.

[13] Pode, Ramchandra, et al. “Solution to Sustainable Rural Electrification in Myanmar.” *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 107-118, 19 Jan. 2016, www.sciencedirect.com/science/article/pii/S1364032115017037.

[14] “Mini-Grids: Powering the next Green Revolution.” Power For All, 29 Apr. 2019, www.powerforall.org/news-media/videos/powering-next-green-revolution (accessed August 18, 2020).

[15] “Myanmar: Analysis of Farm Production Economics.” *World Bank*, 2015, www.worldbank.org/en/country/myanmar/publication/myanmar-analysis-of-farm-production-economics (accessed March 22, 2020).

[16] Zorya, Sergiy. “Unleashing Myanmar's Agricultural Potential.” *World Bank Blogs*, East Asia & Pacific on the Rise, 27 May 2016, blogs.worldbank.org/eastasiapacific/unleashing-myanmar-agricultural-potential (accessed May 9, 2020).

[17] Chandel, S.S., et al. “Review of Solar Photovoltaic Water Pumping System Technology for Irrigation and Community Drinking Water Supplies.” *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 1084-1099, 21 May 2015, www.sciencedirect.com/science/article/pii/S1364032115003536.

[18] “Solar Water Pump Technology Roadmap .” *Efficiency for Access*, UKaid, May 2019, storage.googleapis.com/e4a-website-assets/Solar-Water-Pump-Technology-Roadmap.pdf.

[19] “What Are Brushless DC Motors.” *Renesas*, 2020, www.renesas.com/us/en/support/technical-resources/engineer-school/brushless-dc-motor-01-overview.html (accessed August 21, 2020).

[20] Goudarzi, Sara. “Made in Myanmar: Solar Irrigation at the Smallest Scale.” *Demand*, 2 Aug. 2016, demandasme.org/made-in-myanmar-solar-irrigation-at-the-smallest-scale/ (accessed July 7, 2020).

[21] Yeoman, Kyla. “Solar Pumps Could Boost Farm Yields in Poor Countries.” *The Christian Science Monitor*, 7 June 2013, www.csmonitor.com/World/Making-a-difference/Change-Agent/2013/0607/Solar-pumps-could-boost-farm-yields-in-poor-countries (accessed August 28, 2020).

[22] Sharma, Chhavi. “Solar Irrigation Pump Is Winner of the 2017 Ashden Award for Sustainable Energy and Water.” *The Ecologist*, 17 Nov. 2017, theecologist.org/2017/jun/12/solar-irrigation-pump-winner-2017-ashden-award-sustainable-energy-and-water (accessed October 19, 2020).

[23] “Solar Water Pumps for Farmers in the Tropics.” *Futurepump*, 20 Mar. 2020, futurepump.com/ (accessed July 26, 2020).

[24] Kirby, Alex. “Solar Energy Powers Sustainable Solutions.” *Climate News Network*, 19 Sept. 2019, climatenewsnetwork.net/solar-energy-sustainable-solutions/ (accessed September 14, 2020).

[25] Morales, Teresa. “Design of Small Photovoltaic (PV) Solar-Powered Water Pump Systems.” *Technical Note No. 28*, United States Department of Agriculture, Oct. 2010, www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_046471.pdf.

[26] Wazed, Saeed Mohammed, et al. “A Review of Sustainable Solar Irrigation Systems for Sub-Saharan Africa.” *Renewable and Sustainable Energy Reviews*, vol. 81, no. 1, pp. 1206-1225, 11 Sept. 2017, www.sciencedirect.com/science/article/pii/S1364032117311814.

[27] Alshamani , Abdulhamid. “Design and Modelling of a Large-Scale Solar Water Pumping System for Irrigation in Saudi Arabia.” *Memorial University of Newfoundland*, 2018.

[28] “Positive Displacement vs Centrifugal Pumps.” *Castle Pumps*, 2020, www.castlepumps.com/info-hub/positive-displacement-vs-centrifugal-pumps/ (accessed November 15, 2020).

[29] “Solar Piston Pump.” *Pompco*, 2020, pompco.com/en/solar-piston-pump.php (accessed December 1, 2020).

[30] “Helical Rotor Pumps - Positive Displacement Pump.” *LORENTZ*, 2020, www.lorentz.de/products-and-technology/technology/helical-rotor-pumps/ (accessed April 9, 2020).

[31] “Centrifugal Pumps.” *Centrifugal Pumps - an Overview | ScienceDirect Topics*, 2020, www.sciencedirect.com/topics/engineering/centrifugal-pumps (accessed May 4, 2020).

[32] Venot, Jean-Philippe. “A Success of Some Sort: Social Enterprises and Drip Irrigation in the Developing World.” *World Development*, vol. 79, pp. 69-81, 7 Dec. 2015, www.sciencedirect.com/science/article/pii/S0305750X15002764.

[33] Byelich, Boyd, et al. “Small Acreage Irrigation Guide.” *Water Rights and Irrigation Management*, Colorado State University, Extension, United States Department of Agriculture, Natural Resources Conservation Service, June 2013, smallfarms.usu.edu/files-ou/smallfarm-irr-guide.pdf.

[34] Polak, Paul. “A Low Cost Drip Irrigation System for Small Farmers in Developing Countries.” *JAWRA Journal of the American Water Resources Association*, vol. 33, pp. 119–124, June 2007, https://www.researchgate.net/publication/229742870_A_low_cost_drip_irrigation_system_for_small_farmers_in_developing_countries.

[35] “Irrigation: RPS Solar Pumps: America's #1 Solar Well Pumps.” *RPS Solar Pumps*, 2020, www.rpssolarpumps.com/irrigation/?gclid=EAIaIQobChMIlKSV_9a67AIVLIlbCh2vWgwjEAMYASAAEgI23PD_BwE (accessed June 18, 2020).

[36] Vyas, Harsh. “Ferrocement Is the Obvious Choice for Water Tanks in Rural India.” *Engineering For Change*, 25 Mar. 2019, www.engineeringforchange.org/news/ferrocement-obvious-choice-water-tanks-rural-india/ (accessed September 22, 2020).

[37] “3000 Gallon Norwesco Dark Green Plastic Vertical Water Storage Tank.” *National Tank Outlet*, 2020, www.ntotank.com/3000gallon-norwesco-darkgreen-vertical-water-tank-x8728422?gclid=CjwKCAjw_Y_8BRBiEiwA5MCBJhekttE-Fk5wIqodZFPtKBVJO-jpuV49q-A8TcgjycnubPlMjQKrCRoCQ_YQAvD_BwE (accessed October 1, 2020).

[38] Cho, Ame, et al. “Crop Production and Profitability in Ayeyarwady and Yangon.” *Feed the Future Innovation Lab for Food Security Policy*, Michigan State University , 1 Aug. 2017, www.canr.msu.edu/resources/crop-production-and-profitability-in-ayeyarwady-and-yangon.

[39] “As Labourers Leave Myanmar Delta, Farmers Struggle to Mechanise.” *Myanmar Times*, 6 Dec. 2016, www.mmtimes.com/business/24067-as-labourers-leave-myanmar-delta-farmers-struggle-to-mechanise.html (accessed May 17, 2020).

[40] Myint, C.C. “Nature Farming in Myanmar.” *Institute of Agriculture, Pyinmana, The Union of Myanmar*, 1989, www.infrc.or.jp/knf/PDF%20KNF%20Conf%20Data/C1-3-005.pdf.

[41] “Cost-Benefit Analysis of Irrigation Using Pumped Water for Economically Important Crops in the Dry Zone during the Early Monsoon Season.” *Livelihoods & Food Security Trust Fund*, UKaid, USaid, Australian Aid, Irish Aid, Mar. 2018, www.lift-fund.org/sites/lift-fund.org/files/publication/CBA%20of%20irrigation-%20Final%20report%20-%20acccepted.pdf .

