



Evaluating Solar Photovoltaic Water Pumping Systems in Khon Kaen, Thailand

An Interactive Qualifying Project Submitted to the Faculty of Worcester Polytechnic Institute and Chulalongkorn University in partial fulfillment of the requirements for the Degree of Bachelor of Science.

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Sponsored by

The Population and Community Development Association

Submitted on

March 4, 2020



Acknowledgments

We would like to thank PDA for the opportunity to carry out this project, and for the continued support of PDA both at Bangkok Headquarters and at the CBIRD Ban Phai. Without Director Mr. Vilas Techo, Dr. Wolfgang Frank, Mr. Chatchai Montklung and Ms. Narudee Aengwanich's assistance in understanding PDA's goals and organizing our visit to Khon Kaen, this project would not have been possible.

We are very thankful for the assistance we received from Mr. Manop Pimsawan, whose guidance and knowledge in all the villages we visited was crucial to understanding the PVWPS's and the communities where they were installed. We would also like to thank Mr. Nipon Lohharattanakorn, Mr. Sangwian Sornban and Mr. Tawon Vichai, as well as the members of the village water committees of Ban Lan, Nong Wang and Ban Wang Saeng, for their willingness to collaborate both during our visits and in correspondence afterwards.

We would like to thank our advisors Professor Numpon Insin, Professor Supawan Tantayanon and Professor Siripastr Jayanta from Chulalongkorn University and Professor Brigitte Servatius and Professor Esther Boucher-Yip from Worcester Polytechnic Institute for their continued guidance throughout our research.

Lastly, we would like to say thank you to Chulalongkorn University for hosting us for the duration of this project. As a team comprised of students from both Thailand and the United States, we were honored to have the opportunity to combine our knowledge and cultures to work on a project of such significance.

Abstract

The Population and Community Development Association installed solar photovoltaic water pumping systems (PVWPS's) in rural villages in the province of Khon Kaen, Thailand, in response to the population's ongoing problem of lack of access to affordable water. Through interviews and observation of three villages, our team compared the cost and technical performance of PVWPS's to those of grid-powered pumps, and identified their socio-economic and environmental effects.

Executive Summary

The Problem

As global temperatures rise, many people across the world struggle to obtain enough clean water from surface or underground reservoirs. For smallholder farmers and residents of rural villages, water sources can be scarce, and using grid electricity to pump water is very costly (Ngumbi, 2019).

In Northeast Thailand, increasingly intense drought seasons and high electricity prices severely impact village life. The Population and Community Development Association (PDA), a Thai non-governmental organization, identified lack of resources to access water as one of the Northeast's greatest barriers to reducing poverty. In the province of Khon Kaen, PDA began to help villages install solar photovoltaic water pumping systems (PVWPS's) to bring a reliable and affordable energy source to pump water in these regions. PVWPS's employ solar arrays to power pumps without the need to purchase electricity from an outside source.

Goal & Objectives

This project aimed to help PDA determine through a holistic analysis if PDA's PVWPS program was worth replicating across Khon Kaen. We did this by visiting three locations in the region of Khon Kaen: Ban Lan, Nong Wang and Ban Wang Saeng. There, we observed the communities and interviewed community members and local authorities.

We developed three main objectives: (1) to provide PDA with updated information on PVWPS's in Khon Kaen, Thailand, (2) to compare the cost and technical performance of PVWPS's installed in Khon Kaen to grid-powered water pumps, and (3) to identify environmental and social changes caused by the PVWPS's in Khon Kaen, Thailand.

Findings

Finding 1: PDA's PVWPS program should be replicated in other villages

Based on our results our group determined that PDA's PVWPS program is worth replicating across Thailand. Villages' participation in PDA's PVWPS program clearly benefits them in many ways, regardless of their size or the PVWPS application, which indicates that the program could be suited for any community.

Finding 2: PVWPS's had little to no technical problems

Each village had different areas that benefited most from a PVWPS installation. For Ban Lan and Ban Wang Saeng, this was household applications, while in Nong Wang, it was irrigation. None of the villages had problems with the PVWPS's.

Finding 3: PDA-installed tanks do not provide enough water pressure for the village

Villages stored water using tanks provided by PDA. In most cases gravity seemed to be the most effective method for distribution, however, in Nong Wang, there was not enough water pressure to irrigate their crops, due to the placement of their tank.

Recommendation 1: Raise tanks to improve water distribution

We propose raising the storage tanks, or building taller tanks to increase water pressure through the use of gravity without having to use more electricity.

Finding 4: Dual systems prove to be the most beneficial method in these villages

Ban Lan and Ban Wang Saeng used grid-powered pumps in a dual pumping system. Water storage was not enough to supply the village throughout the night so pumping needed to be continued for household use. Increasing storing capacity is not economically feasible because the village would also need to increase the number of PVWPS's. Batteries are another option, but they can be harmful to the environment, although they may be affordable. A dual system is the most effective way for these villages to obtain water.

Finding 5: PVWPS's benefit villages financially

All villages had different water fees in THB per cubic meter and in Ban Lan residents paid a monthly maintenance fee. These payments went to the village water committee, who in turn paid the electric company on behalf of the entire village. Since the installation of PVWPS's, the fee paid by the village to the electric company decreased. While some residents may spend more on water month-to-month, they profit through improved water availability and village savings.

Finding 6: PVWPS's for irrigation become cheaper than grid-powered systems after 9.25 years

For villages that are considering installing a PVWPS for irrigation pumping, a cost comparison between solar and grid power reveals that after 9.25 years, grid power would be more expensive than solar power, barring any necessary maintenance.

Finding 7: Users are pleased with PVWPS performance

There had been no instances of the equipment breaking down or crisis situations that could lead residents to question the new system. All users expressed satisfaction with the system and shared that it greatly improved their quality of life

Finding 8: Village water committees were empowered, but need additional training

In all cases we witnessed an extraordinary level of organization when it came to water management and farming. Village initiatives also show the beginnings of a creative mentality that is developing in these communities. However, while village committees seemed to have taken ownership of the day-to-day maintenance of the PVWPS's, such as cleaning the panels and operating the system, this sense of ownership did not extend to all aspects of the PVWPS. All villages mentioned that they would need to contact PDA to perform any technical maintenance.

Recommendation 2: Provide technical training to village water committee members

While PDA currently prides itself on empowering local communities to take charge of their own system, it is clear that these villages require additional technical education so that they feel confident enough to make repairs on their own. Teaching the residents about the maintenance of the PVWPS would provide them added independence, and simplify PDA's role in several villages.

Finding 9: Statistics do not always reflect the reality of village committee gender ratios

PDA encourages balanced gender ratios as the organization believes that it leads to healthy community life. In all the villages, this ratio seemed to approach equality, but the social dynamics we witnessed did not necessarily reflect the reality on paper. It is possible that women felt the need to stay quiet due to lack of education, which might affect the dynamics between genders, with women deferring to men's decisions.

Recommendation 3: Provide technical training to women in village water committees

It would be beneficial to ensure that women are educated on technical matters just as much as men, to give them equal standing among local authorities. Ensuring that residents of these villages can look to women as much as men in cases of crisis may empower village water committees to have a more balanced participation between genders.

Finding 10: None of the three villages financed the installation of their PVWPS's

None of the village residents personally financed the installation; the PVWPS's were financed by PDA's donors. This does not lead to financial empowerment from residents of these villages.

Recommendation 4: Implement a payback plan for villages with many users

PDA could consider implementing a payback system with some of these villages to allow them to develop financial independence and empower them to make decisions for the PVWPS's. Each village could aspire to pay back the installation cost of approximately 250,000 THB. While the villages where PVWPS are currently installed may not be willing to begin to pay for what they received as a donation, PDA could keep this strategy in mind for future projects.

Finding 11: Villages have no environmentally-sound disposal plan

The PVWPS's did not generate any air pollution while used. They also took up very little space. However, none of the villages had a plan for disposal of the solar panels once they stop working. PDA stated that each village will have to decide what to do once that moment comes; however, the authorities in each village had no disposal plan.

Recommendation 5: Prepare an environmentally-sound disposal plan

We recommend that PDA assist the villages in developing a method for properly disposing of the PVWPS's without harming the environment, such as training on how to take apart the solar arrays so that they can be recycled and informing them of the resources they have at their disposal. We also recommend that PDA begin to initiate a larger discourse with regional or national authorities on the topic.

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1. Introduction

As global temperatures rise, many people across the world struggle to obtain enough clean water from surface or underground reservoirs. For smallholder farmers and residents of rural villages, water sources can be scarce, and using grid electricity to pump water is very costly (Ngumbi, 2019). Lack of sufficient electricity to access usable water puts crops and human health at risk, and the need to resort to outside energy sources often leaves villages in severe debt (Kroeksakul, Naipinit, & Sakolnakorn, 2011).

In Northeast Thailand, increasingly intense drought seasons and high electricity prices severely impact village life. The Population and Community Development Association (PDA), a Thai non-governmental organization focused on community development, identified lack of resources to access usable water as one of the Northeast's greatest barriers to reducing poverty. In the province of Khon Kaen, PDA began to help villages install solar photovoltaic water pumping systems (PVWPS's) in the last decade to bring a reliable and affordable energy source for water pumping in these regions.

PVWPS's employ solar arrays to power pumps at a lower cost than pumps powered by grid electricity. Although PVWPS's are expensive upfront, it takes only a few years for users to see a return on investment (García et al., 2019). Their installation can offer small communities a chance at financial independence and reliable energy.

This project aimed to help PDA determine through a holistic analysis if PDA's PVWPS program is worth replicating across Khon Kaen. This report provides PDA with updated information on three PVWPS's, comparing their cost and technical performances to those of grid-powered pumps, and identifying the environmental and social changes they caused in the communities where they were installed.

2. Background

Our project looked at the effect of using PVWPS's to partially replace the use of grid electricity to pump water for household and irrigation applications. In this chapter, we introduce Khon Kaen, the Thai province where this project took place, and its population's struggle to power water pumps. We also present this project's sponsor, the Population and Community Development Association (PDA), whose PVWPS initiative we studied in three different communities. Viewing these in light of global studies on PVWPS's, a clear pattern for assessing their impact emerges.

2.1 Khon Kaen

Khon Kaen (Figure 1) is a province in Northeastern Thailand with an area of 4,203 square miles and has a population of 1,802,872 according to the Official Statistics Registration System's population and house statistics report for the year 2019. Sixty-two percent of the province relies on agriculture, and these regions are impacted the heaviest by water shortages (Friend & Thinphanga, 2018). Khon Kaen's geography consists mostly of lowland plateaus along with limestone mountain areas at an altitude of about 200-250 meters above sea level (Esri Thailand, 2012).



Figure 1: Map of Thailand with Khon Kaen indicated in red
(Thailand Khon Kaen Locator Map, 2009)

Khon Kaen depends on agriculture for economic stability. Farms, both large-scale and family-owned, mostly grow sugarcane, rice and rubber trees (Kuehn, 2019). Unfortunately, crops in Khon Kaen struggle to survive due to the hot climate and the strongest solar radiation in the country (Janjai, Masiri, Pattarapanitchaim, & Laksanaboonsong, 2013). The fact that the region rarely experiences rainfall during the dry season only intensifies these arid conditions.

To power pumps that extract water from nearby lakes, rivers, or underground reservoirs, residents often resort to expensive grid electricity (Baltas & Russell, 1991). Families often go into debt during the dry season to obtain steady grid electricity, contributing to the statistics that make the Northeast the poorest region of Thailand (Kroeksakul, Naipinit, & Sakolnakorn, 2011).

According to 2019 data from the Provincial Waterworks Authority (PWA), Khon Kaen residents consume roughly 4.2 million cubic meters of water per month. Current groundwater maps of Khon Kaen are inaccurate, so residents do not know where to dig to find more reliable sources of water, or whether there is a danger of depleting the ones they find.

Khon Kaen experiences the worst water shortage during the winter season between late October and February, when the terrain is at its driest and there may be occasional wildfires. In coming years, the drought is predicted to become worse. The province receives strong solar radiance throughout the year,

particularly during the cold season from October to February, and the summer season between February to May.

Normally, temperatures in Khon Kaen are between 22 to 30 °C, rising up to 36.3 °C in April and falling to 15.7 °C in January (Table 1). The period with the least sun is the rainy season from May to September, when rain is frequent and can last for up to 18 days with scarce sunlight (“Monthly weather...”, 2019). However, water shortages can still occur during the rainy season, due to delays in the monsoon’s arrival and long gaps between rainy days (Pholpeuch, 2015).

Table 1: Khon Kaen Province temperatures in different months (°C/ °F) (Khon Kaen climate, 2019)

	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature (°C)	22.8	25.5	28.4	30.2	29.6	28.8	28.1	27.8	27.3	26.6	24.5	22.7
Min. Temperature (°C)	15.7	18.6	21.9	24.1	24.6	24.4	24	23.9	23.5	22.2	19	16.1
Max. Temperature (°C)	29.9	32.4	35	36.3	34.7	33.2	32.3	31.7	31.2	31	30.1	29.3
Avg. Temperature (°F)	73.0	77.9	83.1	86.4	85.3	83.8	82.6	82.0	81.1	79.9	76.1	72.9
Min. Temperature (°F)	60.3	65.5	71.4	75.4	76.3	75.9	75.2	75.0	74.3	72.0	66.2	61.0
Max. Temperature (°F)	85.8	90.3	95.0	97.3	94.5	91.8	90.1	89.1	88.2	87.8	86.2	84.7
Precipitation / Rainfall (mm)	9	13	35	70	160	174	164	188	265	65	14	5

Khon Kaen is organized into 26 districts, which are subsequently divided into sub-districts. These, in turn, are composed of villages. In Thai, the word ‘Muban’ (‘village’) is shortened to ‘Ban’ and placed before a location’s name to indicate that it is a village. However, many of these villages are divided once more into smaller sections, which are referenced by number—‘Village 1’, ‘Village 2’, etcetera—although locals will still identify themselves with the larger village name.

Residents of these villages obtain water using electricity obtained through various methods, of which some are more efficient than others. The reliability of an electric power source is contingent on its application, and finding a reliable source for electricity generation is not a one-size-fits-all. In Khon Kaen, rural communities typically rely on grid electricity, but a new shift towards solar power is a more sustainable and affordable option.

2.1.1 Grid electricity in Khon Kaen

Grid electricity in Khon Kaen comes from several different sources. According to the Electricity Generating Authority of Thailand (EGAT), the Nam Phong Power Plant produces 710 MW from 2 steam turbines and 4 natural gas turbines. An additional source of energy is the Ubol Ratana Dam (Electricity Generating Authority of Thailand [EGAT], 2013), which produces hydroelectric power.

Hydroelectric power is produced by water exiting a dam and spinning a turbine that generates electricity. These systems are effective on a large scale when used on large bodies of running water. However, hydroelectric systems harm the ecosystems surrounding them by manipulating the natural flow

of water and disrupting animal habitats (Kesa, 2014). The water in the dam is also often used for irrigation, although this was not the case with the villages studied in this report.

The Ubol Ratana Dam's total capacity is 25.2 MW (EGAT, n.d.). According to the EGAT reservoir storage condition report, the dam was at 17.5% of its maximum storage level in February 2020 (EGAT, 2020). The Ubol Ratana Dam ran dry in 2016 (Draper, 2016). Currently, electric power is also imported from the Xayaburi Hydroelectric Power Plant in Laos, which supplies 1220 MW to 3 provinces, including Khon Kaen (EGAT, 2012).

Grid electricity is easily transported across cities in both high and low voltages. However, communities connected to grid power are also subject to blackouts, when energy supply is lost for several hours, inconveniencing hundreds or thousands of people. The average Thai citizen reported at least five blackouts per year (Panya, 2010).

2.1.2 Solar energy in Khon Kaen

Modern photovoltaic solar energy was first used in the mid 1950's, but it was too expensive for the public to purchase and was only implemented by large government corporations such as space companies. The continuous rise in oil prices in recent years has led countries such as the United States to push for the implementation of solar technology, and efforts made to commercialize solar energy reduced the price and made it affordable to the public (Sabas, 2016). In the last few years, Thailand has greatly intensified its efforts to incorporate solar energy into all aspects of life—from solar panels at public institutions such as Chulalongkorn University, to art shows in the streets of Bangkok showcasing the impact harnessing solar energy can have on communities. Photographs of panels at Chulalongkorn University and an art show at the Bangkok Culture & Arts Centre can be found in Appendix A.

Small communities all around Thailand are learning the benefits of incorporating solar arrays into their daily life, particularly in Khon Kaen.

Solar energy is a promising option for residents in Khon Kaen, due to a high average of sunshine hours throughout the year, as seen in Figure 2. With solar arrays, users no longer have to buy electricity; the only costs tend to be those of equipment, installation and maintenance (Lee, 2018). Solar power also benefits villages by decentralizing their energy source, making them less susceptible to malfunctions or cyber-crimes that cause blackouts. Arvizu et al (2011) reports that photovoltaic systems do not create byproducts while they produce electricity, but their manufacturing process and the lack of regulations for their disposal are ongoing environmental concerns.

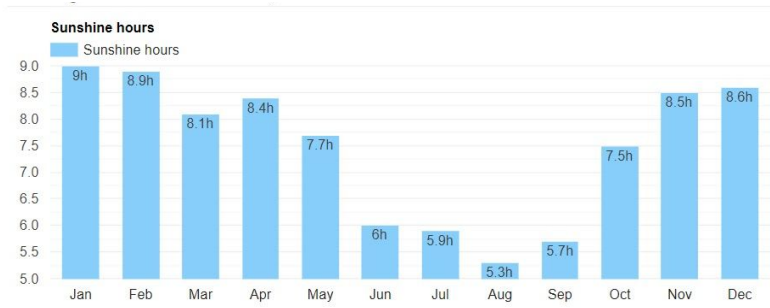


Figure 2: Average sunshine hours in Khon Kaen, Thailand (“Monthly weather...”, 2019)

Photovoltaic solar arrays can have a voltage of 12, 24, or 36 V. These arrays use solar energy to generate electricity through the photovoltaic effect. This DC power is then converted to AC power to run a machine, with individual photovoltaic panels in series or parallel to obtain the required voltage. Individual panels range from 50 to 80 W with the resulting array wattage ranging from 100 to 320 W. Larger PV panel surface areas act as a linear current booster that would allow the pump to turn on in low-light conditions. In direct-coupled systems where the panel is directly wired to a pump, 20% more wattage is usually needed in addition to the typical extra 25% just to kick-start the pump (Qazi, 2017).