[42] Bebs. “How to Sprout Mung Beans in a Jar (in Only 3 Days).” *Foxy Folksy*, 23 Apr. 2017, www.foxyfolksy.com/how-to-sprout-mung-beans/ (accessed September 5, 2020).

[43] Kaysha, Kawte, et al. “Performance of Mung Bean (Vigna Radiata L.) Varieties at Different NPS Rates and Row Spacing at Kindo Koysha District, Southern Ethiopia.” *Taylor & Francis*, vol. 6, 2020, www.tandfonline.com/doi/full/10.1080/23311932.2020.1771112 (accessed October 1, 2020).

[44] Garner, Reid. “Making the Right Filter Decisions for Landscape Irrigation.” Irrigation.org, 2012, www.irrigation.org/IA/FileUploads/IA/Resources/TechnicalPapers/2012/MakingTheRightFilterDecisionsForLandscapeIrrigation.pdf

[45] “Rubber Cable Pp Water Level Float Switch Differential Pressure Switch Float Level Switch.” *Alibaba*, Bingo, 2020, www.alibaba.com/product-detail/Water-Level-Switch-Rubber-Cable-PP_1959376005.html?spm=a2700.7724857.normalList.15.669e6c60k1XZNN (accessed November 2, 2020).

[46] Henke, Mike. “Friction Loss.” Potter Signal, 28 Feb. 2017, www.pottersignal.com/product/bulletin/FrictionLossMemo.pdf.

[47] “Pump Handbook.” *GRUNDFOS*, 2016, www.grundfos.com/content/dam/Global%20Site/Market%20areas/Industry/Downloads/Irrigation%20pump%20handbook.pdf.

[48] “3HP Submersible Motor 79GPM Deep Well Water Pump - 230V - 3P - 4’ - 250ft.” *Pumpsupermarket.com*, 15 Oct. 2020, www.pumpsupermarket.com/product/3hp-submersible-230v-3ph-motor-79gpm-deep-well-potable-water-pump/?utm_source=googleshopping (accessed October 15, 2020).

[49] “Tier 1 Brand And Oem 280w 330w 370w 440w High Efficiency Solar Panel.” *Alibaba*, 2020, www.alibaba.com/product-detail/Tier-1-brand-and-OEM-280w_62374239053.html?spm=a2700.galleryofferlist.topad_creative.d_title.2e4169ccDPdZCX (accessed October 15, 2020).

[50] “Aluminum Solar Mounting Ground Pv Module Support Racking.” *Alibaba*, Ckiko, 2020, www.alibaba.com/product-detail/Aluminum-solar-mounting-ground-pv-module_60737567169.html?spm=a2700.galleryofferlist.normal_offer.d_title.7ec54105kavFHK (accessed October 16, 2020).

[51] “DC-DC 5-32V to 12V 3A Automatic Voltage Stabilizer Power Converter Regulator.” *Wish*, 2020, www.wish.com/product/dc-dc-5-32v-to-12v-3a-automatic-voltage-stabilizer-power-converter-regulator-5dc1142c24bbf00a3c27374a?hide_login_modal=true (accessed October 20, 2020).

[52] “Full Power High Efficiency 1200w 24v To 12v Dc Converter 100a.” *Alibaba*, WeMaxPower, 2020, www.alibaba.com/product-detail/Full-power-high-efficiency-1200W-24v_60819377142.html?spm=a2700.7724857.normalList.166.3d9f2764a3eon4 (accessed November 1, 2020).

[53] Freling, Robert. “Solar Market Garden (SMG).” *Changemakers*, 2016, www.changemakers.com/technologywomen/entries/solar-market-garden-smg (accessed March 18k, 2020).

[54] Janjai, Serm, et al. “Satellite-Derived Solar Resource Maps for Myanmar.” *Renewable Energy*, vol. 53, pp. 132-140, 12 Dec. 2012, www.sciencedirect.com/science/article/pii/S0960148112007173.

[55] “Advanced Solar Design Software.” *HelioScope*, 2020, www.helioscope.com/ (accessed November 12, 2020).

[56] Henderson, Bill. “Comparing Electric & Diesel Water Pumps for Farmers.” *T&T Power Group*, 17 June 2019, web.ttpowergroup.com/blog/comparing-electric-diesel-water-pump (accessed October 4, 2020).

[57] Aung, Htin Linn. “Farmers Fight to Mortgage Their Farmland .” *Myanmar Times*, 7 July 2016, www.mmtimes.com/business/21251-farmers-fight-to-mortgage-their-farmland.html (accessed July 7, 2020).

[58] “Burma (Myanmar) Diesel Prices, 30-Nov-2020.” *GlobalPetrolPrices*, 30 Nov. 2020, www.globalpetrolprices.com/Burma-Myanmar/diesel_prices/ (accessed November 30, 2020).

[59] “Solar Water Pump Outlook 2019: Global Trends and Market Opportunities .” *Efficiency for Access Coalition* , UKaid, Sept. 2019, storage.googleapis.com/e4a-website-assets/Solar-Water-Pump-Outlook-2019.pdf.

[60] “Burma (Myanmar) Electricity Prices, March 2020.” *GlobalPetrolPrices*, Mar. 2020, www.globalpetrolprices.com/Burma-Myanmar/electricity_prices/ (accessed November 8, 2020).

[61] “Powering Agriculture.” *U.S. Agency for International Development*, 25 Aug. 2020, www.usaid.gov/energy/powering-agriculture (accessed December 2, 2020).

[62] “Use discounted cash flow models to make capital investment decisions.” *BC Campus,* Principles of Accounting Volume 2 Managerial Accounting*,* 2018, https://opentextbc.ca/principlesofaccountingv2openstax/chapter/use-discounted-cash-flow-models-to-make-capital-investment-decisions/ (accessed October 2, 2020).

[63] Aiman, Ummay. “Burma - Agriculture.” Burma Country Commercial Guide, US Embassy, 9 Oct. 2019, www.export.gov/apex/article2?id=Burma-Agriculture (accesssed August 6, 2020).

[64] “Irrigation.” *Australian Mungbean Association*, 2020, www.mungbean.org.au/irrigation.html (accessed December 2, 2020).

[65] ZD. “Green Gram Is New Cash Cow in Kenya's Drylands amid Climate Change.” *Xinhuanet*, 6 Jan. 2018, www.xinhuanet.com/english/2018-01/06/c_136876675.htm (accessed December 2, 2020).

[66] “Myanmar CO2 Emissions.” *Knoema*, 2019. https://knoema.com/atlas/Myanmar/CO2-emissions#:~:text=In%202019%2C%20CO2%20emissions%20for,48.3%20million%20tonnes%20in%202019 (accessed May 9, 2020).

[67] Charyulu, Kumara. “Marketing and Profitability of Crops in Pyawt Ywar Pump Irrigation Project.” ResearchGate, International Crops Research Institute for Semi Arid Tropics, Apr. 2019, www.researchgate.net/publication/334082465_Marketing_and_Profitability_of_Crops_in_Pyawt_Ywar_Pump_Irrigation_Project.

[68] “Digital Credit Scoring for Farmers: Opportunities for Agritech Companies in Myanmar.” *GSMA*, UKaid, Feb. 2020, www.gsma.com/mobilefordevelopment/wp-content/uploads/2020/02/Digital_credit_scoring_for_farmers_Opportunities_for_agritech_companies_in_Myanmar.pdf .

[69] Moore, Molly. “Myanmar: Main Crops by Production Volume 2018.” *Statista*, 18 June 2020, www.statista.com/statistics/1060675/myanmar-main-crops-by-production-volume/ (accessed July 17, 2020).