Solar panels can be made of various materials, such as copper indium gallium selenide (CIS), polymer, and amorphous silicon cells. CIS cells work well up to temperatures of 100 °C, polymer cells can withstand up to 109 °C, and amorphous silicon cells withstand up to 122 °C (Ray, 2010).

A fixed structure must be installed facing true south (not magnetic south), with the panel tilted perpendicular to the sun or pointing directly towards it, depending on solar irradiance for that day. This structure is less expensive and can tolerate extreme weather conditions (Qazi, 2017). Figure 3 shows the tilt of a solar array.



Figure 3: Tilt of a fixed solar array

When mounting a solar array, shading from trees, weeds, and other obstructions can cast shadows on the solar panels and limit power output. It is advised to avoid these obstructions when picking a site for the panels, especially in the winter, when the arc of the sun is lowest. Depending on location, additional protection from animals or humans may be required. It is highly desirable to place the solar array as close as possible to the pump to minimize wire size and installation costs (Shouman, Shenawy, & Bahr, 2016).

2.2 Water Pumps

A water pump is a device that can move liquid water from one place to another. Use of water pumps can be traced back to 2000 BCE (Yannapoulos et al., 2015), and hand water pumps (Figure 4) are still useful for rural areas that lack reliable electricity (Chandrappa & Das, 2014). These pumps are a sustainable option for smaller villages and households that need access to water. However, most communities today employ electrical pumps, powered by the energy source most convenient to them.



Figure 4: Photograph of a manual pump in Khon Kaen

Electric water pumps can be organized into two major categories: surface pumps and submersible pumps. Surface pumps (also known as displacement pumps) are primarily used when drawing water from a lake or pond, as the water moves through pipelines located at or near the water's surface. They use diaphragms, vanes, or pistons to seal water into a chamber and force it upward through a discharge outlet. They maintain lift capacity throughout the solar day at slow but varying speeds due to the available sunlight. Figures 5 and 6 shows a surface and a submersible pump, and Table 2 outlines the advantages and disadvantages of surface and submersible pumps.



Figure 5: Surface pump in Nong Wang



Figure 6: Submersible pump in Ban Lan

Table 2: Advantages and disadvantages of surface and submersible pumps (Qazi, 2017)

Type of pump	Advantages	Disadvantages
Surface pump	Designed to maintain lift capacity throughout the day at slow, variable speeds.	Cannot be used for a well.
	Includes delivery, pressure or booster pump.	Requires protection since it is at surface level.
	Used to draw water from a lake or pond.	
Submersible pump	Flow output increases with the amount of water current.	Cannot be used in a lake or pond.
	Does not need special protection from weather conditions since it is submerged.	
	Can be suitable for moving water across long distances or high elevations.	

Submersible pumps are centrifugal pumps, and use a rotating impeller to add energy to the water and push it towards the discharge outlet. Water flow gradually increases with the amount of current obtained. These types of pumps are commonly used for low lifts or well pumping. Their submersibility allows them to be protected from extreme weather conditions, and therefore they require little protection. These pumps can develop high heads and are more suitable for moving water long distances or to high elevations.

Both types of electric pumps can be powered by either solar energy or traditional grid electricity.

2.2.1 Grid-powered Water Pumping Systems

Grid-powered water pumping systems use alternating current (AC) to power electric water pumps as mentioned in section 2.1. They can be used at any time, and electricity can be transported over long distances to reach the water pump with minimal losses.

However, grid-powered pumps cannot function during blackouts, and paying for the grid electricity required to power a water pump over long periods of time can be costly, especially if it is used every day. For reference, if a 1.5 kW water pump were to run for three hours, it would require 4.74 kW. The price of 1 kW depends on the provider, but typically costs about 3 THB. The more use the pump receives, the more money has to be paid to power it, steadily reducing its value as time goes on (García et al., 2019).

2.2.2 Photovoltaic Water Pumping Systems (PVWPS)

In a PVWPS, a photovoltaic array converts solar energy into direct current (DC), which powers a motor that runs an electric water pump, which supplies residents with the necessary water. Regardless of the energy source, the pumps themselves work the same. However, a solar-sourced pump's water flow rate and velocity will vary with the available sunlight, while pumps that run with grid electricity have more consistent flow rates and velocities.

A basic comparative schematic of a submersible PVWPS and grid powered pump is shown below in Figure 7. This shows that the system configurations themselves are the same, the only difference between them being the power source.

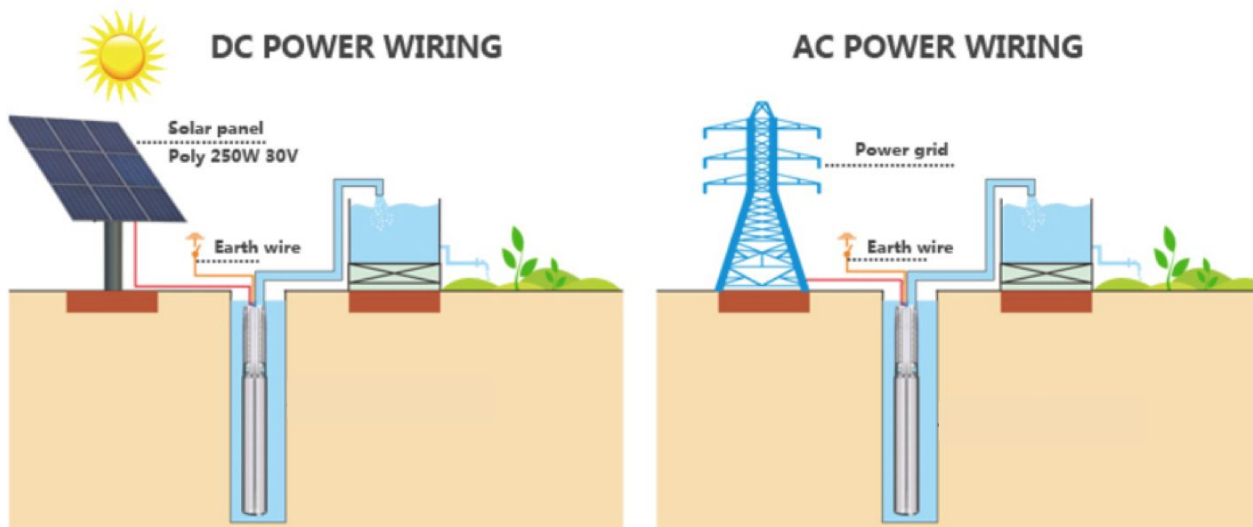


Figure 7: Schematic Diagram of Solar powered pump and grid powered pump (“3hp solar...”, n.d.)

PVWPS's are economically beneficial for longtime users as shown in section 5.2. While the initial installation is expensive, the more use the system receives, the more value the user receives for its worth. The average return on investment of a PVWPS is about five years (García et al., 2019). Another advantage PVWPS's have is the ability to produce electricity from anywhere; even in remote locations that don't have grid access. On the downside, PVWPS's will not run at night unless a battery is present in the system.

2.2.3 Water Distribution

Research from Qazi (2017) and Fernquest (2015) found that typical domestic household use varies according to climate, but is generally between 0.22 and 0.28 cubic meters per day for cooking, drinking and bathing. However, water use data obtained through our fieldwork indicates that Khon Kaen households require greater amounts of water than typical domestic households—between 0.4 and 0.6 cubic meters. This may be because residents of rural villages also use their water to irrigate small vegetable gardens in their homes in arid climate, and classify this small-scale irrigation as 'household' use, separate from their larger-scale farming businesses.

The total dynamic head (TDH) is defined as the pressure the pump must overcome to move the water. TDH is found by looking at the total vertical pumping distance between the water source and the water tank, which is normally about 8 meters. If a pump is underground, knowing the pump's maximum pressure will facilitate finding the depth the pump can reach (Qazi, 2017).

Most pumps' flow rates range between 6.06×10^{-5} and 0.0003 cubic meters per second. A WCL-15-5T pump model has a flow rate of up to 0.0183 cubic meters per second. For reference, a typical shower uses about 0.0001 cubic meters of water per second (Home Water Works, 2019). Because these flows are so low, there will not be sufficient water velocity through a large pipe to keep any suspended solids from settling at the bottom if water has not been filtered beforehand. For that reason, and to account for friction loss, smaller pipes measuring 1.27 centimeters to 5 centimeters are preferable; this lowers the cost of materials. A larger diameter distribution pipe can be used to overcome pressure loss due to friction (Qazi, 2017).

In order to avoid pressure issues due to vertical distance, some communities choose to create larger reservoirs set at a higher altitude than the original source, such as man-made ponds, that store large quantities of water pumped from the original water source and also collect rainwater. They then use a separate pump and gravity to obtain water from this reservoir.

Typically, water pumping systems also employ some type of smaller water reservoir to store water for nighttime use rather than electricity in batteries to continue pumping through the night, reducing the cost and complexity of the system. Water tanks use gravity to distribute water. Ideally, storage capacity should equal between 3 and 10 days of water depending on usage and climate. The use of a tank with a PVWPS makes the system more reliable. In the ideal scenario, with a consistent amount of water being pumped, the mechanical energy stored in the tank should remain the same throughout the year (Badescu, 2003).

Tanks are often made of food-grade plastic or polyethylene, as well as other materials like concrete and stainless steel to prevent sunlight penetration for controlling algae growth. They are typically placed at a higher point on the property for gravity feed for easier distribution (Shouman et al., 2016). Figure 8 shows one of these storage tanks.



Figure 8: Photograph of a water storage tank built by PDA

Water storage tanks should be designed properly to ensure effective water distribution. The pumps need to be strong enough to transport the water up the vertical distance to the top of the tanks. As the tank fills with water, the potential energy stored in the tank is equal to the mass of the water times the acceleration due to gravity times the tank's height from the ground. This potential energy is converted to kinetic energy as it flows out of the tank, and it creates water pressure for distribution. It's essential for a tank to be at an elevation higher than where it's being distributed to, otherwise the energy used to pump the water up to the top is wasted. In a scenario where the elevation of the tank cannot be higher than where it's being distributed, a tank should not be used. Instead, the pump should transport the water directly from the water source to its beneficiaries.

2.3 The Population and Community Development Association (PDA)

The Population and Community Development Association (PDA) is a Thai non-governmental organization in operation since 1974. PDA aims to incorporate the study and dissemination of knowledge, information, services, promotion and support for community development in both urban and rural areas. It has over 800 employees and 12,000 volunteers across the country, with 18 regional centers in 15 provinces.

PDA sees lack of access to water as one of the biggest problems faced by rural villages in Thailand. It aims to address two of the United Nations' Sustainable Development Goals, "Clean Water and Sanitation" (Goal 6) and "Affordable and Clean Energy" (Goal 7) through the installment of PVWPS's across Northeast Thailand (Andrews, Rodrigues, Guevara, & Kimmel, 2012). PDA recognizes that while the government does not have the ability to tackle all water problems, local communities can

learn to take charge themselves. According to Cho (2009) “local people are best suited to shape and sustain their own development”.

PDA’s first goal is to make water available; the second is to teach communities to manage it. The organization offers villages a chance at economic prosperity, with the goal of empowering them to become promoters of this knowledge in their own community, independent of PDA. To achieve this, PDA maintains a close relationship with the local government of every region it operates in, working with District Ministers to identify communities that require the most help, and prioritizing villages that use family planning (historically a main area of focus for PDA’s community development programs). This helps to ensure that villages can sustain the expenses of new endeavors.

After selecting recipient communities, PDA reaches out to the heads of each (paid positions funded by the sub-district administration) and educates them on the advantages of PVWPS’s through information sessions and tours of locations where water pumps are already installed. Village heads then communicate what they have learned to the people, and the community decides if it will move forward with the program. In order for a project to take place, the village needs a unanimous vote for the project.

In cases where projects are approved, PDA dispatches technical experts, tools, equipment and raw materials to the village, but residents provide the labor and sometimes the finances (Andrews et al., 2012). They also annually elect a village water committee, which PDA encourages to be composed of an equal number of male and female residents. This focus on gender equality has come as a result of PDA’s insight from working in many Thai communities: while male residents tend to be overly ambitious, female residents are more likely to be overly cautious; therefore, a committee that equally represents both genders is better equipped to make better decisions. The village water committee receives training from PDA’s technicians on maintaining and operating the pump, and eventually takes on a leadership role, making all management decisions related to the pumps. Activities in villages like Ban Lan, Nong Wang and Ban Wang Saeng are administered from PDA’s center in Ban Phai, Community-based Integrated Rural Development Center (CBIRD).

A challenge PDA faces in these communities is changing the way people think about water. In communities where pumps were not previously in use, especially for irrigation, residents struggled to accept the idea that they must now regularly pay water tariffs. PDA aims to assist communities in understanding that water is not free, and that by using a village pump, the entire village can achieve financial independence and improve their quality of life.

PDA extended help to many communities across Thailand. Our project focused on three of these communities, each one in one of the following districts: Ban Phai, Nong Wang and Phra Yuen. In Ban Phai, the PVWPS was installed in Ban Lan Village 5. In Nong Wang, the PVWPS was overseen by the sub-district administration, not any of the villages. And in Phra Yuen, the PVWPVS was installed in Ban Wang Saeng Village 1. For the purposes of this report, we will refer to each village by its name, without its number.

These three villages report to PDA's CBIRD office in Ban Phai, located centrally to these locations, as seen in Figure 9.



Figure 9: Map of Khon Kaen indicating Ban Lan, Nong Wan and Ban Wang Saeng (red) and PDA's CBIRD center (yellow) (Google Maps)

2.3.1 Ban Lan

Ban Lan is a village in Khon Kaen that has been split into smaller regions, which are named as smaller numbered villages. According to the Official Statistics Registration System in 2019, Village No. 5, which our project focuses on, had 182 families and consisted of 679 people. The headman of the village was Mr. Sangwian Sornban. Ban Lan's closest sources of water were the Wang Khaen and Kut Chueak canals, which they used to irrigate their crops. However, they pumped groundwater to provide for household needs.

Ban Lan is located on higher land than the villages around it, leading water to run on to the others and leave Ban Lan with a shortage. As a result, they had a separate water system since 2008, and PDA has worked closely with this village since 2016.

2.3.2 Nong Wang

Nong Wang is a sub-district in Khon Kaen and a community that PDA considered a model for villages to learn about finances, agriculture and community development. As of 2019, according to the Official Statistics Registration System, Nong Wang had 5028 people in 1484 families. The head of the village was Mr. Nipon Lohharattanakorn (Chief Executive of the SAO). Nong Wang used the Chi River and a man-made village pond as its main water sources.

The former headman of Nong Wang was the first to introduce solar power for pumping purposes when he bought a PVWPS to fill the man-made pond with water from the Chi River. Sixteen years later, the village elected a new headman and he replaced the PVWPS with a grid-powered pump. The community then used the grid-powered pump to distribute water for household needs, and simply filled buckets to irrigate farms.

To provide more convenient water storage to the farming area near the pond, the sub-district administrator gave Nong Wang four blue tanks. The Nong Wang village water committee tried to use water from these with a small grid powered pump, but it did not run well and neither the pressure nor the storage space were enough for irrigation. As a result, the head of Nong Wang asked PDA to install a new PVWPS and build a new tank to supply water to their crops, as seen in Figure 10 below.



Figure 10: Old tanks (blue) and tank installed by PDA (red)

2.3.3 Ban Wang Saeng

Ban Wang Saeng is a village in Khon Kaen that according to the Official Statistics Registration System had 611 people in 174 families as of 2019. The head of the village was Mr. Tawon Vichai. The nearest clean water source to Ban Wang Saeng is the Chi River, which they used to fill a man-made pond that acts as their main water source.

Ban Wang Saeng struggled to finance water obtention because they required three grid-powered pumps, and electricity cost them 23,000 to 25,000 THB per month. In 2009, the residents established a water committee in Ban Wang Saeng. At the start, PDA offered to provide two separate PVWPS for irrigation and household uses. The village committee talked with the irrigation committee, and they concluded that they only needed a tank and pipes for irrigation, as irrigation pumping was not so costly. However, household water use was high and required a PVWPS.

2.4 Challenges and Solutions

A Worcester Polytechnic Institute (WPI) Interdisciplinary Qualifying Project (IQP) sponsored by PDA had noted that education on the importance of PVWPS's was essential for the program's success (Andrews et al., 2012). PDA's commitment to educating and empowering the population of these villages also necessitated that any assessment of the PVWPS's go beyond simply the technical. In order to assess

the progress made in Khon Kaen, we first decided on what we considered good measures of efficiency and how we planned to collect those measurements.

Assessments of already installed PVWPS's from around the world often include diagnostic analyses of systems, field observations, interviews with users, reviews of technical literature, economic impact evaluations, and identifying gaps in research and impediments to use (Chandel, Naik, & Chandel, 2015). Therefore, our team looked to understand how researchers have assessed technical performance, cost and socio-economic and environmental changes. Below is a summary of various relevant studies performed on PVWPS's around the world.

2.4.1 Technical Performance

A study done in India analyzed 12 different types of PVWPS's, testing the temperature, flow rate and seasonal groundwater levels to determine the technical performance of each pump. They found that the PVWPS increased in efficiency due to the higher solar radiance but underperformed during the summer due to lower water amounts (Renu, et al., 2017).

In Brazil, populations using PVWPS's looked at materials that could potentially increase system efficiency. They found polycrystalline solar panels to be more beneficial than monocrystalline ones, as they could produce greater daily averages of pumped water as well as higher percentages of efficiency. They presented residents with pictorial representations to make it easier for them to understand the results (Nogueira, Bedin, Niedzialkoski, Souza, & Neves, 2015).

2.4.2 Cost

The high cost of the electricity required to pump enough water for irrigation will often make grid-powered pumping counterproductive. A study in Jordan compared the economic feasibility of a PVWPS against that of a grid-powered pumping system. It compared the cost of irrigation for three sets of crops—greenhouse (low water requirements), citrus (medium water requirements) and bananas (high water requirements), which can be seen in Table 3. Using highly optimistic values for electrical cost and crop yield, the study found that the installation cost for a grid-powered system was on average two times cheaper than the installation cost of a PVWPS, but that the cost of electricity could eventually make a PVWPS a cheaper alternative (Jones, Odeh, Haddad, Mohammad, & Quinn, 2016).