[70] Win, Su Phyo. “Cultivation of Market-Oriented Crops Important for Myanmar” *Myanmar Times*, 12 Oct. 2017, www.mmtimes.com/news/cultivation-market-oriented-crops-important-myanmar.html (accessed July 14, 2020).

[71] Thida, Lay, and Timothy May. “The Melon Value Chain: How Collaboration with the National Horticulture Trade Association Improved Prospects for Farmers of Myanmar's Most Valuable Fruit Crop.” *USAID's Value Chains for Rural Development* , USaid, Winrock International, Dec. 2019, winrock.org/wp-content/uploads/2020/01/VCRD-Melon-Value-Chain-20200116.pdf.

[72] “Off-Grid Solar Market Trends Report 2020.” Lighting Global, Lighting Global, GOGLA, ESMAP, Mar. 2020, www.lightingglobal.org/wp-content/uploads/2020/03/VIVID%20OCA_2020_Off_Grid_Solar_Market_Trends_Report_Full_High.pdf.

[73] "Annex 1 – Call for Proposals." *Department of Rural Development*, 2020.

[74] "Applications Invited for Solar Irrigation for Agricultural Resilience (SoLAR) Innovation Fund (IF)." *International Water Management Institute (IWMI)*, 15 June 2020, ngobox.org/full_grant_announcement_Applications-Invited-for-Solar-Irrigation-for-Agricultural-Resilience-(SoLAR)-Innovation-Fund-(IF)-International-Water-Management-Institute-(IWMI)-_3732 (accessed October 9, 2020).

[75] "Powering Agriculture." *U.S. Agency for International Development*, 25 Aug. 2020, www.usaid.gov/energy/powering-agriculture (accessed October 10, 2020).

[76] "Powering Agriculture: An Energy Grand Challenge for Development Final Report 2013-2019." *Powering Agriculture*, USaid, Duke Energy, OPIC, Sweden Sverige, German Cooperation, 2020, pdf.usaid.gov/pdf_docs/PA00WRSR.pdf.

[77] Woodeneh, Gelila. "World Bank Provides Additional Support for Agriculture Growth and Better Livelihood Opportunities for Ethiopia's Smallholder Farmers." *World Bank*, 15 Sept. 2020, www.worldbank.org/en/news/press-release/2020/09/15/world-bank-provides-additional-support-for-agriculture-growth-and-better-livelihood-opportunities-for-ethiopias-smallholder-farmers (accessed October 11, 2020).

[78] "Project Signing: $10 Million Grant for Solar Irrigation in Bangladesh." *World Bank*, 30 Sept. 2013, www.worldbank.org/en/news/press-release/2013/09/30/project-signing-10-million-grant-for-solar-irrigation-in-bangladesh (accessed November 5, 2020).

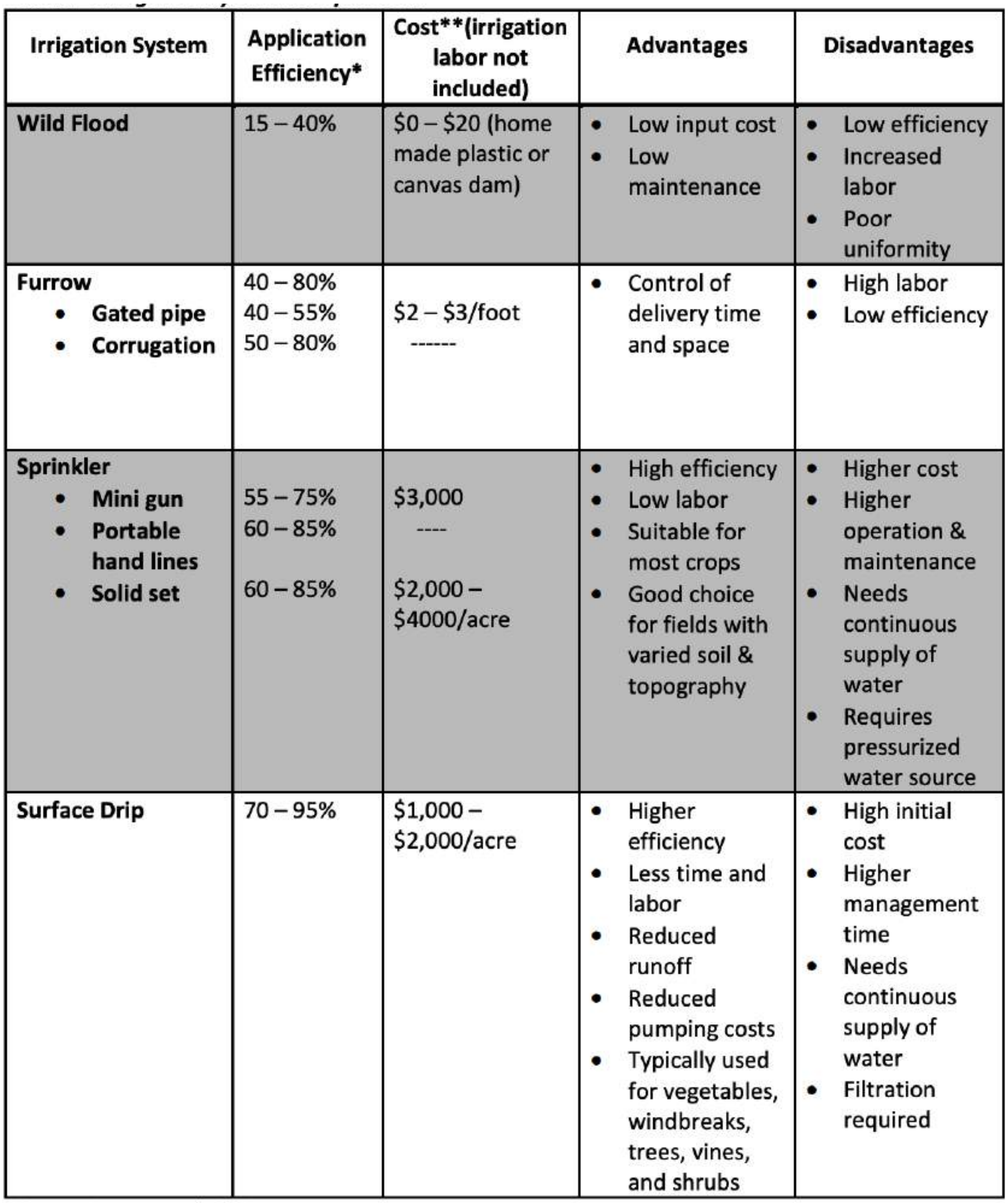
[79] "Accelerating Solar Water Pumping via Innovative Financing." *World Bank*, 2020, projects.worldbank.org/en/projects-operations/project-detail/P161757 (accessed November 1, 2020).

[80] Tian, Jun. "Enhancing Sustainability of Rural Energy Projects: Pro-Poor Public Private Partnership (5P) Approach." *5 Approach Partnerships for a Resilient Future*, United States ESCAP, 2019, www.unescwa.org/sites/www.unescwa.org/files/events/files/s5p3-un_tian.pdf.

9. Appendices

Appendix A: Irrigation methods

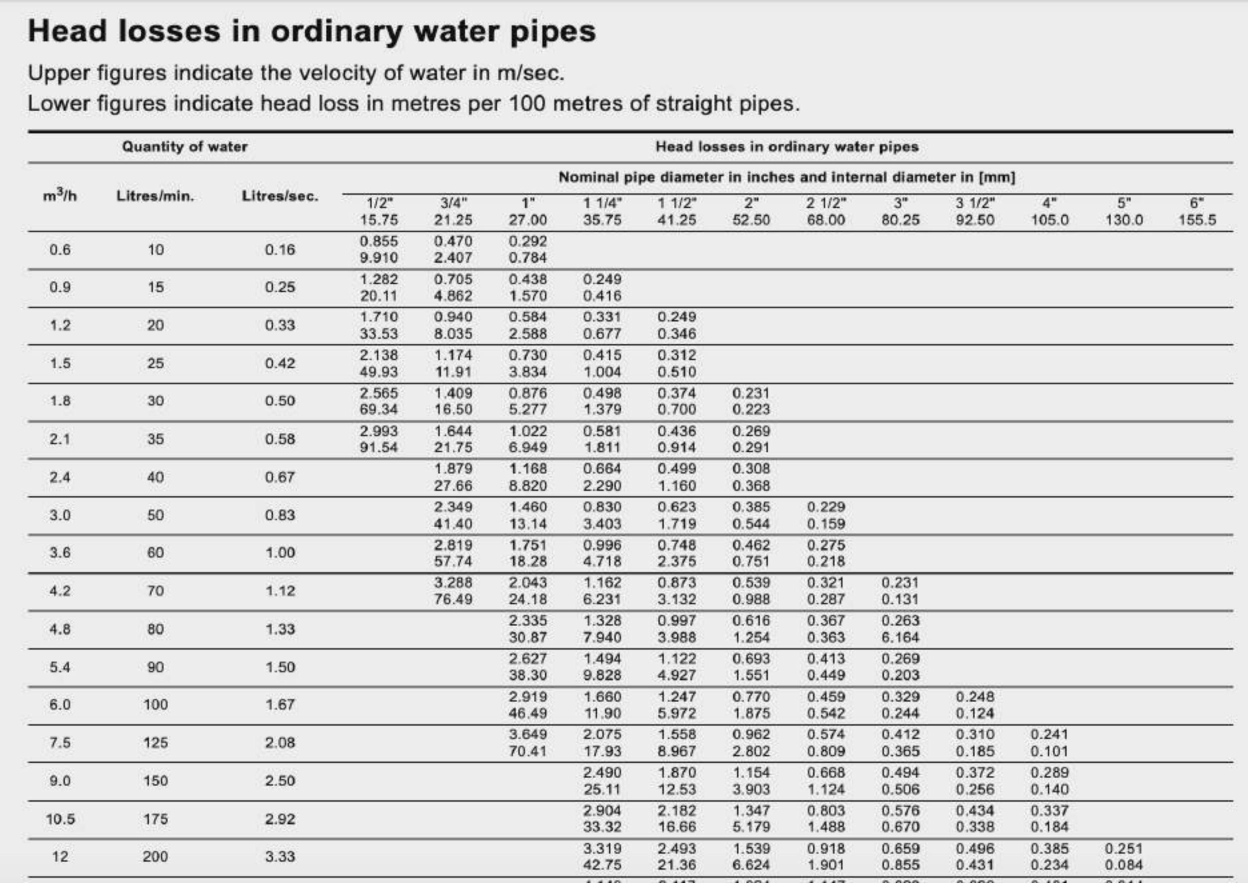
Table 15: Irrigation system comparisons [33]



Irrigation System	Application Efficiency*	Cost**(irrigation labor not included)	Advantages	Disadvantages
Wild Flood	15 – 40%	$0 – $20 (home made plastic or canvas dam)	• Low input cost • Low maintenance	• Low efficiency • Increased labor • Poor uniformity
Furrow	40 – 80%		• Control of delivery time and space	• High labor • Low efficiency
• **Gated pipe**	40 – 55%	$2 – $3/foot		
• **Corrugation**	50 – 80%	------		
Sprinkler			• High efficiency • Low labor • Suitable for most crops • Good choice for fields with varied soil & topography	• Higher cost • Higher operation & maintenance • Needs continuous supply of water • Requires pressurized water source
• **Mini gun**	55 – 75%	$3,000		
• **Portable hand lines**	60 – 85%	----		
• **Solid set**	60 – 85%	$2,000 – $4000/acre		
Surface Drip	70 – 95%	$1,000 – $2,000/acre	• Higher efficiency • Less time and labor • Reduced runoff • Reduced pumping costs • Typically used for vegetables, windbreaks, trees, vines, and shrubs	• High initial cost • Higher management time • Needs continuous supply of water • Filtration required

Appendix B: Head loss of water in pipes

Table 16: Head losses in ordinary pipes [47]



Head losses in ordinary water pipes

Upper figures indicate the velocity of water in m/sec.
Lower figures indicate head loss in metres per 100 metres of straight pipes.

Quantity of water			Head losses in ordinary water pipes											
			Nominal pipe diameter in inches and internal diameter in [mm]											
m^3/h	Litres/min.	Litres/sec.	1/2" 15.75	3/4" 21.25	1" 27.00	1 1/4" 35.75	1 1/2" 41.25	2" 52.50	2 1/2" 68.00	3" 80.25	3 1/2" 92.50	4" 105.0	5" 130.0	6" 155.5
0.6	10	0.16	0.855 9.910	0.470 2.407	0.292 0.784									
0.9	15	0.25	1.282 20.11	0.705 4.862	0.438 1.570	0.249 0.416								
1.2	20	0.33	1.710 33.53	0.940 8.035	0.584 2.588	0.331 0.677	0.249 0.346							
1.5	25	0.42	2.138 49.93	1.174 11.91	0.730 3.834	0.415 1.004	0.312 0.510							
1.8	30	0.50	2.565 69.34	1.409 16.50	0.876 5.277	0.498 1.379	0.374 0.700	0.231 0.223						
2.1	35	0.58	2.993 91.54	1.644 21.75	1.022 6.949	0.581 1.811	0.436 0.914	0.269 0.291						
2.4	40	0.67		1.879 27.66	1.168 8.820	0.664 2.290	0.499 1.160	0.308 0.368						
3.0	50	0.83		2.349 41.40	1.460 13.14	0.830 3.403	0.623 1.719	0.385 0.544	0.229 0.159					
3.6	60	1.00		2.819 57.74	1.751 18.28	0.996 4.718	0.748 2.375	0.462 0.751	0.275 0.218					
4.2	70	1.12		3.288 76.49	2.043 24.18	1.162 6.231	0.873 3.132	0.539 0.988	0.321 0.287	0.231 0.131				
4.8	80	1.33			2.335 30.87	1.328 7.940	0.997 3.988	0.616 1.254	0.367 0.363	0.263 6.164				
5.4	90	1.50			2.627 38.30	1.494 9.828	1.122 4.927	0.693 1.551	0.413 0.449	0.269 0.203				
6.0	100	1.67			2.919 46.49	1.660 11.90	1.247 5.972	0.770 1.875	0.459 0.542	0.329 0.244	0.248 0.124			
7.5	125	2.08			3.649 70.41	2.075 17.93	1.558 8.967	0.962 2.802	0.574 0.809	0.412 0.365	0.310 0.185	0.241 0.101		
9.0	150	2.50				2.490 25.11	1.870 12.53	1.154 3.903	0.668 1.124	0.494 0.506	0.372 0.256	0.289 0.140		
10.5	175	2.92				2.904 33.32	2.182 16.66	1.347 5.179	0.803 1.488	0.576 0.670	0.434 0.338	0.337 0.184		
12	200	3.33				3.319 42.75	2.493 21.36	1.539 6.624	0.918 1.901	0.659 0.855	0.496 0.431	0.385 0.234	0.251 0.084	