Table 3: Simulation cost comparison for solar and grid-powered water pumps (Jones et al, 2016)

	Crop	Case 1	Case 2	Case 3
		Greenhouse vegetables ^a	Bananas	Citrus ^b
PV results	Total capital cost (US\$)	261,000	278,000	233,000
	Annual operating cost (US\$)	18,300	18,100	15,710
	Overall water unit cost (US\$/m ³)	0.83	0.97	1.23
	Net present value	389,000	202,000	- 346,000
	Internal rate of return	26%	16%	- 183%
	Return on investment	83%	42%	- 84%
Grid powered results	Total capital cost (US\$)	106,000	142,000	117,000
	Annual operating cost (US\$)	18,600	23,600	18,900
	Overall water unit cost (US\$/m ³)	0.70	0.82	0.99
	Net present value	713,000	276,000	- 266,000
	Internal rate of return	204%	32%	- 188%
	Return on investment	223%	67%	- 79%

a

Greenhouse vegetables consist of tomato, cucumber, melon, hot and sweet pepper, eggplant, and bean.

b

Citrus consists of clementine, mandarin and other oranges, lemon, and pomelos.

Grid electricity is a profitable option only for crops with high returns, fairly low water requirements, and locations with shallow groundwater depths and high solar insolation (Jones et al, 2016). This study also did not account for the power shortages that are common in Thailand. A power outage can pose a serious inconvenience to crops that depend on grid electricity for irrigation. Without power, the crops are at risk of dehydrating and dying, which can lead to a loss in revenue for the farmers that own them.

PDA provided us with a table of values for the average cost of installing PVWPS's. The complete table can be found in Appendix B, but we present a summary here, which was the basis for our grid vs. solar comparison calculations:

Solar panels and mounting: 40,000 THB

Control box with inverter: 10,000 THB

Water Storage tank: 180,000 THB

Piping: 30,000 THB

The investment payback of PVWPS's only comes after an average of 4 to 6 years, with some studies reporting paybacks in half that time (Chandel et al., 2015). In Spain, solar and grid-powered systems' life cycle costs for 30 years were estimated from past data, finding that in spite of PVWPS's being more expensive than grid pumping systems initially, they are cheaper in the long run—a fact that often causes misconceptions among users (García et al., 2019).

2.4.3 Social Dynamics

A study in the Amazon discovered that it was difficult to accurately estimate a community's need for water before they had improved access to it. Once locals were able to pump with PVWPS's, they discovered new uses for water, and therefore raised water demand, eventually requiring more high-scale performances (Fedrizzi, Selles, Ribeiro & Zilles, 2009). Other experiences showed that when technicians approached farmers with a sense of superiority or dominance, projects consistently failed. Governmental agencies who imposed PVWPS's in communities against their will, values and social structures, found that residents purposefully misused the pumps in protest. Technicians' failure to properly empower locals bred passivity and put projects at risk, as locals did not see themselves as capable of operating or maintaining systems, much less responding to challenges (Fedrizzi et al., 2009).

A one-year study in northern Benin found that families who had recently implemented PVWPS's for irrigation were 17% less likely to experience chronic food insecurity, vegetable intake increased by about 150 g per person per day, and improved crop yields led to better financial stability—all of which lead to an overall improvement in farming families' quality of life (Burney, Woltering, Burke, Naylor & Pasternak, 2010).

2.4.4 Environmental Changes

Currently, policies regulating the disposal and recycling of photovoltaic arrays are uncommon. A study found that frameless photovoltaic arrays lower material costs and can incentivize recycling, as they are easy to disassemble, and that with the proper education, communities can be encouraged to recycle and reuse PVWPS materials such as aluminum, iron and glass. However, while many regions have the ability to recycle common materials, more expensive cell materials go to waste, harming both the environment and the economy (Goe & Gaustad, 2014). As PVWPS's have an average lifecycle of 30 years, this challenge will worsen as PVWPS's become more widespread.

While PVWPS's perform well in researched locations such as Jordan, India, the United States (Mahmoud, 1990; Renu, et al., 2017; Morales, Busch & Yasumiishi, 2010) and other parts of Thailand (Andrews et al., 2012), Khon Kaen's unique weather patterns, financial conditions and social dynamics demand additional study before concluding that the same applies to this province.

3. Methodology

The goal of our project was to determine through a holistic analysis if PDA's PVWPS program is worth replicating across Khon Kaen, Thailand. To achieve this goal, we developed three main objectives: (1) to provide PDA with updated information on PVWPS's in Khon Kaen, Thailand, (2) to compare the cost and technical performance of PVWPS's installed in Khon Kaen to grid-powered water pumps, and (3) to identify environmental and social changes caused by the PVWPS's in Khon Kaen, Thailand.

3.1 Data Collection

Our team wished to evaluate the performance of installed PVWPS's to determine if they truly responded to villages' water needs better than conventional systems. PDA assigned us visits to three villages: Ban Lan, Nong Wang, and Ban Wang Saeng. Ban Lan and Ban Wang Saeng had a PVWPS to supply their water needs for household use, while Nong Wang used the PVWPS for irrigation.

We were also given the opportunity to visit the villages of Ban Nong Thum and Ban Thanon Ngam: the first was an example of a village where the PVWPS operated smoothly for household use, and the second a village that still used a grid-powered system but planned to adopt PVWPS's later in 2020 with PDA's help. We also visited Muban Siharat, a village that employed a PVWPS but was unrelated to PDA.

Data collection took place in Ban Lan, Nong Wang and Ban Wang Saeng. In order to gather the required data in four days, the team carried out interviews with the residents of the villages and observed both the communities and the PVWPS's in them. In this way, data collection accounted both for residents' perceptions of the PVWPS's and the team member's perceptions as outsiders.

3.1.1 Interviews

Interviews took place in Ban Lan, Nong Wang, and Ban Wang Sawng in a structured meeting organized by PDA and set in each village's community center, January 28 through January 30, 2020. We were accompanied by Mr. Manop Pimsawan, who acted as our guide in all the village visits; as the installation and maintenance engineer, he was familiar with each village PVWPS and knew the village members personally. The head of the village, village water committee members, and the residents who use the PVWPS's were present at these gatherings and knew that they would be providing the team with information about water obtention in their community. Opening statements typically included an introduction of all those present, a brief overview of the village, and an explanation of how the PVWPS installed in the village was being used.

We conducted interviews in a group setting, with groups of two to four interviewers interviewing one to three interviewees. Each WPI student was paired with a Chulalongkorn student to translate the questions, as seen in Figure 11. While a list of questions was prepared by the team, interviewers made an effort to carry the interview in a conversational manner, recording answers on forms the team prepared. Recorded answers often included the words of multiple people, or conclusions that two or more interviewees came to based on discussion.



Figure 11. Interviewing residents of Nong Wang

We interviewed a total of 30 people across all three villages, both authorities and PVWPS users. Numbers for each village varied, depending on the size of the gathering (examples can be seen in Figure 11 and Figure 12), how talkative interviewees were, and the limited time.



Figure 12. Residents at the meeting in Ban Wang Saeng

The number of interviewees can be seen in Table 4 below.

Table 4. Interview statistics for all three villages.

Village	Authorities		Users		Total
	Female	Male	Female	Male	
Ban Lan	1	3	3	3	10
Nong Wang	4	4	3	0	11
Ban Wang Saeng	0	3*	2*	4*	9

*Not all participants were willing to answer all the questions.

Our team was committed to respecting research ethics, and therefore provided a clear verbal explanation of the purpose of our research, as our sponsor determined that a consent form might be intimidating to residents of the villages who were not accustomed to such documentation. Interviewees were therefore verbally made aware that participation was entirely voluntary, and that they were free to end the interview at any time or skip questions they did not want to answer. The team was transparent about the type of information we were looking for, what it was being gathered for and in what form it would be recorded and published. Questions were posed in an open manner. Interviews were not recorded without receiving explicit verbal consent from the interviewee. A draft of the consent form, which guided our conversation with every interviewee, can be found in Appendix C.

We sought to compare the technical performance and amount of money spent on the previous system to the performance of the PVWPS and expenses incurred in installing and operating the PVWPS, to determine if PVWPS's are truly a more economical option. In order to do this, interview questions pertained to installation costs, water fees and water fees. To determine the environmental impact PVWPS's had on these communities, our team inquired as to noise caused by the pump, space taken up by the pump, amount of earth disturbed to install the pump and plans to dispose of and/or recycle the pump once it reaches the end of its lifetime.

It was also important to determine how social dynamics and quality of life had changed in each village, particularly due to changes in expenses, water availability, and PDA's influence. Through interview questions and observations, we sought to understand how people perceive the impact of PVWPS's, how the behavior and culture of the residents has been affected by the presence of the PVWPS, how quality of life has changed and how empowered residents and authorities feel to operate the PVWPS.

Separate interviews were conducted for system users and for authorities such as the water committee and the head of the village. As seen in Figure 13, we tried to interview an equal ratio of women to men. Questions pertained to the information we wished to gather on technical performance, cost, socio-economic and environmental effects of the PVWPS's on the village. These questions can be found in Appendix D.



Figure 13. Interviewing residents of Ban Lan

3.1.2 Observations

We observed the PVWPS's installed in the village as well as their water tanks and the land where the water pumped with the PVWPS was used (in the case of Nong Wang, where the purpose was irrigation). Both the village authorities and Mr. Pimsawan were able to respond to questions, and showed us how the PVWPS's worked, as seen in Figure 14. Our team recorded findings in observation sheets, which can be found in Appendix E.



Figure 14. The head of Ban Lan explaining how the PVWPS works

Observing the PVWPS's allowed our team to see the equipment and structures built around it, their state and location in these communities, responding to the list of questions our team prepared beforehand. After the trip, the team compared observations and compiled detailed lists of information for each PVWPS visited. We gathered information on the following through interview questions and observation: pump type, pump model, panel type, use of batteries, use of a tank, location, water source, water uses, date of installation, shade over arrays due to obstructing structures and protective structures around the pump.

3.2 Challenges

The nature of the environment in which the interviews took place created some difficulties in ensuring the validity and reliability of interview responses. In each village, all interviewees were present on PDA's invitation, there was always at least one PDA representative (Mr. Pimsawan) present, and village residents and village authorities mingled freely. Therefore, it was impossible to determine if there was tension between any of the parties present, or if certain residents were not invited to attend due to dissenting opinions about the PVWPS's.

The limited timeframe also made it difficult to establish a rapport with the interviewees, which may have led to hasty responses that did not reflect the interviewee's true feelings. It also made it impossible to interview all of those present, which makes it possible that only the more outspoken members of the community's opinions were shared, with those of quieter residents unspoken. An additional difficulty was the language barrier, as many farming communities in Khon Kaen speak a different Thai dialect than Bangkok, making communication difficult even for our Chulalongkorn team members.

The team attempted to circumvent these challenges by purposefully seeking out both the more extroverted village residents and those sitting quietly at the back, and asking additional questions when answers were not clear. Team members also observed the non-verbal attitudes and mannerisms of the interviewees to identify any points of dissension, excitement or discomfort, particularly for questions relating to socio-economic effects.

3.3 Data Analysis Methods

Once interviews and observation concluded, we compiled all interview responses into spreadsheets, organized by village and by category (authorities or users). This allowed us to see where interviewees in each category agreed with each other, where they contradicted each other, and where the village lacked information or an understanding of the PVWPS's. We kept interviewees' names and interview transcriptions confidential and these are not included in this report.

We also compiled our observations into spreadsheets by village to enable easy comparison and to understand how different water sources, water use and pump location may affect the way a village uses their PVWPS. Calculations based on the numbers provided by interviewees provided us with data on water consumption and overall expenses.

4. Results

This chapter outlines the results of our observation and interviews regarding the PVWPS's and their impact on Ban Lan, Nong Wang and Ban Wang Saeng. Through this chapter we provide PDA with updated information about these three communities as of March 2020, in response to our first objective. Our list of findings and recommendations, responding to our second and third objectives, can be found in Chapter 5.

4.1 Ban Lan

Ban Lan used their PVWPS, installed in July 2016, to provide water for village households, in conjunction with a grid-powered system that activated during the nighttime. They filled the water tank during the day using the PVWPS, and decreased grid expenses as they used grid electricity only during the night, at off peak rates.

Ban Lan employed eight BYD 255 W solar arrays that power a submersible pump, suitable for moving water across long distances or high elevations, because groundwater is their main water source. This pump has 1.5 Hp and uses polycrystalline photovoltaic arrays, since Khon Kaen temperatures can be very hot and polycrystalline panels can resist high temperatures. The arrays, storage tanks and the pump were located in a field, which did not require much modification to the environment. This PVWPS used to have a battery that could be charged and used to pump water during the night, but it was stolen. They did not have a plan for how to dispose of this PVWPS at the end of its lifetime, but assumed that PDA would provide a new system.

The village had not financed the installation of the PVWPS; PDA had installed a tank (funded by Coca Cola, one of PDA's sponsors) and the PVWPS, which they continued to regularly maintain. The total cost of installation, paid by PDA, had been 250,000 THB.

Villages across Thailand benefit from the Thai Niyom Yangyuen scheme, a government grant of 200,000 THB given to communities that wish to improve their livelihood. The program aims to reduce financial inequality, and villages can apply with a proposal (Bangrapa, 2018). In 2018, Ban Lan used this grant to finance a new pipe system for water distribution and four raised water tanks (Figure 15) that now function in conjunction with the tank installed by PDA. This allowed Ban Lan to store more water.



Figure 15. The solar panel and water tank that were installed in Ban Lan

The village water committee expressed that there was a 40% decrease in their monthly electric payment from before the PVWPS was installed. This estimate was given by a village water committee member familiar with expenses, although they did not provide hard numbers. While local authorities were unable to provide us with exact expenses before the installation of the PVWPS, they estimated that the village water committee spent about 5,800 THB monthly on electricity alone. This led them to deplete

their savings. Since the installation of the PVWPS, the village water committee spent about 3,500 THB on electricity each month, allowing them to save money.

Before the installation of the PVWPS, residents of Ban Lan paid 3 THB (baht) per cubic meter, on top of a maintenance fee of 5 THB. Residents now paid a monthly water fee of 4 THB per cubic meter and a maintenance fee of 5 THB, which financed both the PVWPS and the grid pumping system. While residents paid more day-to-day, the money the committee saved in electricity fees went into the village savings, allowing them to invest money in other areas that profit residents. The committee expressed that once savings reach 40,000 THB, they intend to pay dividends to the residents every 5 to 6 years.

Total payment and water use for five interviewees can be seen in Table 5. The average resident of Ban Lan used about 20 cubic meters of water per month, paying a total of 80 THB per month. It can be assumed that the entire village consumed about 3,600 cubic meters per month.

Table 5. Fees Paid by Users in Ban Lan

Per month	Water fee (THB/cubic meter)	Maintenance Fee (THB)	Total paid (THB)	Water use (cubic meters)
User 1	4	5	70	18.0
User 2	4	5	100	24.0
User 3	4	5	30	10.0
User 4	4	5	80	20.0
User 5	4	5	120	28.0

Based on our calculations using theoretical data from literature, which can be found in Appendix I, the average time it should take residents to pump the amount of water they need for the entire day should be 2.9 hours. However, this is significantly lower than the amount of time they currently pump water, indicating that these villages use more water than the average Thai household. As mentioned in a previous section on water distribution, this may be due to residents using water for small-scale irrigation in their gardens for personal use. There is no evidence that these villages have a higher number of people per household than other regions of Thailand. Further investigation as to the causes behind this discrepancy is required.

The Ban Lan village water committee had two times more men than women, between the ages of 30 and 60. All seemed to share authority equally and felt empowered. Everyone we interviewed was talkative and willing to share information about the PVWPS and their community. Additional observations from Ban Lan are outlined in Appendix F.

4.2. Nong Wang

Nong Wang needed a PVWPS because the grid-powered system did not pump enough water for their farming needs. Forty-two farmers use the PVWPS, installed in August 2019, for irrigation, while the

grid-powered system is used for household applications. The pump pulled water from a man-made pond (Figure 16) that lay beside land reserved for farming, and filled a tank that distributed water for irrigation. The man-made pond gathered water during the rainy season, but was often filled with a grid-powered pump connected to the Chi River during the dry season, as seen in Figure 17. In this way, farmers could ensure that they would have year-round access to water.



Figure 16. Man-made pond in Nong Wang (main water source for irrigation)



Figure 17. Water from the Chi River pumped into the man-made pond by a grid-powered water pumping system.

Nong Wang's PVWPS employed eight SHARP 320 W solar arrays that power an AC surface pump. This pump had 1.5 kWh and uses polycrystalline photovoltaic arrays. In order to install it, dirt was piled into the edge of the man-made lake to create a 20 square meter flat land where the pump and arrays could be installed near the farming area. The village water committee did not have a plan for how to dispose of this PVWPS at the end of its lifetime, but assumed that PDA would provide a new system.

The PVWPS did not have a battery, as farmers hoped that using gravity for distribution would be just as efficient and more affordable, and water was not used for irrigation during the night. However, farmers found that due to a lack of water pressure, the water flow rate was insufficient to provide farmers with a steady stream of water.

This was likely due to the fact that the work performed by the pump was wasted because the tank was not at a level higher than the crops. The water was pumped up a distance of 8 meters, but allowed to drop back down to the bottom as it was used for irrigation. The difference in height between the crops and the bottom of the water tower was very small, which didn't allow for enough potential energy to be stored in the tower. When converted to kinetic energy, the amount wasn't large enough to allow for the water to flow out quickly. Further discussion can be found in section 2.2.3.

Regardless, the arrays performed very well. Based on our calculations using theoretical data from literature, which can be found in Appendix I, the average time it should take farmers to pump the amount of water they need for the entire day should be 0.79 hours. Nong Wang found that the PVWPS produced more electricity than the pump needed to irrigate the crops. In the future, they planned to use the excess energy to power the community center nearby. However, farmers believed that a more efficient option could be to use the excess energy to power another pump closer to the tank PDA installed (Figure 18) that could increase the water pressure.



Figure 18. Water tanks in Nong Wang, red tank was installed by PDA and the blue tanks were not in use

The village had not financed the installation of the PVWPS; PDA had installed a tank (funded by Coca Cola) and the PVWPS, which they continued to regularly maintain. However, village residents had worked at the construction. The total cost of installation, paid by PDA, had been between 200,000 and 300,000 THB. Residents paid a monthly water fee of 3 THB per cubic meter and no maintenance fee. The average farmer in Nong Wang used about 39 cubic meters of water per month to irrigate a 300 square meter property, paying a total of about 117 THB per month. This means that Nong Wang farmers consumed roughly 1,600 cubic meters of water each month.

A summary of the expenses and water use of three Nong Wang users can be found in Table 6.

Table 6. Fees Paid by Users in Nong Wang

Per month	Water fee (THB/cubic meter)	Total paid (THB)	Water use (cubic meters)
User 1	3	100	33.3
User 2	3	200	66.7
User 3	3	50	16.7

The members of the village water committee were between the ages of 40 and 70, with slightly more women than men in the village water committee. However, all seemed to share authority equally and felt empowered. Everyone we interviewed was talkative and willing to share information about the PVWPS and their community. Further observations from our team can be found in Appendix G.