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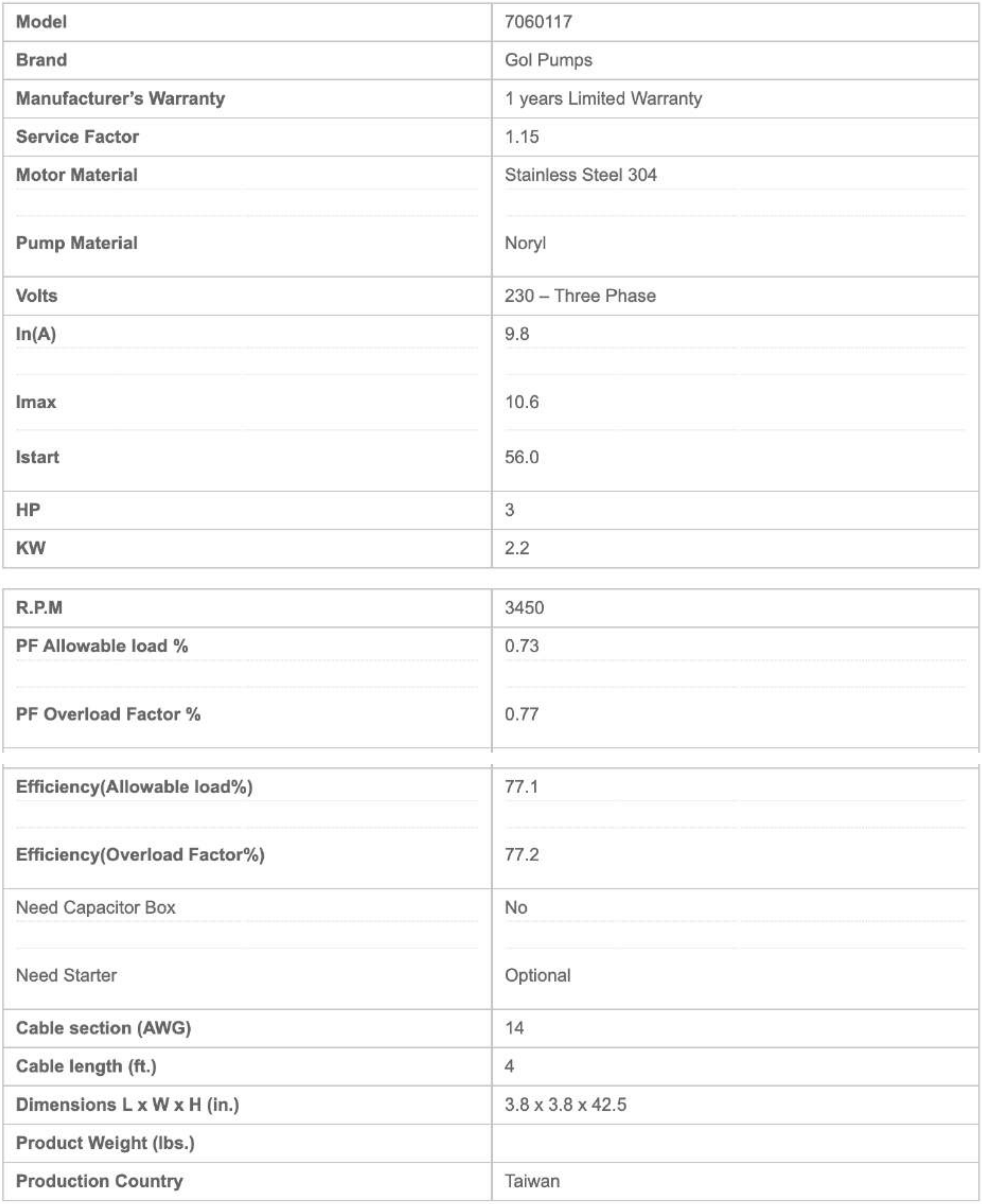
Appendix C: Submersible pump specs

Table 17: 2.2 kW pump specs [48]



Model	7060117
Brand	Gol Pumps
Manufacturer's Warranty	1 years Limited Warranty
Service Factor	1.15
Motor Material	Stainless Steel 304
Pump Material	Noryl
Volts	230 – Three Phase
In(A)	9.8
Imax	10.6
Istart	56.0
HP	3
KW	2.2
R.P.M	3450
PF Allowable load %	0.73
PF Overload Factor %	0.77
Efficiency(Allowable load%)	77.1
Efficiency(Overload Factor%)	77.2
Need Capacitor Box	No
Need Starter	Optional
Cable section (AWG)	14
Cable length (ft.)	4
Dimensions L x W x H (in.)	3.8 x 3.8 x 42.5
Product Weight (lbs.)	
Production Country	Taiwan

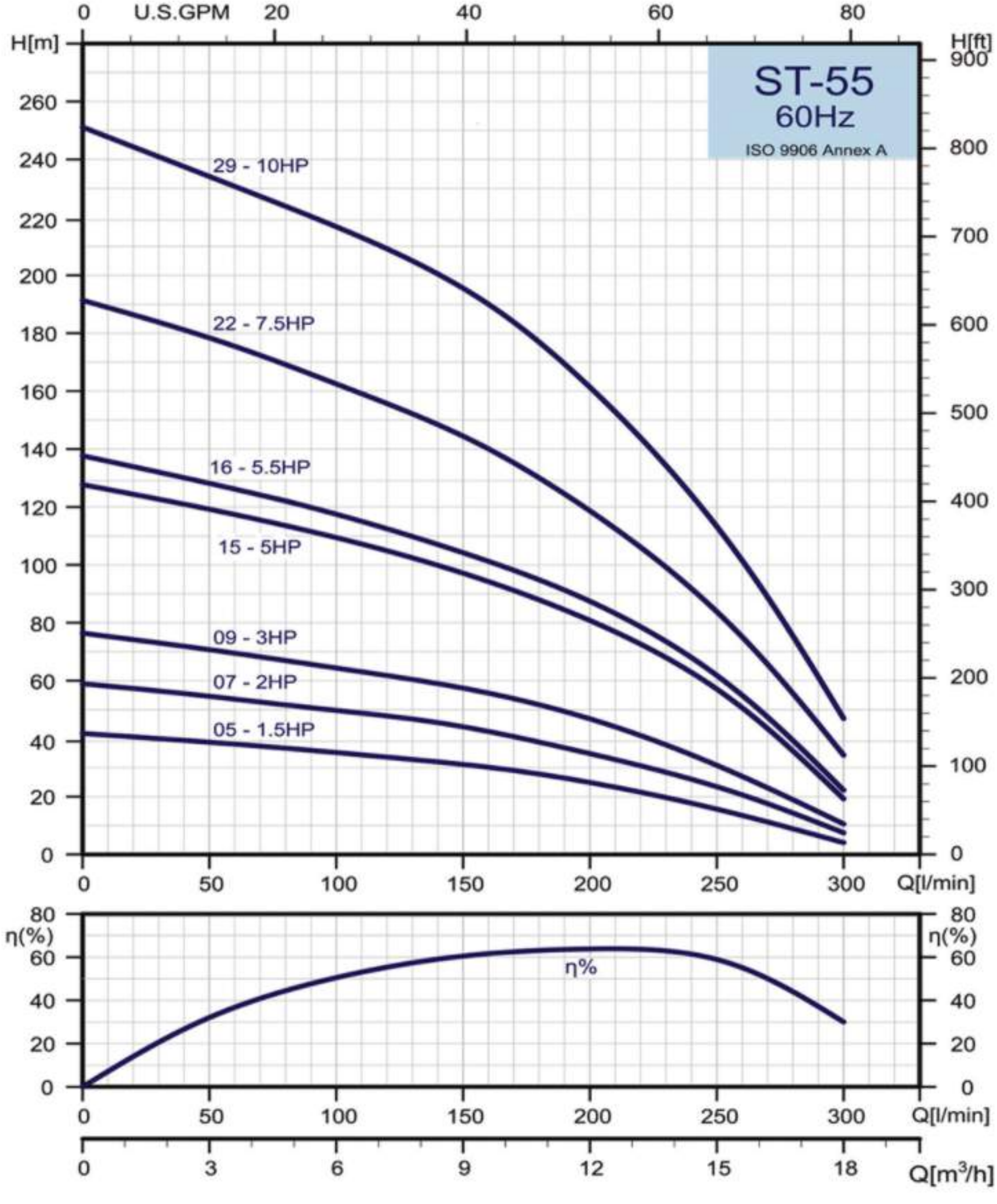
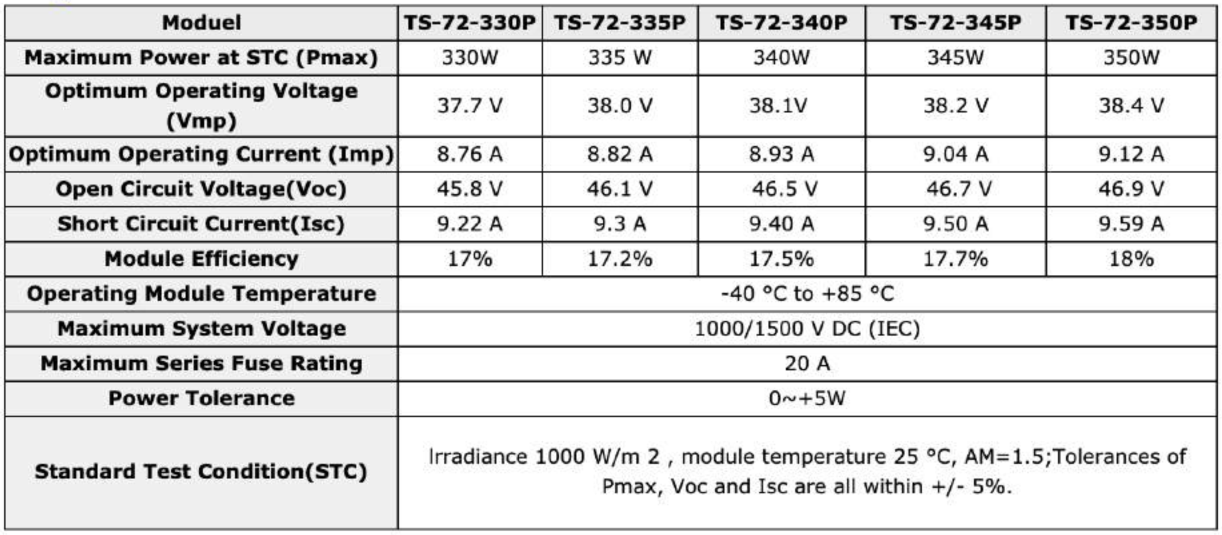


Figure 32: 2.2 kW pump curve [48]

Appendix D: Solar PV manufacturing information

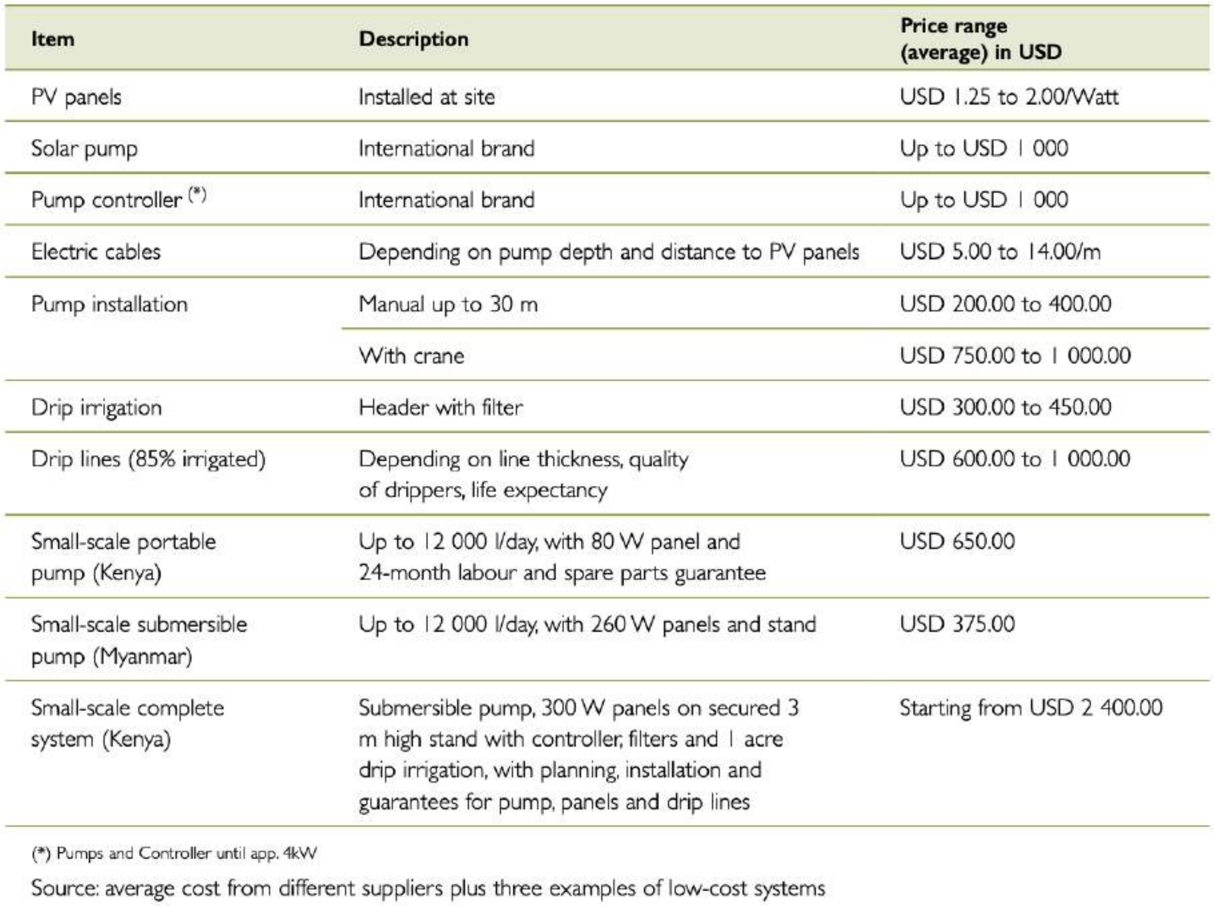
Table 18: PV Cell mfg info - Poly 72 [49]



Moduel	TS-72-330P	TS-72-335P	TS-72-340P	TS-72-345P	TS-72-350P
Maximum Power at STC (Pmax)	330W	335 W	340W	345W	350W
Optimum Operating Voltage (Vmp)	37.7 V	38.0 V	38.1V	38.2 V	38.4 V
Optimum Operating Current (Imp)	8.76 A	8.82 A	8.93 A	9.04 A	9.12 A
Open Circuit Voltage(Voc)	45.8 V	46.1 V	46.5 V	46.7 V	46.9 V
Short Circuit Current(Isc)	9.22 A	9.3 A	9.40 A	9.50 A	9.59 A
Module Efficiency	17%	17.2%	17.5%	17.7%	18%
Operating Module Temperature	-40 °C to +85 °C				
Maximum System Voltage	1000/1500 V DC (IEC)				
Maximum Series Fuse Rating	20 A				
Power Tolerance	0~+5W				
Standard Test Condition(STC)	Irradiance 1000 W/m 2 , module temperature 25 °C, AM=1.5;Tolerances of Pmax, Voc and Isc are all within +/- 5%.				