4.3. Ban Wang Saeng

In Ban Wang Saeng, a grid-powered pump distributed water both for household and irrigation. The PVWPS, installed in June 2016, pumped water from those pipes up to a tank for household water.

Ban Wang Saeng also employed grid-powered pumps for use during the night, at off peak rates. The village found that this was a more affordable alternative to purchasing a battery and using it to run the PVWPS over twenty-four hours. They filled the water tank during the day using the PVWPS, and decreased grid expenses during the night. The head of Ban Wang Saeng expressed that when the village needed to make decisions, it was for the benefit of the majority, not only for a small group of people.

This PVWPS employed eight SHARP 320 W solar arrays that power a 1.5 Hp surface pump with polycrystalline photovoltaic arrays. The system was installed in the local temple, adjacent to the existing buildings that store multiple pumps and contain water filtration systems. The PVWPS connected via a series of pipes to a grid-powered surface pump, which took water from a man-made pond besides the major farming area.

However, the PVPWS still could not fully address the water shortage problem. Ban Wang Saeng still suffered during the dry season, when the man-made pond dried out and the village had to use another grid-powered pump to take water from the Chi River. They did not have a plan for how to dispose of this PVWPS at the end of its lifetime, but assumed that PDA would provide a new system.

The village had not financed the installation of the PVWPS; PDA had installed a tank (funded by Coca Cola, one of PDA's sponsors) and the PVWPS, which they continued to regularly maintain. However, village residents worked at the construction of the tank. The total cost of installation, paid by PDA, had been between 200,000 and 300,000 THB.

Previously, residents paid 7 THB per cubic meter, on top of installation costs for the grid-powered pump which were about 300 THB per household. Now residents paid a monthly water fee of 7 THB per cubic meter, with no maintenance fee. The average resident consumed about 12 cubic

meters monthly, paying 81 THB per month. It could be assumed that the entire village consumed about 2,000 cubic meters per month.

A summary of the expenses and water use of five Ban Wang Saeng users can be found in Table 7.

Table 7. Fees Paid by Users in Ban Wang Saeng

Per month	Water fee (THB/cubic meter)	Total paid (THB)	Water use (cubic meters)
User 1	7	150	21.4
User 2	7	40	5.7
User 3	7	100	14.3
User 4	7	70	10.0
User 5	7	45	6.4

Based on our calculations using theoretical data from literature, which can be found in Appendix I, the average time it should take residents to pump the amount of water they need for the entire day should be 2.9 hours. However, this is significantly lower than the amount of time they currently pump water, indicating that these villages spend more water than the average Thai household. As mentioned in a previous section on water distribution, this may be due to residents using water for small-scale irrigation in their gardens for personal use. There is no evidence that these villages have a higher number of people per household than other regions of Thailand. Further investigation as to the causes behind this discrepancy is required.

Ban Wang Saeng residents felt very uncomfortable speaking with us, as they spoke a different Thai dialect. It is also possible that the head of the village may have influenced residents' attitudes, as he often spoke on their behalf. While women had been elected to the village water committee, and seemed very involved in social situations, they had no voice during the interviews and remained at the back of the room. They were not invited by the head of the village to speak, although their male counterparts were. Village water committee members seemed to be between 40 and 60 years of age. Additional observations from our team in Ban Wang Saeng can be seen in Appendix H.

5. Findings and Recommendations

The following chapter outlines our team's findings regarding the PVWPS's in Ban Lan, Nong Wang and Ban Wang Saeng. This project sought to determine if PDA's PVWPS program is worth replicating across Khon Kaen, by comparing the cost and technical performance of PVWPS's installed in these three communities to grid-powered water pumps, and identifying the environmental and social changes they caused. Our findings are outlined below.

Finding 1: PDA's PVWPS program should be replicated in other villages

Based on our results, we can confidently assert that PDA's PVWPS program is worth replicating across Khon Kaen. PDA takes into account each village's situation and circumstances and responds to their needs with the most appropriate implementation of PVWPS's. Villages' participation in PDA's PVWPS program benefits them regardless of their size or the PVWPS application, which indicates that the program could be suited to any community in Khon Kaen.

Findings regarding the comparison of technical performance and cost from before and after the installation of PVWPS's, as well as additional findings regarding the socio-economic and environmental effects of PVWPS's follow. Our team also identified areas for improvement and provided recommendations for possible solutions.

5.1 Comparing the technical performance of PVWPS's to that of grid-powered systems

Finding 2: PVWPS's had little to no technical problems

Each village was flexible when implementing the PVWPS, identifying which areas could benefit the most. For Ban Lan and Ban Wang Saeng, this was household applications. For Nong Wang, it was irrigation. None of the villages experienced problems with the PVWPS's, and none of them needed to do any repairs to their system. However, it is important to note that the systems are all still less than four years old.

Finding 3: PDA-installed tanks do not store enough water pressure for the users

Villages stored water for later distribution by employing tanks; sometimes only those installed by PDA, and sometimes PDA's tanks in conjunction with their own. Using gravity seemed to be an effective method of distribution in Ban Lan and Wang Saeng. However, in Nong Wang, there was not enough water pressure, as farmers relied only on the tank installed by PDA, which was smaller and closer to the ground compared to the raised tanks other villages installed.

Recommendation 1: Raise tanks to improve water distribution

Nong Wang residents proposed installing a new pump to improve water pressure. However, our team proposes that raising the storage tanks or building taller tanks would be an easier long-term solution. By increasing the pump head, water pressure would increase through gravity as it is dispelled from the tank, without requiring additional electricity.

The tank PDA installed had a diameter of 2.00 meters and a height of 6.60 meters with a storage capacity of 20 cubic meters. At the moment, the water pressure flows at 65,000 Pascal and exits the tank through a 10 centimeter wide polyvinyl chloride pipe. If PDA decided to raise the tank by 1.00 meter and increased the length of pipe accordingly, water pressure would be raised to 75,000 Pascal. This is within

the threshold of acceptable water pressure before distribution. Typical water pressure in Thai households is between 19,608 and 29,412 Pascal, according to data from the PWA.

The current tank PDA installs costs 180,000 THB. To install a raised tank would require significant organization as well as resources; however, Ban Lan and Nong Wang had excess plastic blue tanks that were unused. A new platform could be built to raise those tanks, solving both the pressure problem and increasing storage capacity.

PDA's trademark for the PVWPS project is the installation of red concrete tanks, so future designs would ideally incorporate a higher head.

Finding 4: Dual systems prove to be the most beneficial method in these villages

Residents using PVWPS's for household use do not have enough water in the tanks to last the night, requiring that more water be pumped into the towers. While theoretical values predict that villages should be able to pump enough water for the entire day within 3 hours, both villages consume more water per household than literature suggests and therefore run the PVWPS's for longer periods of time (theoretical calculations can be found in Appendix I). To address this, Ban Lan and Ban Wang Saeng used grid-powered pumps in a dual pumping system. At night, the systems for household applications automatically switched from solar to grid power.

None of the PVWPS's have batteries to stay powered throughout the night. Ban Lan and Ban Wang Saeng local authorities said that having a battery would be too expensive for the villages, with Ban Lan authorities expressing concern about security after their battery was stolen. In the case of battery installation, new security measures would need to be taken, which would require additional spending for a guard, locks or surveillance equipment. However, it is not out of the scope of what these two villages could feasibly pay.

A PVWPS operating for 12 hours every day would require about nine batteries. Common brands for solar storage batteries in Thailand are FB Battery and 3K Battery, whose batteries cost about 6,000 THB each. They have a life cycle of about 510 cycles, which usually amounts to between 5 and 7 years (Wholesale Solar, n.d.). In a worst-case scenario, this means that each village would have to purchase 54,000 THB worth of batteries every 5 years (FB deep..., 2011). Based on Ban Lan's expenses, the village water committee spends about 180,000 THB in a 5-year period to finance grid power for nighttime water pumping. Theoretically, installing batteries could save them 126,000 THB, although battery prices are known to fluctuate.

Village savings might be able to finance this amount upfront. And if authorities decided to split the cost across users, it amounts to a total of 296.70 THB and 310.30 THB per household, respectively, as seen in Table 8 below.

Table 8. Cost of Battery Installation in Ban Lan and Ban Wang Saeng

Cost of battery installation		
Village	Ban Lan	Ban Wang Saeng
Total battery cost	54,000 THB	
Users	182 families	174 families
Total cost per family	296.70 THB	310.30 THB

However, it is important to consider that batteries are not environmentally-friendly; when they decompose, they cause the emission of greenhouse gases. If handled irresponsibly near a water source, they can contaminate the water and cause harmful effects to anyone consuming the water (Metson, 2017).

The addition of batteries into the system would be a temporary fix, as in the long run it is detrimental to the environment and potentially village finances if prices rise. A more long-term solution could be to increase water storage, although this would require the installation of more powerful water pumps. However, the current arrays would not have the capacity to sustain a more powerful pump to fill a larger tank. Ban Lan's current 255W polycrystalline panels produce a maximum of 1,530W per hour. An AC 1.5 Hp Franklin pump consumes 1,100 W per hour.. If they decide to upgrade the pump to an AC 2.0 Hp Franklin Pump model 100LPM-16STG that requires 1,500W, the current solar panel at Ban Lan would barely produce the energy needed (FB deep..., 2011).

In order to do away with grid power for pumping entirely, Ban Lan and Ban Wang Saeng would have to install batteries, which bring environmental, financial and security concerns with them, or install new PVWPS's, including new arrays and pumps. Otherwise, they would not be able to increase the amount of water they store. Therefore, it is clear that a dual system is the most effective way for these villages to obtain water.

5.2 Comparing the cost of PVWPS's to that of grid-powered systems

Finding 5: PVWPS's benefit villages financially

All villages had different water fees in THB per cubic meter. In Ban Lan, residents also paid a monthly maintenance fee that covered village water committee salaries as well as potential repairs.

Since the installation of PVWPS's, the overall fee paid by the village to the electric company decreased. In the case of Ban Lan, individual households paid 1 THB more under the new system, but the village was able to pump more water combining both solar and grid power. Any unspent money resulting from the 40% decrease in expenses was then saved by the committee to profit the entire village. All residents are aware that while they may spend more on water month-to-month, they profited through improved water availability and the committee's ability to increase spending in other areas for their benefit.

In Nong Wang, cost per cubic meter decreased by 9 THB, while in Ban Wang Saeng expenses remained the same. Overall, combining PVWPS's with grid-powered pumps seemed a more economically sound choice than simply using grid-powered pumps, especially since less water is used during the night. A full comparison is outlined in Table 9.

Table 9. Comparison of Fees per household in Ban Lan, Nong Wang, Ban Wang Saeng

Village	PVWPS Water Fee (THB/cubic meter)	PVWPS Installation Cost (THB)	PVWPS Maintenance Fee (THB)	Previous System Installation Cost (THB)	Previous System Water Fee (THB/cubic meter)
Ban Lan	4	Funded by PDA	5	-	3
Nong Wang	3	Funded by PDA	-	-	9*
Ban Wang Saeng	7	Funded by PDA	-	300	7

*No exact number provided, this is based on a single user's difference in monthly expenses between the grid pump and PVWPS.

In Nong Wang, all PVWPS users expressed that the PVWPS led them to a better income than before, as the time and effort farmers once spent carrying buckets of water from the man-made pond could now be put towards other productive activities, and there was more water available, leading to healthier crops and a greater yield. This also positively impacted their food security. Because they had reliable water to irrigate their crops, crops were healthier and more abundant, providing the village with a steady flow of income and food. However, as this system is still relatively young, there were no numbers to clearly prove this was the case.

Finding 6: PVWPS's for irrigation become cheaper than grid-powered systems after 9.25 years

For villages that are considering installing a PVWPS for irrigation pumping, a cost comparison between solar and grid power reveals that after 9.25 years, grid power would be more expensive than solar power. This time takes into account the wet and dry seasons but excludes additional maintenance costs. Figure 19 demonstrates this relationship.

Figure 19 assumes that the grid powered pumping system would be run from 9:00 AM until 6:00 PM for $\frac{2}{3}$ of the year to account for the rainy season, between June and October. Farmers will water their crops every month besides the rainy season, although if the rainy season doesn't supply enough water for the crops, users may choose to run the pump. This would reduce the amount of time for the grid-powered pump to exceed the cost of installing a PVWPS out of pocket. If the grid powered pump was run year-round without accounting for the rainy season, we would obtain the expected payback value of 4.25 years, consistent with theoretical data which suggested it would take 4-6 years (Chandel et al., 2015).

The cost of the solar panels with installation would be 40,000 THB. In addition to this, an inverter and control box would cost 10,000 THB. According to the Provincial Electricity Authority, the grid electricity rate for agricultural pumping has a service charge of 115.16 THB per month. In addition to

this, the user needs to pay for 2.0889 THB per kW for the first 100 kW and 3.2405 THB for anything over 100 kW. Assuming a two-horsepower pump is used for nine hours of the day, the number of kW used is 13.43, which is less than 100 kW. Because of this, we used the lower rate of 2.0889 THB per kW. We multiplied this rate by $\frac{2}{3}$ to accurately represent the amount of time the grid pump would be running throughout the year. Prices are based on data obtained from PDA Headquarters in Bangkok, which can be found in Appendix B.

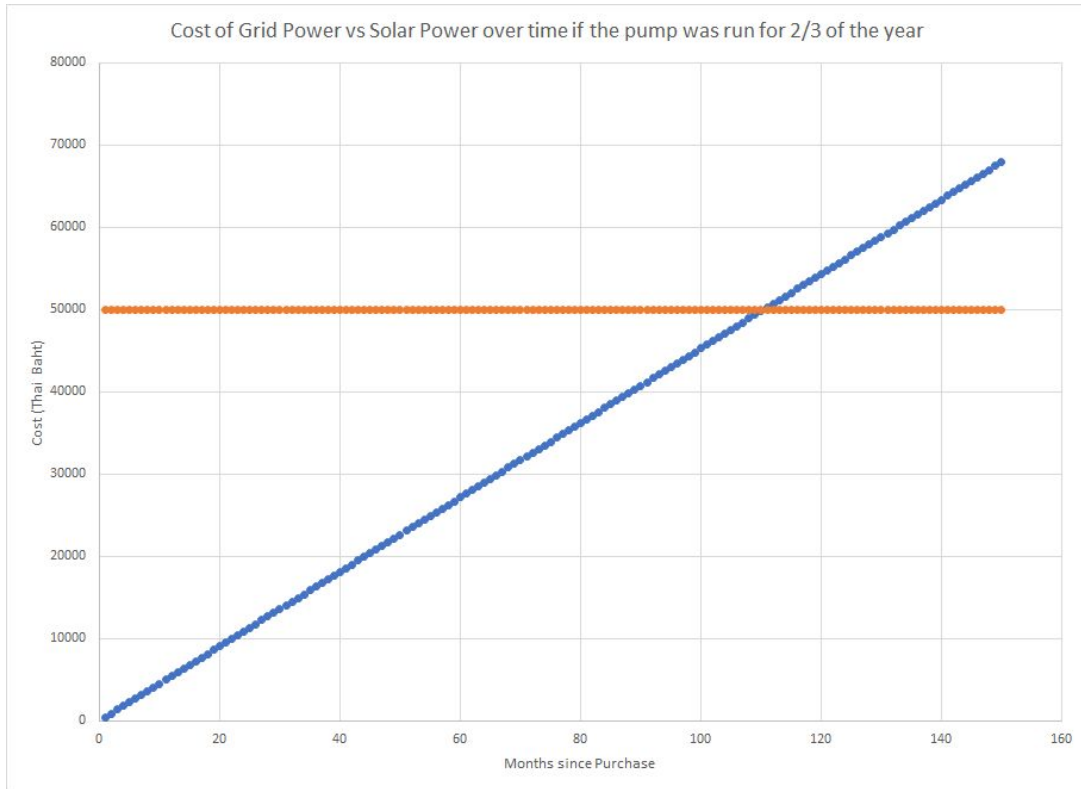


Figure 19. Cost comparison between grid and solar pumps used for irrigation over time

Costs that were considered the same for both grid-powered systems and PVWPS's were excluded, such as pumps, water towers, and pumping accessories. This graph only compares the remaining costs that were not the same in both scenarios. The expenses included in the solar scenario were PV arrays with installation and electrical appliances (converter and control box). In the grid electricity scenario, the cost estimate was based off the grid electricity for irrigation rate given by the Provincial Electricity Authority (Provincial Electricity Authority, n.d.).

After nine years and three months, grid electricity expenses would exceed those of a PVWPS. If a village paid out of pocket for the installation of PVWPS equipment, it would take nine years and three months before it could be seen as more profitable for the community compared to a pump powered by grid electricity. This does not take into account possible fees that could result from the need for maintenance, which may be higher for PVWPS's than grid-powered systems, as maintenance cost may

fall on the users rather than a larger corporation (such as an electric company). Finding technicians and materials suitable for PVWPS's may also prove more expensive, as it is relatively new technology.

However, based on Ban Lan's maintenance fee of 5 THB per month, which did not change with the installation of the PVWPS, the graph would not change, as Ban Lan accumulated savings in the case that repairs would be needed. However, if maintenance fees were based on the frequency of maintenance, this would increase the amount of time it would take for grid-powered pumps to overcome the cost of PVWPS's. The physical labor that goes into maintaining a PVWPS is also greater than that of a grid powered system, which can negatively impact health and time availability.

5.3 Socio-economic effects of PVWPS's

Finding 7: Users are pleased with PVWPS performance

In all these villages the PVWPS's were still less than four years old, so there had been no instances of the equipment breaking down or crisis situations that could lead residents to question the new system. It remains to be seen if opinions on the PVWPS's change after a decade or more post-installation. However, all users expressed satisfaction with the system and shared that it greatly improved their quality of life.

Finding 8: Village water committees were empowered, but need additional training

In order for a village to receive a PVWPS from PDA, the village must unanimously agree to the installation. This is a very important policy for PDA to know that the village will accept the changes to their community. For contrast, in Ban Siharat, another village in Khon Kaen that employs a PVWPS unrelated to PDA, the village water committee shared that it was difficult to get residents to agree to switch over from a grid-powered pump to a PVWPS. Although the committee and head of the village invited a professional to explain the way the PVWPS worked, concerns did not subside completely until the PVWPS began to function.

This shows how effective the leadership in Ban Lan, Nong Wang and Ban Wang Saeng had to have been for residents to trust authorities before even experiencing the positive effects of the PVWPS's. However, the successful organization of these villages cannot be fully attributed to PDA, as they were already organized before the PVWPS's were installed, and this was likely a big factor in their successful management.