Appendix E: Project costing examples

Table 19: Cost estimation for SPIS [1]



Item	**Description**	**Price range (average) in USD**
PV panels	Installed at site	USD 1.25 to 2.00/Watt
Solar pump	International brand	Up to USD 1 000
Pump controller (*)	International brand	Up to USD 1 000
Electric cables	Depending on pump depth and distance to PV panels	USD 5.00 to 14.00/m
Pump installation	Manual up to 30 m	USD 200.00 to 400.00
	With crane	USD 750.00 to 1 000.00
Drip irrigation	Header with filter	USD 300.00 to 450.00
Drip lines (85% irrigated)	Depending on line thickness, quality of drippers, life expectancy	USD 600.00 to 1 000.00
Small-scale portable pump (Kenya)	Up to 12 000 l/day, with 80 W panel and 24-month labour and spare parts guarantee	USD 650.00
Small-scale submersible pump (Myanmar)	Up to 12 000 l/day, with 260 W panels and stand	USD 375.00
Small-scale complete system (Kenya)	Submersible pump, 300 W panels on secured 3 m high stand with controller, filters and 1 acre drip irrigation, with planning, installation and guarantees for pump, panels and drip lines	Starting from USD 2 400.00

(*) Pumps and Controller until app. 4kW

Source: average cost from different suppliers plus three examples of low-cost systems

Appendix F: Solar radiation maps of Myanmar

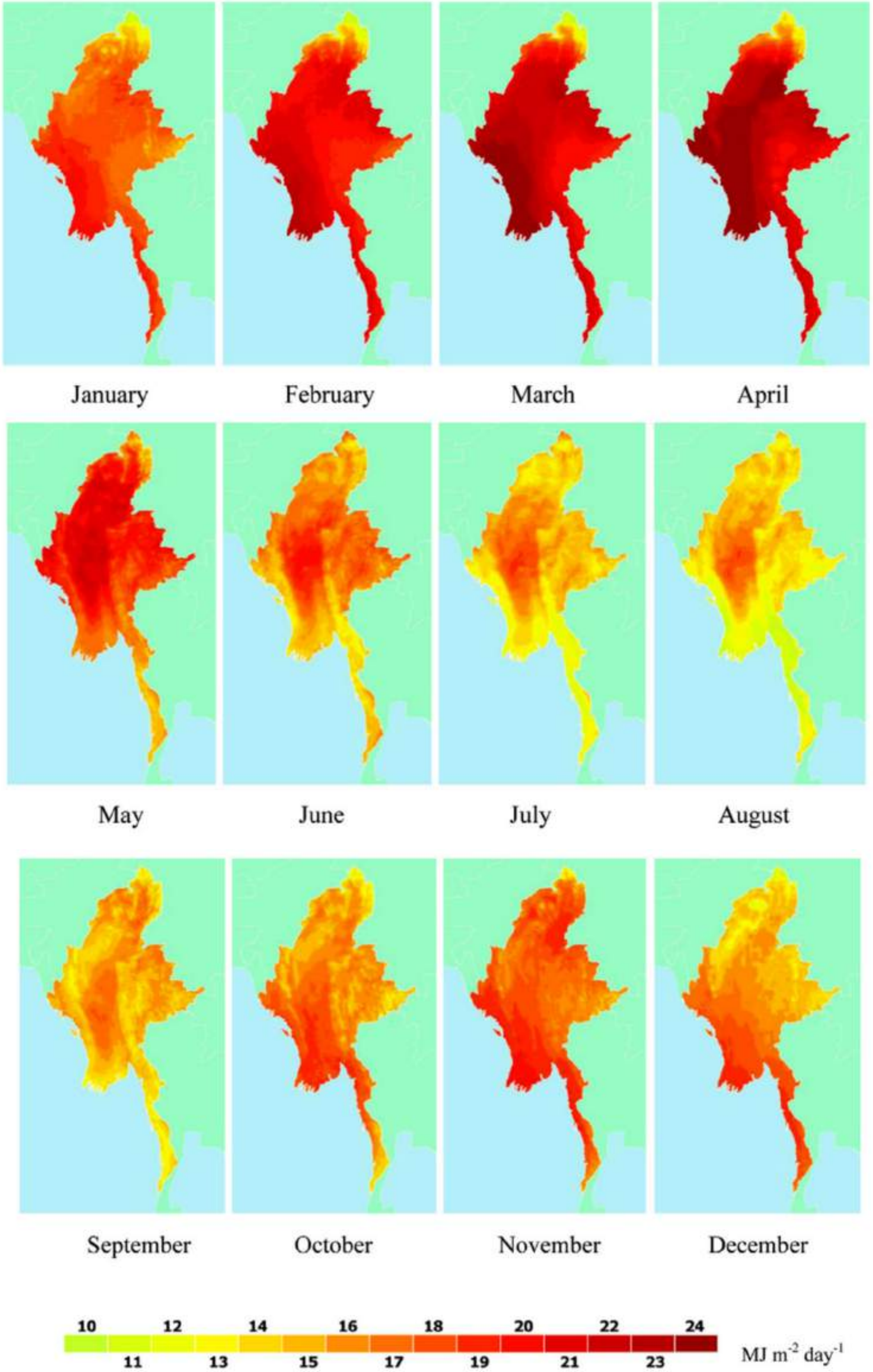
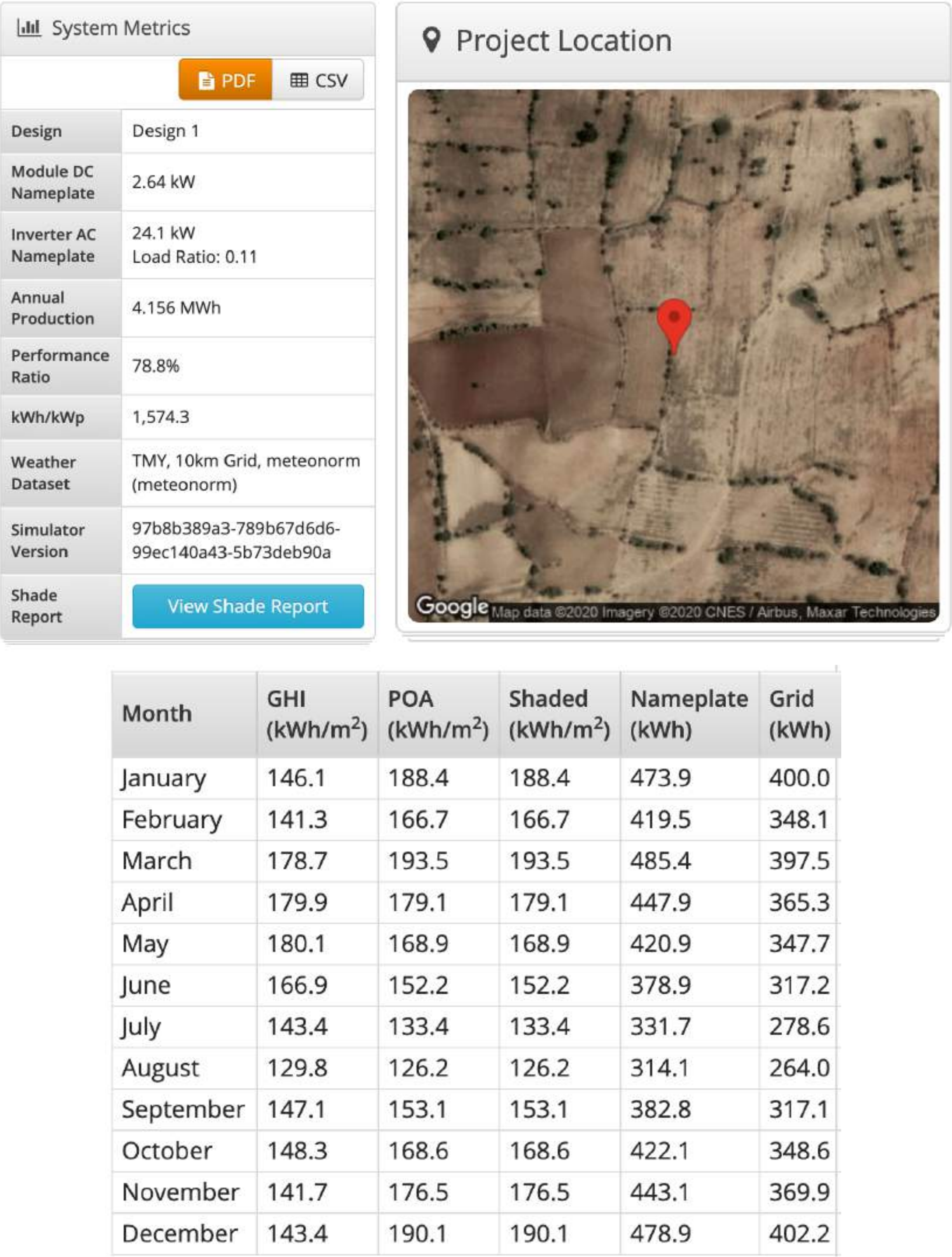


Fig. 5. Geographical distribution of monthly average solar irradiation.