In all cases we witnessed an extraordinary level of organization when it came to water management and farming. Ban Lan's water bottling business sprung as a village initiative, and provides additional revenue to village residents, as well as filtered water. Nong Wang's idea to use excess electricity from the PVWPS to power their community center nearby also stands out as an inventive solution that increases the efficiency of the village. Both of these cases show the beginnings of a creative mentality developing in these communities.

However, while village committees seemed to have taken ownership of the day-to-day maintenance of the PVWPS's, such as cleaning the panels and operating the system, this sense of ownership did not extend to all aspects of the PVWPS. All villages mentioned that they would need to contact PDA to perform any technical maintenance, indicating that they did not feel able to take charge of the system in moments of crisis, even in the cases where the residents themselves had worked on the construction. The village heads reported that it can take up to a week for PDA to address problems, which could lead to a breakdown in a crisis. However, villages report that the response time of the grid companies in case of power outages is significantly longer than PDA's response time.

Recommendation 2: Provide technical training to village water committee members

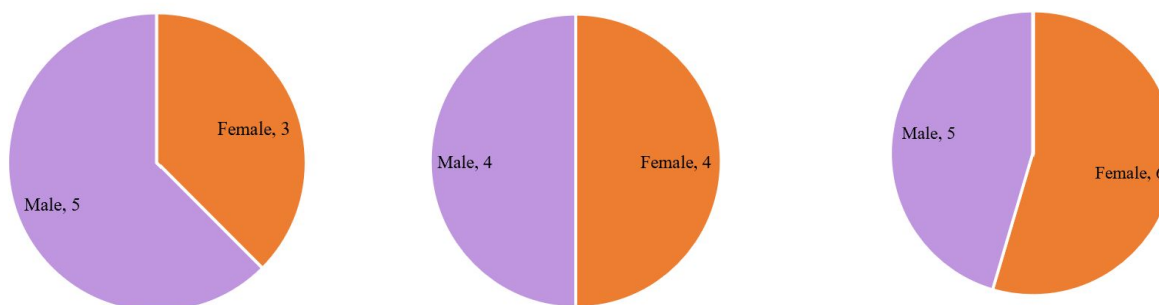
While PDA currently prides itself on empowering local communities to take charge of their own system, it is clear that these villages require additional technical education so that they feel confident enough to make repairs on their own. Teaching the residents about the maintenance of the PVWPS would provide them added independence, and simplify PDA's role in villages.

Finding 9: Statistics do not always reflect the reality of village committee gender ratios

PDA encourages balanced gender ratios as the organization believes that it leads to healthy community life. In all the villages, this ratio seemed to approach equality (Figure 20), but the social dynamics we witnessed did not necessarily reflect the reality on paper. While in Ban Lan and Nong Wang, men and women were equally talkative and sociable, in Ban Wang Saeng women remained on the fringes of conversation, and men were quick to take over and speak on their behalf. Interestingly, Ban Wang Saeng's records show that there are more women in positions of authority than men.

It is possible that women felt the need to stay quiet due to lack of education. If men in Ban Wang Saeng tend to be more educated than the women, they may feel more comfortable speaking to outsiders than the women. This inequality in education might also affect the dynamics between genders, with women deferring to men's decisions. However, as our time in these villages was limited, we cannot say with certainty that this inequality stretches into every aspect of village interaction. It is possible that when the village water committee meets privately, all have equal say in making decisions.

Ban Lan Authority Gender Ratio Nong Wang Authority Gender Ratio Ban Wang Saeng Authority Gender Ratio



*As we don't have a comprehensive list of Nong Wang authorities, this is the number of people we interviewed.

Figure 20. Gender Ratios of the Water Committees in Ban Lan, Nong Wang and Ban Wang Saeng

Recommendation 3: Provide technical training to women in village water committees

It would be beneficial to ensure that women are educated on technical matters just as much as men, to give them equal standing among local authorities. PDA may have to make a concerted effort to recruit women to an educational program of this sort, as it is possible that culturally, men are more expected to participate in these activities.

Ensuring that residents of these villages can look to women just as much as men for technical repairs may help the committees feel that women have more to contribute when making decisions.

Finding 10: None of the three villages financed the installation of their PVWPS's

None of the village residents personally financed the installation; the PVWPS's were financed by PDA's donors. Once the village decides to move forward with the project, they specifically request what they require from PDA. However, this does not necessarily lead to the financial empowerment of residents of these villages, and may generate dependency on PDA or other non-profits to further their quality of life.

Recommendation 4: Implement a payback plan for villages with many users

PDA could consider implementing a payback system with some of these villages to allow them to develop financial independence and empower them to make decisions for the PVWPS's. Each village could aspire to pay back the installation cost of approximately 250,000 THB.

In Ban Lan, the village water committee collects about 9,000 THB per month and spends about 4,000 THB on electricity and salaries (equipment maintenance is not included in this assessment as it is not a regular need). This leaves an average of 5,000 THB that the committee saves to later pay back to the village in dividends. Without charging residents a higher fee, Ban Lan’s village committee could collect money over a period of 50 months (a little over 4 years) and pay for the PVWPS. While our team does not have expense records for Ban Wang Saeng, it is not unrealistic to imagine that Ban Wang Saeng is in a similar situation.

Another option would be for each family to contribute a monthly fee over an extended period of time, such as one year or five years. The expenses per family were calculated in Table 10 below.

Table 10. Potential Payback Plan Example in Ban Lan, Nong Wang and Ban Wang Saeng

	Ban Lan	Nong Wang	Ban Wang Saeng
Installation Cost	250,000 THB	250,000 THB	250,000 THB
Users	182 families	42 farmers	174 families
Total cost per family	1,373 THB	5,952 THB	1,436 THB
Monthly for 1 year	114.40 THB	496 THB	119.70 THB
Monthly for 5 years	22.88 THB	99.20 THB	23.90 THB

While the cost per month over the course of one year would be excessive for residents of Ban Lan and Ban Wang Saeng, the cost over 5 years would not be impossible to afford, judging by the amount each household spends on water alone already. However, this may not be a possibility in Nong Wang, where the 250,000 THB cost would only be split across 42 farmers. Although we were not given specific income data, the average income of a Khon Kaen citizen is 19,848 THB per month, which may indicate that farmers could also find a 5-year plan feasible (Household Socioeconomic Conditions, 2017).

Even if the installation costs are paid off over a longer period of time, PDA would benefit, allowing residents to finance PVWPS’s in other communities more often and also empowering local communities to take charge of their resources. While the villages where PVWPS are currently installed may not be willing to begin to pay for what they received as a donation, PDA could keep this strategy in mind for future projects.

5.4 Environmental effects of PVWPS’s

Finding 11: Villages have no environmentally-sound disposal plan

The PVWPS’s did not generate any air pollution while used. They also took up very little space, as the structure of eight arrays could be built above other equipment and act as a roof, providing shade and cooling the area. This area can be used to store small water tanks, which could be kept cool in the shade.

None of the villages had a plan for disposal of the solar panels once they stop working. The average lifespan of arrays is 30 years, which means that ideally it will be a long time until these PVWPS's will need to be replaced. PDA stated in conversations with us that each village will have to decide what to do once that moment comes; however, the authorities in each village had no disposal plan, stating that they would ask PDA what to do and hopefully have their pump replaced and disposed of by PDA.

This is indicative of a much larger problem. On a global scale, users of solar energy and the authorities that oversee them do not know what to do with solar arrays once they reach the end of their lifecycle. No country currently has policies mandating how solar arrays should be disposed of, whether they are recycled, and how they are recycled, and users of these systems are not aware of their options. This could eventually lead to a larger environmental problem, where “clean” energy simply creates more waste.

Recommendation 5: Prepare an environmentally-sound disposal plan

We recommend that PDA assist the villages in developing a method for properly disposing of the PVWPS's without harming the environment, such as training on how to take apart the solar arrays so that they can be recycled and informing them of the resources they have at their disposal.

We also recommend that PDA begin to initiate a larger discourse with regional or national authorities on the topic, especially considering how many people employ solar panels across Thailand, both in the private and public sectors. PDA could lay the groundwork not only for future communities such as Ban Lan, Nong Wang and Ban Wang Saeng, but for the entire country to take the first steps towards establishing a national environmentally-sound photovoltaic disposal plan.

Research in Ubon Ratchathani is currently focused on Hydro-Floating Solar Hybrid Systems made of completely recyclable materials, which will be installed at Sirindhorn Dam, the largest hydro power plant in the world (Electricity Generating Authority of Thailand, 2020). PDA may be able to use this project as a resource to learn how other organizations are dealing with the issue of disposing of solar arrays.

6. Conclusions

PDA's project in Khon Kaen aims to help villages bring a reliable and affordable energy source to pump water in rural areas of Northeast Thailand through the installation of PVWPS's. As PVWPS's theoretically are more financially and environmentally advantageous, they act as a favorable alternative to fully grid-powered pumps. In Ban Lan, Nong Wang and Ban Wang Saeng, residents have identified the areas of water use that are most costly, and combined solar and grid power to ensure that they have a constant flow of water for a lower cost.

This project aimed to help PDA determine through a holistic analysis if PDA's PVWPS program is worth replicating across Khon Kaen. Through interviews and observations, we provided PDA with

updated information on the PVWPS's and the communities where they are installed, comparing their cost and technical performances to those of grid-powered pumps, and identified the environmental and social changes we observed.

In all villages, the water fee varied for each household according to how much water it used, and sometimes included a maintenance fee. While in some cases residents spend more month-to-month, they profit through improved water availability and dividends, as the committee's expenses have decreased. Farmers also expressed that the PVWPS's led them to a better income than before. Overall, combining PVWPS's with grid-powered pumps seems the more economical choice than simply using grid-powered pumps.

Since installation, none of the villages have had major problems with the PVWPS's. Only in Nong Wang does the PVWPS lack water pressure, which could be solved with additional equipment. Residents have a favorable impression of PDA, and they continue to rely on it for most maintenance. Implementing more extensive technical education for the residents might give them more independence. Educating women in this respect might also help even out the gender ratio in village water committees, which currently approaches equality on paper but does not always manifest in committee interactions.

In all cases we witnessed an extraordinary level of organization and innovation when it came to water management and farming, showing that leadership has had an overall positive effect on these villages. PDA could consider implementing a payback system with some of these villages or future villages to allow them to develop financial independence and empower them to make decisions for the PVWPS's. Villages like Ban Lan and Ban Wang Saeng could use their savings, or each family could contribute a monthly fee over an extended period of time, such as a year or five years.

The PVWPS's did not generate any pollution. However, none of the villages currently have a plan of how to responsibly dispose of their PVWPS's. We recommend that PDA assist the villages in developing a method for properly disposing of the PVWPS's, and initiate a larger discourse with regional or national authorities on the topic. In fact, Hydro-Floating Solar Hybrid Systems research in Ubon Ratchathani might be a useful resource (Electricity Generating Authority of Thailand, 2020).

While water shortages continue to be a problem in Khon Kaen and PVWPS's cannot fully respond to problems caused by drought, they allow residents of these villages to obtain larger quantities of water for less money than they were able to under the grid system, enabling them to have better income and a thriving community life. If replicated in more villages in Khon Kaen, PDA's program has potential to drastically improve the region's economy, quality of life, and community identity.

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Abu-Aligah, M. (2011). Design of photovoltaic water pumping system and compare it with diesel powered pump. *Jordan Journal of Mechanical and Industrial Engineering*, 5(3), 273-280. Retrieved from https://pdfs.semanticscholar.org/8632/6e94e74aa2f6e744f7b5f9d43a81751bc1f8.pdf?_ga=2.57560618.1202682411.1579249331-1959995850.1573639426

This article compares photovoltaic water pumps to diesel water pumps, with a thorough analysis of advantages, disadvantages, installation and cost, as well as the components of the system, configurations, system sizing and site conditions. Our team found the information very helpful for our background, particularly the graphics and statistics. The information is clear and concise and offers an image of how these pumps function in real life.

Allaby, M. (2007). *Encyclopedia of weather and climate* (2nd ed., Vol. 1). New York, NY: Facts on File. Retrieved from <http://www.armchairpatriot.com/Encyclopedias/Encyclopedia of Weather and Climate.pdf>

This is a source about the climate and weather of the whole world, it doesn't focus on one place. The parts that are useful for this project are the sections on groundwater and layers of ground and water in an aquifer. This source is a bit overwhelming with the amount of information, especially since it isn't all relevant, however this article is able to provide is useful.

Andrews, J. T., Rodrigues, M. P., Guevara, M., & Kimmel, R. H. (2012). *Improving Energy Supply & Demand in Rural Thai Villages*. Retrieved from http://www.wpi.edu/Pubs/E-project/Available/E-project-030212-020648/unrestricted/IQPSSP3_Final_IQP.pdf

This IQP project looks at the impact of PVWPS's used in rural Thai communities, and summarizes the social and economic factors that influence how these communities meet their water and energy needs. This project was sponsored by PDA, so it provides a helpful vision of how research might take place in these communities, and how our project might be a continuation of PDA's efforts in 2012.

Anna University. (n.d.). Financial analysis solar PV pumps. 53-65. Chennai. Retrieved from https://shodhganga.inflibnet.ac.in/bitstream/10603/182176/9/09_chapter%203.pdf

This article provides the block diagram comparing the cost of solar pumping systems against diesel water pumping systems. It includes the capital cost and the future costs; including the operating cost, maintenance cost and the replacement cost. All of these

calculations are taken before government subsidy and potential other benefits from solar pumping systems, such as selling back to the grid. Additionally, this data is useful for its information on the operating systems of diesel or solar pumping system to further improve efficiency.

Armanuos, A. M., Negm, A., & Tahan, A. H. M. H. E. (2016). Life cycle assessment of diesel fuel and solar pumps in operation stage for rice cultivation in Tanta, Nile Delta, Egypt. *Procedia Technology*, 22, 478-485. doi: 10.1016/j.protcy.2016.01.095

This article is a case study of PVWPS's used for irrigation in a semi-arid region of central Nile Delta, Egypt. It performs a life cycle assessment (LCA) of the environmental impacts of groundwater pumping systems that run on diesel fuels and solar power specifically for the irrigation of rice. This article gave our project excellent data on base environmental measurements as well as the equations to replicate them if necessary. However, this article only focuses on the comparison between diesel pumps and solar pumps, and our project needs to also incorporate grid electric pumps. It also does not explore cost or social impact.

Arvizu, D., P. Balaya, L. Cabeza, T. Hollands, A. Jäger-Waldau, M. Kondo, C. Konseibo, V. Meleshko, W. Stein, Y. Tamaura, H. Xu, R. Zilles. (2011). Direct solar energy. In IPCC special report on renewable energy sources and climate change mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved from http://www.ipcc-wg3.de/report/IPCC_SRREN_Ch03.pdf

This is a book chapter from a large report on the state of alternative energies that addresses direct solar energy. There is a lot in this chapter that is helpful, specifically about the manufacturing of the solar panels and their environmental impact, as well as resource potentials and how to make the manufacturing process more environmentally friendly. This chapter also goes over costs and potential areas the industry could improve overall.

Average sunshine Khon Kaen, Thailand. (2019). Retrieved from <https://www.weather-th.com/en/thailand/khon-kaen-climate>

This website gives average temperatures in Khon Kaen Province, Thailand for the last year. It also gives average humidity, rainfall and daylight/sunshine. All of these are very useful toward our project as the efficiency of the PVWPS's relies significantly on the weather conditions. This data is for the entire Province of Khon Kaen, so some of the data may be skewed in our specific villages, but it gives very useful information that we otherwise did not have.

Badescu, V. (2003). Time dependent model of a complex PV water pumping system. *Renewable Energy*, 28(4), 543–560. doi: 10.1016/s0960-1481(02)00069-1

A water storage tank and a battery used with a PV array would improve the stability of the whole system. The mechanical power stored in the tank should remain the same throughout the year. The use of a battery also increases the stability of a PV water pumping system.

Bangrapa, M. (2018). Thai Niyom scheme comes under scrutiny. Retrieved from <https://www.bangkokpost.com/thailand/special-reports/1528630/thai-niyom-scheme-comes-under-scrutiny>

The Thai Niyom Yangyuen program is involved in the state-funded distribution grants of 200,000 baht per village. This program was launched in February 2018, with a budget of 95.75 billion baht to spread for local development projects through Thailand. The money was to go to welfare-card holders, finance the farm sectors, and the largest chunk of money is to help with community development. There are criticisms of the program, including people accusing the government giving out money in hopes of gaining political popularity. The benefits and the downsides of this program are laid out well in this article.

Baltas, P. E., & Russell, P. E. (1991). Control considerations for photovoltaic powered water pumping systems. Paper presented at *European Photovoltaic Solar Energy Conference*, 449–452. Dordrecht: Springer. doi: 10.1007/978-94-011-3622-8_115.

This report provided us with an understanding of PVWPS models, component designs, size specifications and data collection information, along with downsides of applications. It includes two case studies, one in Arizona, USA and the other in Attica, Greece. Although many calculations are beyond the scope of our project, this report gave our team good insight on how to replicate measurements in differing environments.

Barnaud, C., Trébuil, G., Dufumier, M., & Suphanchaimart, N. (2006). Rural Poverty and Diversification of Farming Systems in Upper Northeast Thailand. *Moussons*, 9(10), 157–187. doi: 10.4000/moussons.2012

This article explores poverty in rural Upper Northeast Thailand, looking at the history of farming in this area and its economic dependency on agriculture. It helped us understand Northeast Thailand and informed of the difficulties farmers face, providing a context for the social impact of PVWPS's.

Biswas, S., & Iqbal, M. T. (2018). Dynamic Modelling of a Solar Water Pumping System with Energy Storage. *Journal of Solar Energy*, 1–12. doi: 10.1155/2018/8471715

This study from Lalmonirhat, Bangladesh, provides information about PVWPS sizing, and an example of a database used to observe daily and monthly solar power production. Based on the issues found in their systems, they create three potential solutions and go into the

advantages and disadvantages of each. This article focuses only on submersible pumps for well water applications, and only compares them to diesel pumps, but it provides helpful information on comparing multiple solutions to PVWPS problems. Additionally, this data on daily radiation and temperature may be similar to that of Ban Phai.

Blance, J. (2011). Brushless DC pump(DC40). Retrieved from [http://www.dbrushlesspump.com/Brushless-DC-Pump\(DC40\)-p26.html](http://www.dbrushlesspump.com/Brushless-DC-Pump(DC40)-p26.html)

This webpage, taken from a catalogue of products, explains the reasoning behind pump labeling criteria and what each part of the name means. Although our team had no need for the catalogue itself, understanding how to identify pump models was essential for us to recognize pumps we might see in Ban Phai and determine whether the appropriate pump is being used.

Brander, M., Sood, A., Wylie, C., Haughton, A., & Lovell, J. (2011). Electricity-specific emission factors for grid electricity. Retrieved from <https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf>

This article is about electricity-specific emission factors for grid electricity. It provides numbers for CO₂ and other greenhouse gas emissions. It also provides emissions per kWh of electricity consumed, as well as other emission-related data for individual countries.

Bureau of Forecasting Statistics National Statistical Office. (2010). Population and home classified by district and sub-district, Khon Kaen province, as of December 2010. Retrieved from <http://service.nso.go.th/nso/nsopublish/districtList/S010107/th/56.htm>

This website contains population, demographics, and geographical data about Ban Phai. While the data was gathered in 2010 and is not accurate for 2020, the population data is still helpful to visualize the demographics that the PVWPS's impact directly and indirectly.

Bureau of Large Scale Water Resources Development, irrigation department. (2015). Nong Wai Dam, Kaen province. Retrieved from <http://lproject.rid.go.th/site/index.php/th/project-information/128-2015-06-22-02-00-17/227-2015-06-22-09-46-30>

This source provides the boundaries, description and statistics of the water that flows through the Nongwai irrigation project. It also provides information about their facility and components such as the rubber dam and sand sluice gate. The Nongwai irrigation project aims to slow down the flow rate in Khon Kaen, so that when the level of water decreases the residents still have some water to use rather than no water in the river at all. This shows how the Thai government is trying to fix the lack of water problem, which is very relevant to our project.

Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-powered drip irrigation enhances food security in the Sudano-Sahel. *Proceedings of the National Academy of Sciences*, 107(5), 1848–1853. doi: 10.1073/pnas.0909678107

This year-long study, using household surveys in the Sudano-Sahel region of west Africa, found that families who recently implemented PVWPS's for irrigation were less likely to experience chronic food insecurity and more likely to have an improved quality of life. They were able to improve rural livelihoods with both economic and environmental benefits. Although our visits to the community will be much shorter and we will rely on short interviews, this study offers good insight on the improvements PVWPS's make to quality of life.

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

This article reviews current PVWPS's used for irrigation and community drinking water. It looks at multiple case studies of countries using these systems and analyzes their effectiveness in terms of investment payback, flow rate, size and solar radiation available. This was useful for our project as it allowed us to see how other countries use qualitative measurements to predict and determine the success of PVWPS's.

Chandrappa, R., & Das, D. B. (2014). *Sustainable Water Engineering: Theory and Practice*. John Wiley & Sons. Retrieved from <https://ebookcentral-proquest-com.ezpxy-web-p-u01.wpi.edu/lib/wpi/detail.action?docID=1712694>

This article provides an understanding of sustainable water engineering. It was useful to gain insight on the usefulness of manual water pumps in rural areas. The rest of the book is about sustainable water management, structures and treatment.

Cho, K. (2009). Blazing a trail towards poverty alleviation in Thailand. Retrieved from <https://knowledge.insead.edu/responsibility/blazing-a-trail-towards-poverty-alleviation-in-thailand-1625>

This article explains how PDA began and what its initial goals were for the future of Thailand. It speaks less about the solar pump project and more about how PDA got their start with their family planning initiative. Although our project is not directly mentioned, this article is still important to our understanding of our sponsor as it explains how Mechai Viravaidya started with a goal and created one of Thailand's largest nonprofit organizations.

Closas, A., & Rap, E. (2017). Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy*, *104*, 33–37. doi: 10.1016/j.enpol.2017.01.035

This article delves deep into the use of solar water pumps that draw from groundwater for irrigation, and the risks posed by a lack of proper guidelines and control measures. Some of the villages our team will work in may draw from groundwater, so understanding these findings is crucial to avoiding the proliferation of bad habits among users.

Dau, Q.V., Kuntiyawichai, K., & Suryadi, F. X. (2018). Drought severity assessment in the lower Nam Phong River Basin, Thailand. *Songklanakarin Journal of Science and Technology*. *40*(4), 985-992. doi: 10.14456/sjst-psu.2018.99

This article outlines the severity of the drought problem in terms of environmental services and socio-economic conditions. It contains facts and figures gathered using the Standardized Precipitation Index (SPI) and the Water Evaluation and Planning (WEAP), and found consistent results from the two sources. Although this research was done in the Khon Kaen Province, it never mentions the district of Ban Phai, but it was useful for our group to familiarize itself with the severity of the drought in this province.

Daud, A., & Mahmoud, M. M. (2005). Solar powered induction motor-driven water pump operating on a desert well, simulation and field tests. *Renewable Energy*, *30*(5), 701-714. Retrieved from <https://doi.org/10.1016/j.renene.2004.02.016>

This case study looked at solar-powered induction motor-driven water pumps in desert wells in Jordan, examining both simulations and field tests. It shares very specific data about costs and solar irradiation, as well as component-specific measurements and how they can be quantified. This was very useful for our background research on other PVWPS studies in other parts of the world.

Department of Groundwater Resources. (n.d.) Groundwater. Retrieved from <http://www.dgr.go.th/th/faq/19>

This article provides information on drilling for water and the use of groundwater. It describes the permissions necessary for drilling in Thailand, and steps to take if salt water is found, which was helpful information for our research.

Draper, J. (2016). A Royal Dam Runs Dry. Retrieved from <https://prachatai.com/english/node/6006>

This article provides information about the state of the Ubol Ratana Dam when it ran dry and stopped producing electric power in 2016. It also provides information on the state of other dams in 2016 when they were also at critically low levels.

Edison Tech Center. (n.d.). The History of Electrification. Retrieved from <https://edisontechcenter.org/HistElectPowTrans.html>

This source gave us some valuable information regarding the beginnings of grid electricity. It enabled us to better understand the differences between AC and DC power, and why one might want to choose one over the other.

Electricity Access: More affordable technology and off-grid renewable energy is giving people increased access to electricity across Africa. (2019). *African Business*, (465), Retrieved from https://link.gale.com/apps/doc/A594663201/AONE?u=mlin_c_worpoly&sid=AONE&xid=2e081928

This article gives us an understanding of some of the factors that play into a lack of energy access in a location that isn't Thailand. Expanding our view to other locations allows us to see this project on a broader scale, evaluating what other communities have been through. We learned that cost, remoteness, and insufficient supply are the largest factors contributing to lack of energy access in African communities.

Electricity Generating Authority of Thailand. (n.d.). Nam Phong Power Plant. Retrieved from <https://www.egat.co.th/en/information/power-plants-and-dams?view=article&id=41>

This website is on Nam Phong Power Plant with information provided by the Electricity Generating Authority of Thailand. It provides the total capacity, what powers the plant and when the plant was installed.

Electricity Generating Authority of Thailand. (n.d.). Ubol Ratana dam. Retrieved from <https://www.egat.co.th/en/information/power-plants-and-dams?view=article&id=56>

This article provides specifications on the height, length, width, and reservoir capacity of the Ubol Ratana Dam. Ubol Ratana Dam is located in the upper part of Khon Kaen, where our project takes place. The dam provides electric power to the grid in Khon Kaen and this website is good to understand the basic information about the dam.

Electricity Generating Authority of Thailand. (2012). Power Development and Future Plan, 82–93. Retrieved from https://www.egat.co.th/en/images/annual-report/2012/ENG_annual_2012_for_web_p82.pdf

There is information on the source of grid electricity in Thailand. One of the sources is the Xayaburi Hydroelectric Power Plant in Laos. Thailand imports electricity from this dam to help support three northeastern provinces.

Electricity Generating Authority of Thailand. (2013). Ubol Ratana dam. Retrieved from <https://www.egat.co.th/en/information/power-plants-and-dams?view=article&id=56>

This article provides specifications on the height, length, width, and reservoir capacity of the Ubol Ratana Dam. Ubol Ratana Dam is located in the upper part of Khon Kaen, where our project takes place. The dam acts like a water reservoir to irrigate the Khon Kaen region, and understanding its influence was crucial to understanding the situation in Ban Phai.

Electricity Generating Authority of Thailand. (2020). Report of EGAT reservoir storage conditions. Retrieved from http://www.thaiwater.net/DATA/REPORT/php/egat_dam_1.php?lang=en

This source provides numbers on how dams across Thailand are performing every day. This is useful to be able to access data that is updated daily, and to compare current performance to numbers in the past.

Electricity Generating Authority of Thailand. (2020). Residents of Ubon Ratchathani attend a public hearing of the Hydro-Floating Solar Hybrid Project at Sirindhorn Dam, the largest hydro power plant in the world. Retrieved from <https://www.egat.co.th/en/news-announcement/news-release/residents-of-ubon-ratchathani-attend-a-public-hearing-of-the-hydro-floating-solar-hybrid-project-at-sirindhorn-dam-the-largest-hydro-power-plant-in-the-world>

On February 4, 2020 the residents of Ubon Ratchathani went to a hearing about the Hydro-Floating Solar Hybrid Project at the Sirindhorn Dam. The Dam is the largest hydro power plant in the world, and now there are plans to install floating solar panels at the dam. The project is scheduled to start December 2020.

Esri Thailand. (2012). Khon Kaen province information. Retrieved from <https://www.arcgis.com/home/item.html?id=24e1b3f966dd4094b27fa2f37beaafc7>

This website has the background information of Khon Kaen province including topography, weather, the area's history and tourism. Therefore, it is a good source in providing us with the information about the natural features of the area in Khon Kaen province. This will allow us to briefly know the area before we survey that area.

FB deep cycle battery 12V 125AH. (2011). Retrieved February 17, 2020, from http://www.thaipowertech.com/index.php?lay=show&ac=cat_show_pro_detail&pid=573131

Fedrizzi, M. C., Ribeiro, F. S., & Zilles, R. (2009). Lessons from field experiences with photovoltaic pumping systems in traditional communities. *Energy for Sustainable Development*, 13(1), 64–70. doi: 10.1016/j.esd.2009.02.002

This article examines some of the common problems PVWPS's face and some relatively easy fixes for them. This was useful for our research as it familiarized us with the common

pitfalls of PVWPS's. Planning around these specific topics, we can predict the longevity of the pumps in Ban Phai.

Fernquest, J. (2015). Thailand's Drought: Time to conserve water is now. *Bangkok Post*. Retrieved from <https://www.bangkokpost.com/learning/learning-news/788433/thailand-drought-time-to-conserve-water-is-now>

This article looks into water usage in Thailand and the fact that it needs to be conserved. This source is helpful for us because it reports how much water people in Thailand typically use per day. Water users in Thailand use water more sparingly than other countries due to the droughts that occur. This information is very important when we calculate how much water a village would need on a daily basis.

Friend, R., & Thinphanga, P. (2018). Urban water crises under future uncertainties: the case of institutional and infrastructure complexity in Khon Kaen, Thailand. *Sustainability*, 10(11), 3921. doi: 10.3390/su10113921

This paper examines the water management crisis in Northeast Thailand and determines how effectively the existing institutional structures adapt to the unknown. They found that the existing infrastructure is the constraining factor, since what is built is outdated in terms of old structures and water needs. This is a good look into water management in Thailand, and the obstacles our project might face.

García, A. M., Gallagher, J., McNabola, A., Poyato, E. C., Barrios, P. M., & Díaz, J. A. R. (2019). Comparing the environmental and economic impacts of on- or off-grid solar photovoltaics with traditional energy sources for rural irrigation systems. *Renewable Energy*, 140, 895-904. doi:10.1016/j.renene.2019.03.122

This paper contains a case study from Cordoba, Spain, that compares the environmental and economic impacts of three different energy sources: off-grid diesel engines, on-grid grid electric pumps, and PVWPS's. In a life-span analysis, it found that PVWPS's were more beneficial than the other two pumps both environmentally and economically. A limitation of this source is that it uses a 30-year life span model, while PDA's PVWPS's have not yet shown that longevity. However, this resource was useful because it compares all three pump models.

Gem. (2015). Water Pumps. Retrieved from <http://www.thegreenbook.com/water-pump-and-its-uses.htm>

This website provides the basics of water pumps, including applications and types of pumps. It lists the types of pumps in a manner easy to understand and states the best applications for each type of pump.

Goe, M., & Gaustad, G. (2014). Strengthening the case for recycling photovoltaics: an energy payback analysis. *Applied Energy*, 120, 41–48. doi: 10.1016/j.apenergy.2014.01.036

This article outlines the environmental risks of not having an efficient system in place to manage, collect and recycle photovoltaic materials. Based on this information, our team can remain aware of these risks and of potential to create new steps for the disposal of photovoltaic materials in Ban Phai, which we can then communicate to our sponsor.

Habib, M. A., Barve, S. B., Shisode, S. P., & Shinde, S. U. (2014). Numerical Flow Simulation of Centrifugal Pump in ANSYS and OpenFOAM. *International Journal of Current Engineering and Technology*, (3). Retrieved from <http://inpressco.com/wp-content/uploads/2014/04/Paper2198-102.pdf>

This article studies the flow of centrifugal pumps. It provides diagrams of the pumps and well-labeled graphs that are easy to understand. The rest of the article does not have that much relevance to our project, but understanding how the pumps work was beneficial to our research.

Home Water Works. (2019). Showers. Retrieved from <https://www.home-water-works.org/indoor-use/showers>

This article gives us information on flow rates. On the technical side of our project, flow rate of water is a very key point of information, but that information means nothing without something to reference it with. This source gives us a reference of flow rate with something we're all familiar with: showers.

Household Socioeconomic Conditions 2017. (2017). Retrieved from http://khonkaen.nso.go.th/index.php?option=com_content&view=article&id=486:-2560&catid=105&Itemid=510

This source allowed us to view the average income of Khon Kaen residents over time. This is useful for us moving forward with our cost comparison calculations.

Jafar, M. (2000). A model for small-scale photovoltaic solar water pumping. *Renewable Energy*, 19(1-2), 85–90. doi: [https://doi.org/10.1016/S0960-1481\(99\)00020-8](https://doi.org/10.1016/S0960-1481(99)00020-8)

This study creates a model that predicts the flow rate of a PVWPS as a function of head length and solar radiance. It found that in terms of head length, the less distance the water has to travel from the ground to the system, the higher the flow rate. This article gave our team insight into the different factors that could affect the water flow rate in Ban Phai.

James, S. (2012). Characteristics of Centrifugal Pumps. Retrieved from <https://www.pumpsandsystems.com/characteristics-centrifugal-pumps>

This article discusses how to read and use centrifugal pump performance curves for a centrifugal pumping system. It was helpful to our research as centrifugal pumps might be

used in the villages in Ban Phai, and this article's equations could be useful for our assessments and for a general understanding of how the pumps work.

Janjai, S., Masiri, I., Pattarapanitchaim S., & Laksanaboonsong, J. (2013). Mapping Global Solar Radiation from Long-Term Satellite Data in the Tropics Using an Improved Model. *International Journal of Photoenergy*, 2013 1–11. doi:10.1155/2013/210159.

This study presents a new model for measuring solar radiation throughout Thailand, accounting for solar radiation scattering between the ground and the atmosphere and creating a map of solar radiation levels. It provided us with information on solar radiation in Khon Kaen and the potential energy that could be generated in Ban Phai.

Jones, M.A., Odeh, I., Haddad, M., Mohammad, A.H., & Quinn, J.C. (2016). Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture. *Desalination*, 387, 35-45. doi: 10.1016/j.desal.2016.02.035

To determine the economic feasibility of photovoltaic desalination compared to conventional systems, this study created hourly simulations of variable pumping and desalination speeds. Our team can draw from this strategy and data when performing our own system comparisons, although there will be many differences due to the different applications of solar energy.

Karume, N. (2018). Proper maintenance practices for solar water pumps. Retrieved from <https://www.pumps-africa.com/proper-maintenance-practices-for-solar-water-pumps/>

This article outlines routine maintenance needed by PVWPS's in order for them to run efficiently. It does not go into much detail when describing the problems and solutions and is more of a general overview, and does not mention instances when a certified technician would need to come in. This article allowed our team to have a basic knowledge of the daily maintenance PVWPS's need.

Kehinde, E. (n.d.). Electrical Grid. Retrieved from <https://www.studentenergy.org/topics/electrical-grid>

This article provides a basic explanation of how the electrical grid works. It goes over the generation, transmission, distribution and consumption of electricity. It is a rather simple explanation of grid electricity but useful as a starting point.

Khon Kaen Climate. (2019). Khon Kaen climate graph and weather by month. Retrieved from <https://en.climate-data.org/asia/thailand/khon-kaen-province/khon-kaen-4291/>

This source provides a summary of Khon Kaen province's climate. This provides the average temperature, and minimum and maximum temperature by month as well as the average precipitation. This information is useful so we know what the climate is like in Khon Kaen, and how it might affect the performance of the pumps. The majority of the

information is clear and easy to understand, however there are some graphs that are difficult to interpret and are not labeled well.

Kesa, L. (2014). (Rep.). S. Rajaratnam School of International Studies. Retrieved February 17, 2020, from www.jstor.org/stable/resrep17177

This source provides crucial information to consider about hydro powered systems. While hydropower is a renewable energy source, it can have some serious environmental repercussions. This information allowed us to draw a comparison to other methods of obtaining energy.

Kroeksakul, P., Naipinit, A., & Sakolnakorn, T. P. N. (2011). The Economic And Social Effects Of Farmers Growing Para Rubber In Northeast Thailand: A Case Study Of Sapsomboon Village, Dun Sad Sub-District, Kranoun District, Khon Kaen Province. *Journal of Business Case Studies (JBSC)*, 7(1). doi: 10.19030/jbcs.v7i1.1588

This article goes over the economic and social factors affecting rubber farmers in Northeast Thailand. These farmers tend to have better income, quality of life and social status after they sell their produce. The Thai government has been involved in expanding agriculture, specifically helping to increase the number of rubber plantations, with the goal of helping farmers get out of poverty. This study takes place in the Khon Kaen district, and offers some useful statistics on this population for our research.

Kuehn, P. R. (2019). Thailand Village Life. Retrieved from <https://wanderwisdom.com/travel-destinations/Living-in-Thailand-Life-in-a-Thai-Village>.

This article offers a vision of the typical village in rural Thailand, comparing the city life to that of the countryside and emphasizing the importance of agriculture within these villages. It was useful to know the normal proceedings of these villages as this is the area our project impacts, and the area we will visit.