Figure 33: Satellite-driven solar resource maps of monthly average solar radiation, 1998-2010 [54]

Appendix G: Helioscope solar design



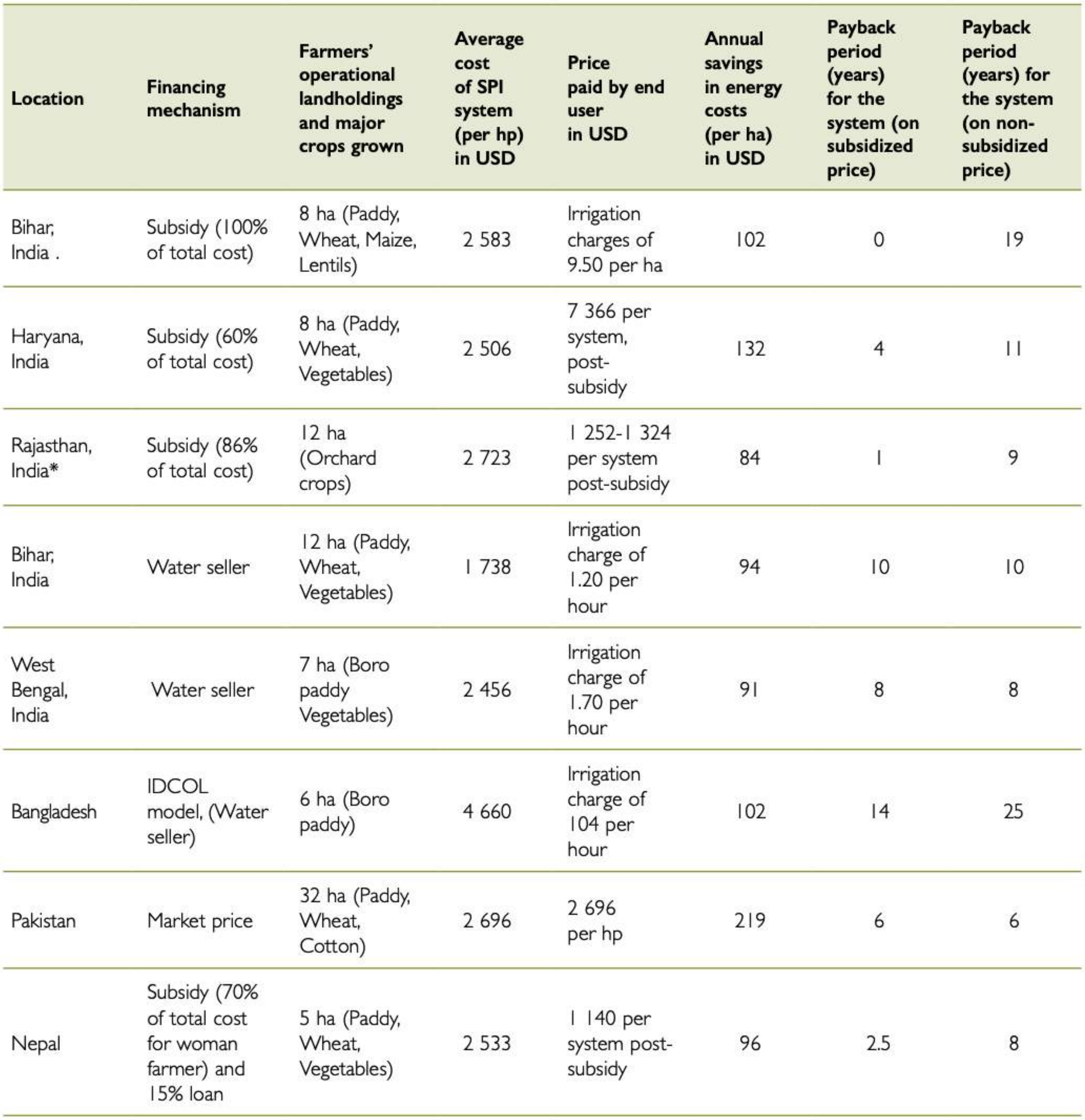
Design	Design 1
Module DC Nameplate	2.64 kW
Inverter AC Nameplate	24.1 kW Load Ratio: 0.11
Annual Production	4.156 MWh
Performance Ratio	78.8%
kWh/kWp	1,574.3
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Simulator Version	97b8b389a3-789b67d6d6-99ec140a43-5b73deb90a
Shade Report	View Shade Report

Month	GHI (kWh/m^2)	POA (kWh/m^2)	Shaded (kWh/m^2)	Nameplate (kWh)	Grid (kWh)
January	146.1	188.4	188.4	473.9	400.0
February	141.3	166.7	166.7	419.5	348.1
March	178.7	193.5	193.5	485.4	397.5
April	179.9	179.1	179.1	447.9	365.3
May	180.1	168.9	168.9	420.9	347.7
June	166.9	152.2	152.2	378.9	317.2
July	143.4	133.4	133.4	331.7	278.6
August	129.8	126.2	126.2	314.1	264.0
September	147.1	153.1	153.1	382.8	317.1
October	148.3	168.6	168.6	422.1	348.6
November	141.7	176.5	176.5	443.1	369.9
December	143.4	190.1	190.1	478.9	402.2

Figure 34: Helioscope results and inputs [55]

Appendix H: Payback period project examples

Table 20: Payback period for solar powered irrigation pumps under different financial models [1]



Location	Financing mechanism	Farmers' operational landholdings and major crops grown	Average cost of SPI system (per hp) in USD	Price paid by end user in USD	Annual savings in energy costs (per ha) in USD	Payback period (years) for the system (on subsidized price)	Payback period (years) for the system (on non-subsidized price)
Bihar, India .	Subsidy (100% of total cost)	8 ha (Paddy, Wheat, Maize, Lentils)	2 583	Irrigation charges of 9.50 per ha	102	0	19
Haryana, India	Subsidy (60% of total cost)	8 ha (Paddy, Wheat, Vegetables)	2 506	7 366 per system, post-subsidy	132	4	11
Rajasthan, India*	Subsidy (86% of total cost)	12 ha (Orchard crops)	2 723	1 252-1 324 per system post-subsidy	84	1	9
Bihar, India	Water seller	12 ha (Paddy, Wheat, Vegetables)	1 738	Irrigation charge of 1.20 per hour	94	10	10
West Bengal, India	Water seller	7 ha (Boro paddy Vegetables)	2 456	Irrigation charge of 1.70 per hour	91	8	8
Bangladesh	IDCOL model, (Water seller)	6 ha (Boro paddy)	4 660	Irrigation charge of 104 per hour	102	14	25
Pakistan	Market price	32 ha (Paddy, Wheat, Cotton)	2 696	2 696 per hp	219	6	6
Nepal	Subsidy (70% of total cost for woman farmer) and 15% loan	5 ha (Paddy, Wheat, Vegetables)	2 533	1 140 per system post-subsidy	96	2.5	8