Kumar, A., & Kandpal, T. C. (2007). Potential and cost of CO₂ emissions mitigation by using solar photovoltaic pumps in India. *International Journal of Sustainable Energy*, 26(3), 159–166. doi: 10.1080/14786450701679332

Even 'green energy' can produce CO₂ emissions, and PVWPS' are no different. This paper develops a system to estimate PVWPS CO₂ emissions, and compares it to that of diesel and electricity systems. This will be useful for our environmental assessment in the event that we can gather data for this estimation from the PVWPS in Ban Phai.

Kummu, M., Ward, P. J., Moel, H. D., & Varis, O. (2010). Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters*, 5(3), 034006. doi: 10.1088/1748-9326/5/3/034006

This paper lists water shortages over the last two thousand years, which had extreme effects on climate change. It also explains the importance of water governance, water management, water policy and environmental integrity, which is helpful to keep in mind as the implementation of PVWPS's will have an impact for years to come.

Lal, R., Delgado, J. A., Gulliford, J., Nielsen, D., Rice, C. W., & Pelt, R. S. V. (2012). Adapting agriculture to drought and extreme events. *Journal of Soil and Water Conservation*, 67(6), 162A-166A. doi: 10.2489/jswc.67.6.162a

In 2012, the United States experienced a drought that was very similar in nature to the dust-bowl in the 1930's. It was the worst drought they had experienced in about 80 years, and resulted in a corn yield reduction that hadn't been experienced since the 90's. Thus drought affected crops, animals, and people across the globe. With reduced yields, the price of crops spiked. This case study helped us understand how a lack of water in certain areas can lead to issues on a global scale, and the importance of reliable water-obtention methods.

Lee, K. (2018). Electric Energy Advantages & Disadvantages. Retrieved from <https://sciencing.com/electric-energy-advantages-disadvantages-6008663.html>

This article provides a brief history of AC and DC electricity. It also gives a short argument about the advantages of having multiple electricity sources and not just relying on one source to give the power needed, with a brief overview of the different sources of electricity. This article also mentions the disadvantages of the different energy sources.

Mahmoud, M. (1990). Experience results and techno-economic feasibility of using photovoltaic generators instead of diesel motors for water pumping from rural desert wells in Jordan. *IEEE Proceedings C Generation, Transmission and Distribution*, 137(6), 391–394. doi: 10.1049/ip-c.1990.0053

This article looks at the techno-economic feasibility of using photovoltaic generators instead of diesel motors for water pumping in rural desert wells located in Jordan. It compared diesel motor pumping systems to photovoltaic systems, looking at reliability and economic feasibility. It explains the cost analysis and the formulas used, which will be beneficial to our research as an already established model for cost analysis. However, this source is 30 years old, which may mean that the data is outdated.

Majandang, J., Sarapirome, S. (2012). Groundwater vulnerability assessment and sensitivity analysis in Nong Rua, Khon Kaen, Thailand, using a GIS-based SINTACS model. 68(7), 2025-2039. doi: 10.1007/s12665-012-1890-x

The purpose of this article is to inform the reader of the different soil zones in Khon Kaen Province; the intermediate zone, and groundwater layer. Unfortunately, we will not be

visiting the specific district of Nong Rua that this article is about, but it gives us an idea of the soil conditions in the neighboring regions of our villages. Knowing this information gives us an idea of how deep to dig in the case that the water source is a well to reach usable groundwater.

Meteorological Department. (2020). Khon Kaen current weather. Retrieved from <https://www.tmd.go.th/en/province.php?id=18>

This website provides current weather in Khon Kaen which can be used to understand how weather affects the PVWPS's performance because the efficiency of these pumps depends heavily on weather conditions.

Metson, E. (2017). Batteries and their effects on the environment. Retrieved from <http://www.ecofriendlylink.com/blog/batteries-and-the-environment/>

This article provides some important facts about the effects batteries can have on the environment. These are important factors for us to consider as we make recommendations in terms of environmental effects of PVWPS's.

Meunier, S., Heinrich, M., Quéval, L., Cherni, J. A., Vido, L., Darga, A., . . . Marchand, C. (2019). A validated model of a photovoltaic water pumping system for off-grid rural communities. *Applied Energy*, 241, 580-591. doi:<https://doi.org/10.1016/j.apenergy.2019.03.035>

The electrification rate in sub-Saharan Africa causes a lack of access to energy which would be necessary to improve the living conditions. A need for electricity specifically mentioned in this paper is needing electrified water pumps since water access can be a challenge. This article is not about the implementation or assessment of a PVWPS already in place, but about providing a model of PVWPS for domestic water to off-grid rural communities in sub-Saharan Africa. This system modelled the flow rate and water level in the storage tank from the irradiance and ambient temperature of the region and the water collection by the users. They determined that this modelling system can be used in different areas, and the main new input that makes it different than other models is the water collection by the users of the PVWPS. This basically says that the water use habits of the people who use the PVWPS can impact the efficiency of the pump.

Ministry of Natural Resources and Environment, & Environmental information center. (2008). Drought. Retrieved from http://local.environnet.in.th/formal_data2.php?id=72

This Thai article provides information about drought, how it occurs, drought seasons and how to solve drought. We used this information to understand the reasons behind the water shortage in Ban Phai.

Monthly weather forecast and climate Khon Kaen, Thailand. (2019). Retrieved from <https://www.weather-th.com/en/thailand/khon-kaen-climate>

This source provides weather forecasts and climate information for Khon Kaen. It provides graphs and is easy to understand and comprehend. This information is useful to know what the climate is like in Khon Kaen and how it might affect how the PVWPS's perform.

Morales, T. D., Busch, J., & Yasumiishi, K. (2010). Design of small photovoltaic (PV) solar-powered water pump systems (Technical Note No. 28). *United States Department of Agriculture & Natural Resources Conservation Service*. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_046471.pdf

This article explains the process of designing PVWPS's, the different types of pumps and PV panels that exist, and how each one works in various scenarios. This helped our team understand the reasoning behind different pump designs. It also outlines the amount of water needed for a farm, which gave us a general idea of water needs in farms, even though the data is for the United States, not Thailand.

National Statistical Office. (2012). The 2010 population and housing census Changwat Khon Kaen. *Statistical Statistics Group Social Statistics Bureau*. Retrieved from http://popcensus.nso.go.th/en/report/WholeKingdom_T.pdf

This report contains Thailand's 2010 census information. Thailand conducts a census every 10 years, so the last official data available is from 2010. The next census will be conducted in 2020. This information was useful to understand the background of the province of Khon Kaen, but it does not delve into the smaller villages that we will be visiting.

Ngumbi, E. (2019). Becoming drought resilient: why African farmers must consider drought tolerant crops. *Inter Press Service*. Retrieved from <https://reliefweb.int/report/world/becoming-drought-resilient-why-african-farmers-must-consider-drought-tolerant-crops>

This article discusses the dangers and impacts of droughts in sub-Saharan Africa. Drought is the main cause of crop yield loss in Africa, causing food insecurity and famine. Although this study was not set in Thailand, many of the same issues occur in rural Thailand. It gave our team important insight into what many of these villages face because they do not have access to clean, reliable water.

Nikzad, A., Chahartaghi, M., & Ahmadi, M. H. (2019). Technical, economic, and environmental modeling of solar water pump for irrigation of rice in Mazandaran province in Iran: A case study. *Journal of Cleaner Production*, 239. doi: 10.1016/j.jclepro.2019.118007

This study in Iran compared conventional diesel pumps to PVWPS's in terms of cost and environmental effects. Solar photovoltaic powered water pumps were found to be more expensive upfront, but with a much lower lifetime maintenance cost. Using the solar panels to generate a surplus of electricity during non-irrigation months also resulted in profit for the farmers if they sold electricity back to the grid. Diesel powered pumps were also measured to be 71% more loud than PVWPS's. This study gave us a sense of how PVWPS's compare to diesel pumps, and what benefits we can look for in other pumping systems.

Nogueira, C. E. C., Bedin, J., Niedzialkoski, R. K., Souza, S. N. M. D., & Neves, J. C. M. D. (2015). Performance of monocrystalline and polycrystalline solar panels in a water pumping system in Brazil. *Renewable and Sustainable Energy Reviews*, 51, 1610–1616. doi: 10.1016/j.rser.2015.07.082

This article compared the performance of monocrystalline and polycrystalline solar panels in water pumping systems found in Brazil. It is very technical, as it focuses primarily on the advantages and disadvantages of using either monocrystalline or polycrystalline. It provided us with photographs of the solar panels themselves, as well as with data that demonstrates both models' strengths and weaknesses. This showed us that, based on the needs of the villages, we could suggest changing the PVWPS materials.

Oi, A. (2005). Design and simulation of photovoltaic water pumping system. Retrieved from: https://courseware.ee.calpoly.edu/~jharris/super_project/ao_thesis.pdf

This article describes how each component of a PVWPS works. PVWPS's function only when there is a direct source of sunlight, and therefore work differently from a conventional pumping system. This article was useful for us to describe how PVWPS design affects technical performance. The downside was that most of the results were taken from computer simulations, which gives a good idea of what the pump should theoretically be running like, but may not be realistic.

Panya, S., Pattaraprakorn, W., Detmote, T., Teansri, P., & Bhasaputra, P. (2010). Economic impact of power outage in Thailand: Industry perspectives. *Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010)*. doi: 10.1109/esd.2010.5598792

This journal gives data on power outages for grid beneficiaries across Thailand. It was helpful in providing us with accurate information on the frequency of power outages in Thailand. This information is crucial in order for us to effectively evaluate the efficiency of grid systems.

Pholkern, K., Saraphirom, P., Cloutier, V., & Srisuk, K. (2019). Use of Alternative Hydrogeological Conceptual Models to Assess the Potential Impact of Climate Change on Groundwater

Sustainable Yield in Central Huai Luang Basin, Northeast Thailand. *Water*, 11(2), 241. doi: 10.3390/w11020241

This study outlines the state of groundwater in Northeast Thailand, the area where our project will take place. It analyzes potential salinity, depth and thicknesses of rock salt layers which might affect drinkability for populations living in these areas. This provided us with a clear vision of the limitations of groundwater in Northeast Thailand and how this affects farmers' sustained access to water.

Pholpeuch, S. (2015). Drought and isolated rain in Thailand. Retrieved from https://library2.parliament.go.th/ebook/content-ebbas/b44658_dry.pdf

This article describes the drought in Thailand and mentions the factors that can cause rain to delay or in some instances, rain less than usual. Included in this report is the past information collected pertaining to drought and which areas are affected. This is a source written in Thai.

Phuangpornpitak, N., & Kumar, S. (2007). PV hybrid systems for rural electrification in Thailand. *Renewable and Sustainable Energy Reviews*, 11(7), 1530-1543. doi:<https://doi.org/10.1016/j.rser.2005.11.008>

This article surveys hybrid systems with photovoltaic and diesel generators in rural Thailand. Photovoltaic systems are unable to provide electricity on a 24-hour basis, since solar electricity generation depends on the site and the season. A hybrid system can help when the battery storage is empty. This article provides a cost analysis of initial, operating and management costs for photovoltaic hybrid systems.

Potera, C. (2007). Beyond batteries: portable hydrogen fuel cells. *Environmental Health Perspectives*, 115(1), 38–41. doi: 10.1289/ehp.115-a38

This article is about portable hydrogen fuel cells, turning the large cells into smaller portable versions. Hydrogen fuel cells work with a simple electrochemical process that does not have any polluting products since they do not burn the fuel during the process of producing electricity. However this article does not mention any disposal method for these fuel cells, or if there are regulations in place for them.

Population and Community Development Association. (n.d.). Vision and Mission. Retrieved from <http://pda.or.th/pda-vision/>

This includes the Population and Development Association's (PDA) vision and mission statement. PDA is the sponsor of this project and their vision and mission statements are important to know so we are aware of PDA's values and what their overall goal is.

Population and Community Development Association. (n.d.). Retrieved from <http://skoll.org/organization/population-and-community-development-association/>.

This citation offers a lot of background figures about PDA. It mentions specific impacts and accomplishments that PDA has had in Thailand and awards that it has received. This was useful to us as PDA is our sponsor, and it was necessary for us to know their accomplishments.

Population and house statistics report for the year 2019. (2019). Retrieved from <http://stat.bora.dopa.go.th/stat/statnew/statTDD/views/showVillageData.php?rcode=40101009&statType=1&year=62>

This site provides numbers for the populations of provinces, cities, sub districts and villages in Thailand. The information is split into male, female, total and amount of households. This information is more recent than the latest official census.

Provincial Electricity Authority. (n.d.). Electricity Tariffs. Retrieved from [https://www.pea.co.th/Portals/1/demand_response/Electricity Tariffs Nov61.pdf?ver=2018-11-21-145427-433](https://www.pea.co.th/Portals/1/demand_response/Electricity%20Tariffs%20Nov61.pdf?ver=2018-11-21-145427-433)

This document provided us with crucial information regarding grid electricity expenses. The document has a list of parameters with rates and service charges based on specific parameters. Using this information, we created a graph to show the cumulative cost of grid powered pumps over time.

Provincial Waterworks Authority. (2019). Provincial Waterworks Authority information. Retrieved from <https://www.pwa.co.th/province/branch/5520211>

This source provides easy to access information about water usage in Khon Kaen. This is useful to know how much water per month is used overall. However, it does not delve into water use per district.

Qazi, S. (2017). Fixed standalone PV systems for disaster relief and remote areas. *Standalone Photovoltaic (PV) Systems for Disaster Relief and Remote Areas*, 139–175. doi: 10.1016/b978-0-12-803022-6.00005-8

This book chapter is about fixed standalone photovoltaic systems for disaster-affected and remote areas. It goes over the application of PVWPS's for livestock watering, irrigation and water purification, and the different designs and functions of surface and submersible

pumps. Additionally, it includes their advantages and disadvantages. This chapter helped us understand the design of PVWPS's and why each model might be chosen.

Ray, K. L. (2010). Photovoltaic Cell Efficiency at Elevated Temperatures. Retrieved from <https://dspace.mit.edu/bitstream/handle/1721.1/59937/676836192-MIT.pdf?sequence=2&isAllowed=y>

This article looks at the different materials used for photovoltaic solar cells. This article focuses on hybrid systems and found that at varying temperatures, CIS or amorphous silicon would be the best suited materials for photovoltaic portions of hybrid systems. Although our pumps are not hybrid systems, this still gives insight on the importance of material when choosing solar cells arrays.

Renu, Bora, B., Prasad, B., Sastry, O., Kumar, A., & Bangar, M. (2017). Optimum sizing and performance modeling of Solar Photovoltaic (SPV) water pumps for different climatic conditions. *Solar Energy*, 155, 1326–1338. doi: 10.1016/j.solener.2017.07.058

This article details how array sizing, height of water table, radiation and temperature impact the efficiency of PVWPS's. It analyzes twelve different water pump models and determines the conditions that lead to greater efficiency, which offered our team a better vision of the strengths and weaknesses in the water pumps installed by our sponsor.

Rezk, H. (2016). A comprehensive sizing methodology for stand-alone battery-less photovoltaic water pumping system under the Egyptian climate. *Cogent Engineering*, 3(1). doi: 10.1080/23311916.2016.1242110

This article provides equations and calculations for the sizing of different components of PVWPS's, which we can use to compute how much power can be produced from the PVWPS's in Ban Phai. It provides a formula to calculate radiation at different tilt angles, which can suggest which area and angle can produce more power. With this information, we can optimize the function of PDA's PVWPS's.

Sabas, M. (2016). History of solar power. *Institute for Energy Research*. Retrieved from <https://www.instituteforenergyresearch.org/renewable/solar/history-of-solar-power/>

This article gave us some important information regarding the history of solar energy. The article is very United States central when discussing the development of PV array technology. This article goes into the development, laws and taxes involving the push for solar energy as well as the things that hindered its growth.

Samrat Solar Energy. (2017). Solar Irrigation Pump. Retrieved from <https://www.indiamart.com/proddetail/solar-irrigation-pump-17837675597.html>

Understanding the mechanics behind a PVWPS is essential to understanding our project. This page contains a diagram that helped our team understand the basics behind how a photovoltaic water pumping system works. Solar rays transfer power to a solar panel, which powers a motor, driving the pump to bring water from the ground to an overflow tank which can be used to distribute the water to crops.

Sawaengsak, W., & Gheewala, S. H. (2016). Analysis of social and socio-economic impacts of sugarcane production: a case study in Nakhon Ratchasima province of Thailand. *Journal of Cleaner Production*, 142, 1169–1175., doi:10.1016/j.jclepro.2016.08.148.

This study looks at the socio-economic reality of sugarcane farmers, their relationship with the wider industry, their living conditions and access to both natural resources and technology. This study gave our team insight into the lives of farmers who are implementing PVWPS's, and helped us form a vision of the challenges they face and how we could respond to their needs.

Shouman, E. R., & Shenawy, E. T. E., & Bahr, M. A. (2016). Economics analysis of diesel and solar water pumping with case study water pumping for irrigation in Egypt. *International Journal of Applied Engineering Research*, 11(2), 950 - 954. doi: 10.4028/www.scientific.net/JERA.38.87

This article shows a cost analysis between PVPWS's and diesel pumping systems by formulating calculations from technical performance data. Furthermore, the irradiation levels on horizontal and tilted surfaces can demonstrate which month generates more solar energy and has a more efficient performance. We can use this article to compare data generated in different seasons in Ban Phai as well.

Tang, A. (2016). Thailand scrambles to drill wells amid drought and water shortages. Retrieved from www.reuters.com/article/thailand-drought/thailand-scrambles-to-drill-wells-amid-drought-and-water-shortages-idUSL8N1532E7.

This article explores the problem of water shortage during drought. The Thai government is concerned about the limited amount of water that can be distributed for drinking, washing and farming in rural communities. Therefore, it has drilled underground water wells that provide enough water for use in the drought season in addition to the other reservoirs across the country. This shows us what resources villages have received from the government.

Thailand Khon Kaen Locator Map. 2009. In Wikimedia Commons. Retrieved February 12, 2020 from https://commons.wikimedia.org/wiki/File:Thailand_Khon_Kaen_locator_map.svg.

This is a map of Thailand with Khon Kaen highlighted, which is useful to know where our project took place.

The Secretariat of The House of Representatives. (n.d.). Groundwater. Retrieved from https://library2.parliament.go.th/ejournal/content_af/2558/oct2558-3.pdf

This article provides information about groundwater in Thailand, such as the locations of important groundwater sources, groundwater use in Thailand, sources in need of maintenance and the impact of using groundwater. This is a Thai resource, in Thai, which our team believes is more reliable as it contains data gathered by Thai people who are familiar with the context. It will be useful to understand the state of groundwater across Thailand when examining the water sources in Ban Phai.

Tiwari, A. K., & Kalamkar, V. R. (2018). Effects of total head and solar radiation on the performance of solar water pumping system. *Renewable Energy*, *118*, 919–927. doi: 10.1016/j.renene.2017.11.004

This study in Nagpur, India and looked at the required system installation and sizing of helical rotor pump PVWPS's. It found the optimal efficiency when the total head was set to 10 bar, and included the appropriate measurements and equations to determine the results. This information might be of use to our team when measuring the efficiency of the pumps in Ban Phai. Unfortunately, this article contains no comparative assessment to other conventional pumping methods, and this research was done specifically for well water applications, but it gave us insight on what other countries use to advance their PVWPS's.

United Nations. (n.d.). Water. *United Nations*. Retrieved from <https://www.un.org/en/sections/issues-depth/water/>

Water is crucial for human life and development, and water demand increases with population growth. Therefore, the water shortage becomes a serious problem in many countries, especially those where water is not widely available. This article goes into the consequences of not having easily accessible water. It was good background knowledge to have as it provided us with an understanding of the main social problem our project faces.

United Nations Children's Fund & World Health Organization. (2019). Progress on household drinking water, sanitation and hygiene: 2000-2017. *World Health Organization*. Retrieved from https://www.who.int/water_sanitation_health/publications/jmp-report-2019/en/

This article focuses on the global progress of obtaining drinking water, sanitation and hygiene over a 17 year period. It provides information about the impact that having access to clean water has on the development of countries such as Thailand. It provided us with global values, which will help our team compare numbers to see how Ban Phai measures relative to other nations and regions.

UN General Assembly. (2015). Transforming our world : the 2030 Agenda for Sustainable Development. A/RES/70/1, Retrieved from <https://www.refworld.org/docid/57b6e3e44.html> [accessed 24 January 2020]

This document introduces the United Nations' 17 Sustainable Development Goals, identifying global issues that will be addressed through the efforts of all member nations. Two of these goals, number 6 and 7, are at the core of PDA's current PVWPS efforts, and help us see how this project fits in the context of a larger movement towards a better world.

Viravaidya, M. (2005). *The Role of PDA during the last 31 years in Thailand*. Population and Community Development. Retrieved from http://mechaifoundation.org/download/media_Presentation/PDA_History_1974-2005.pdf

This book is about PDA, and explores Mechai Viravaidya's goals for Thailand and its accomplishments over the 31 year period, 1974 to 2005. This book was a great resource in providing us with a thorough history of PDA from the beginning to the present.

Viravaidya, M. (2016). The Population and Community Development Association in Thailand. *Journal of Politics and Governance*, 6. Retrieved from: <https://bit.ly/2MTVklF>

This paper, written by the founder of PDA, outlines the approach and methods used by our sponsor in rural Thailand. Its explanation of how PDA empowers locals and arms them with an understanding of the technology at their disposition aided us in refining our own approach and understanding the social environment where our project takes place.

Leithead, W.E., (2007). Wind energy. *Philosophical Transactions*, 365, 957-970. Retrieved from <https://www-jstor-org.ezpxy-web-p-u01.wpi.edu/stable/25190482>

This report gave us insight to wind energy over recent years. We learned that despite how unpopular it can be, it's one of the most important forms of renewable energy. The report helped us compare other forms of energy to see what alternatives there were.

Wholesale Solar. (n.d.). Off-grid battery bank sizing. Retrieved from <https://www.wholesalesolar.com/solar-information/battery-bank-sizing>

World Meteorological Organization. (2019). Khon Kaen. Retrieved from <https://worldweather.wmo.int/en/city.html?cityId=571>

This website provides monthly weather and climate conditions in Khon Kaen, and allows us to know how much sunlight and rainfall occurred in different months. It also contains a table with temperature maximums and minimums. All this information can help us measure how efficiently PVWPS's can work in different seasons, and which period is most suitable to generate power.

Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A., & Angelakis, A. N. (2015). Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide. *Water*, 7, 5031–5060. doi: 10.3390/w7095031

This paper provides an overview of the history of water lifting devices. It is useful to learn more about different types of water pumps and where the modern day pumps evolved from. The timeline in the article is useful however, it assumes that the person reading it is already knowledgeable about pump engineering firms and companies.

3hp solar agricultural water pumping system for irrigation. (n.d.). Retrieved from <http://www.felicitysolar.com/3hp-solar-agricultural-water-pumping-system-for-irrigation-p00106p1.html>

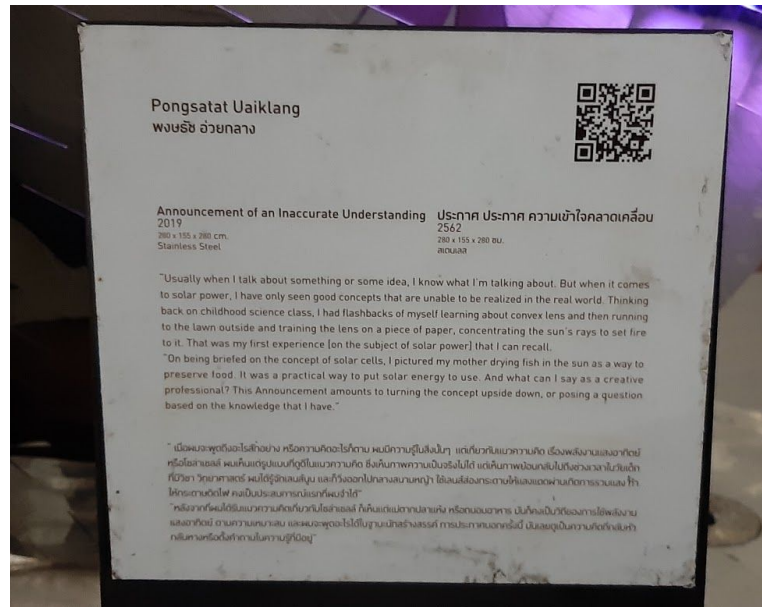
This website provides information on how water pumps work. There is a useful schematic about the differences between DC and AC power wiring for water pumps. There is a lot of information on this website, the only problem is that it is not organized in a coherent manner.

Appendices

Appendix A: Photographs of solar-related presentations in Bangkok



Prototype of a solar panel at Chulalongkorn University (left). Solar panel on the roof of Engineering Building 4 at Chulalongkorn University, which powers the entire building in conjunction with grid electricity (right).



'Announcement of an Inaccurate Understanding' by Pongsat Uaiklang, an art piece questioning the concept of solar energy as free energy, at the Bangkok Culture & Arts Centre.



Solar-powered charging station for electric cars at Chulalongkorn University

Appendix B: Expenses table provided by PDA Headquarters in Bangkok

SOLAR PV WATER SYSTEM PACKAGES - Detailed Cost Data		COSTS ¹			
ITEM	EXPLANATION	THB (thousands)		EUR (RoE 38)	
		Low ²	High ²	Low ²	High ²
HARDWARE		270	980	7105	25789
Water Storage/Tank	Plastic or Alu, cement construction by villagers, connected jars	180	360	4737	9474
Piping and Accessories	PVC pipes (div. lengths and diameters); valves, connectors, gates, meters	30	150	789	3947
Pump	Submersible/stationary pumps with capacity from 10 to 100 m ³ per day	10	60	263	1579
Electrical Appliances	Control box for centrifugal pump with/without inverter; cables	10	30	263	789
Solar Panels w. mounting	i.e. alu frame with 4 to 20 solar panels, 400 to 4000 Wp	40	380	1053	10000
Water Treatment/Filtering	optional				
SOFTWARE		270	500	7105	13158
Survey/Design/Testing	Depends on site	30	50	789	1316
Site preparation, drilling	"	90	200	2388	5263
Training/guidance	For examples of training/counselling topics see footnote 3 below	160	250	3947	6579
MANAGEMENT	See explanation under footnote 4 below	135	370	3553	9737
TOTAL		675	1850	17763	48884
			ca.USD	19184	52579
Footnotes					
<i>1 Budgeted costs can be significantly lower, especially for hardware, if tanks, piping, accessories, are already available, and/or software, i.e. survey, testing, drilling, has already been provided</i>					
<i>2 Low may refer to household use and small irrigation plot of 5-20 rai, high to larger one</i>					
<i>3 Training/counselling topics may include:</i>					
<i>Solar PV water systems project planning, procurement, management</i>					
<i>O&M of solar PV water supply systems</i>					
<i>Energy consumption and energy savings in agriculture, transport, household (fridge, TV, lighting, home industries)</i>					
<i>Rational use of water source, storage, distribution; e.g. drip irrigation</i>					
<i>Community institutions, i.e. village development bank, village water committee, women/youth groups</i>					
<i>Income generation and food security; vegetable banks, aquaculture, mini-farms</i>					
<i>4 This comprises all costs related to operations, administration, accounting, including M&E and auditing</i>					

Appendix C: Interview Consent Form

The following form will be given to each interview participant to be filled out.

Interview Consent Form	
<p>This is an invitation to participate in an interview. We are a group of students from Worcester Polytechnic Institute (WPI) in the United States, and Chulalongkorn University in Bangkok, in collaboration with the Population and Community Development Association (PDA). We are conducting interviews of Baan Phai residents to learn more about the performance of the solar photovoltaic water pumps they use. We strongly believe this kind of research will ultimately improve the performance of the solar photovoltaic water pumps in this region by providing PDA with important statistics about their performance and cost, as well as their environmental and social impact on the community.</p>	
<p>This interview should take around 30 minutes, though the time may vary. We will ask you questions about how you use the pump, how often you use it, what you use the water pumped for, how well the pump functions, who operates and/or maintains the pump, how much money you have spent on the pump, and the effect the pump has had on your property, your family and your community.</p>	
<p>Your participation in this interview is completely voluntary and you may withdraw at any time. You may also skip any questions you do not want to answer. The combined findings of all these interviews will be published, but your answers will remain confidential. No names, addresses or identifying information will appear in any of the project reports or publications. All documentation with identifying information and responses will be held securely by the students or PDA at all times.</p>	
<p>If you have any questions, please feel free to ask them at any point during the interview.</p>	
_____	_____
Participant signature	Date (DD/MM/YYYY)

Participant name	
_____	_____
Student signature	Date (DD/MM/YYYY)

Student name	

Appendix D: Interview Scripts

To assess the PVWPS's, we interviewed a total of 30 individuals across two categories: residents who used the pumps, and water committee members including the head of the village. These categories allowed us to obtain a variety of perspectives of the pumps based on the role each group played in the community. 30 interviews provided us with a reasonable amount of data for this study given the time constraint.

PVWPS users for irrigation

1. What crops does the PVWPS supply water to?
2. What size is the land you irrigate?
3. Does the PVWPS supply enough water for your crops?
 - a. If no, what needs aren't covered by the PVWPS?
4. Do you have any other methods of collecting water?
 - a. Do you also currently have another type of pump?
 - b. Which water collection method works best for you? Why?
5. What type of water collection system was used before the PVWPS?
 - a. Did it supply enough water for your crops?
 - b. How much water did the previous pump produce, compared to the PVWPS?
 - c. If you had a grid system before the PVWPS, did you ever experience a blackout? How often did blackouts occur?
6. Since the implementation of the PVWPS's:
 - a. Are more or less crops being grown compared to your previous water collection method?
 - b. Are different crops being grown than when the previous water collection method was in use?
7. Did you spend any money upfront on installation of the PVWPS?
8. Roughly, how much is the water fee for the PVWPS, and how often do you pay it?
 - a. Do you have any other expenses related to the PVWPS?
 - b. Roughly, how much did the previous pumping system cost?
9. How much noise does the PVWPS make in comparison to the previous pump?
10. Who can perform maintenance on the pump?
11. If you had questions about the PVWPS and the program, were answers provided and to what extent?
12. Do you feel that the PVWPS is beneficial or harmful to the community? Why?

Water Committee Members/Headmen

1. How long have you been a member of the water committee/headman?
2. How many people use the water pumped from the PVWPS for something other than irrigation?
 - a. Other than irrigation, what is the water used for?
3. What pumps were in place before the PVWPS?

- a. Were they privately owned or did they belong to the community?
 - b. Did they produce enough water for the village?
 - c. Were they better or worse than the PVWPS? Why?
 - d. Did you have any responsibilities related to these pumps?
 - e. Did you collect or spend any money on behalf of the community for those pumps?
How much?
 - f. Where are those pumps now?
4. What other types of water pumps are used in the village?
 - a. Are the other pumps more practical than the PVWPS?
 5. Was money collected to pay for the PVWPS's installation? Roughly, how much money?
 6. Roughly, how much money has been spent on the PVWPS since installation, and how often?
What was it spent on?
 - a. How much is the water fee?
 - b. Do you have a list of expenses that we can reference for our financial assessment?
 7. How much earth was disturbed by installing the PVWPS? Was dirt dug out, flattened, or manipulated?
 8. Is the space taken up by the PVWPS larger or smaller than the previous pump?
 9. Do you have any photographs of the land before/during installation?
 10. Since the implementation of the PVWPS:
 - a. Do the members of the village seem more or less satisfied with the PVWPS water collection system?
 11. How much noise does the PVWPS make in comparison to the previous pump?
 12. Is the water produced by the PVWPS available to everyone?
 13. Is there a plan of how the PVWPS's will be disposed of when the time comes?
 14. If you had questions about the systems and the program, were answers provided and to what extent?
 15. How have the daily proceedings of the village changed since the installment of the PVWPS?
 - a. Have individuals' roles in the community changed?
 16. Do you feel that the PVWPS was a positive or negative addition to the community? Why?

PVWPS users for non-irrigation purposes

1. Do you have any other methods of water collection?
2. How much is the water fee? Do you spend money on anything else related to the PVWPS?
3. Before the installation of the PVWPS, how did you collect your water?
 - a. How much money did you spend on the previous water collection system?
4. Did the previous water collection method provide you with more or less water than the PVWPS?
5. If you had questions about the PVWPS and the program, were answers provided and to what extent and by whom?
6. Do you feel that the PVWPS is beneficial or harmful to the community? Why?

Grid-powered water pumping system users for irrigation purposes

1. What crops does the grid powered pump supply water to?
2. What size is the land you irrigate?
3. Does the grid-powered pump supply enough water for your crops?
 - a. Do you have any other methods of collecting water?
 - b. What needs aren't covered by the pump?
4. How much is the water fee?
5. Who performs maintenance on the pump?
6. Has the village ever experienced a blackout?
 - a. If so, how often?

Grid-powered water pumping system users for non-irrigation purposes

1. How much is the water fee?
2. Does the grid-powered pump supply enough water?
 - a. Do you have any other methods of collecting water?
3. Who performs maintenance on the pump?
4. Has the village ever experienced a blackout?
 - a. If so, how many?

Grid-powered water pumping system authorities

1. Is there a water tank or do residents depend on the pump running constantly?
2. What other types of water collection methods are used in the village?
 - a. Are the other water collection methods more practical than the pump?
3. Was money collected to pay for the pump's installation? Roughly, how much money?
4. Roughly, how much money has been spent on the pump since installation, and how often?
What was it spent on?
5. Has the pump ever needed fixing? Has it been easy to get it fixed?
6. If you had questions about the PVWPS and the program, were answers provided and to what extent?
7. Why do you feel that the PVWPS could be beneficial to the community?

Appendix E: Observation Sheets

Team members filled out these sheets during visits to each village, in order to ensure that we gathered all information. Village-wide observations were filled in throughout the visit, either by listening to speeches by authorities or by asking in conversation while on-site. Interview-specific observations were filled in by a WPI team member, while their Chulalongkorn partner recorded interview responses in Thai.

Village-Wide Observations	
Date: _____	
Team Member: _____	
Observation	Answer
What type of pumps are being used (submersible pumps or surface pumps)? (picture)	
What are the pump models?	
What type of panels are being used (fixed arrays or tracking arrays)? (picture)	
Is there a storage tank?	
Is there a battery?	
Where in the villages are these pumps located? (picture)	
What sources of water are they using? (picture)	
Type of panels being used (fixed arrays or tracking arrays) (picture)	
Shade over arrays due to obstruction	

Protective structures around the pump	
Gender ratio	

Interview-Specific Observations

Date: _____

Category: Irrigation user Non-irrigation user Authority

Interviewee's Name:

Interviewers' Names: _____

Observation	Answer
How did we choose this interviewee?	
Gender of the interviewee	
Age range of the interviewee	
Mood of the interviewee at the start of the interview	
Is the interviewee uncomfortable with us taking notes?	
Is the interviewee uncomfortable with us recording the interview?	
Is there anyone else around during the interview?	
Does the interviewee feel comfortable talking to us?	

Does the interviewee change their answers for any particular questions?	
Any reaction to a particular question?	
Mood of the interviewee at the end of the interview	
Additional Notes	

Appendix F: Observations from Ban Lan

Observation	Ban Lan
Population	679 people (182 families)
Type of Pumps	Submersible
Pump Model	AC 1.5 Hp Franklin pump
Installation date	July 2016
Type of Panels	Eight fixed arrays, all facing South.
Storage Tank	One large tank beside the PVWPS, and another PDA-built tank near the filtration area a short drive away.
Battery	No
Location	In the middle of a field used for farming
Water source	Groundwater, 50 m deep.
Shade due to obstruction	None, the arrays were angled away from the tank structure towards a field.
Protective structures	Barbed wire, lock boxes around converters.
Village committee gender ratio	1:3, women to men
Funding	PDA installed and paid for the PVWPS's and one tank paid by a sponsor. The new tank and pipes were provided as a grant by the government.
PVWPS Use	Household
PVWPS Water fee	4 THB/cubic meter
PVWPS Installation cost	Funded by PDA (250,000 THB)
PVWPS Maintenance Fee	5 THB
Previous System Water Fee	3 THB/cubic meter

Appendix G: Observations from Nong Wang

Observation	Nong Wang
Population	5028 people (1484 families)
Type of Pumps	Surface
Pump Model	AC 2 Hp Mitsubishi SuperPump WCL-1505T
Installation date	August 2019
Type of Panels	Eight fixed arrays, facing South.
Storage Tank	One large PDA-installed one and four smaller blue ones.
Battery	No
Location	The PVWPS is right next to the crops.
Water source	The canal next to the farm. In the summertime when the canal dries up, they used to use a grid pump to bring water from the Chi river to the canal. Now, they connect the PVWPS to the tubing of the grid pump and pump directly from the river.
Shade due to obstruction	None, the arrays were angled away from the small tree nearby.
Protective structures	A locked fence around the arrays and pump.
Village committee gender ratio	More women than men (committee was created 2 days ago).
Funding	PDA installed the entire system paid by a sponsor.
PVWPS Use	Irrigation
PVWPS Water fee	3 THB/cubic meter
PVWPS Installation cost	Funded by PDA (200,000-300,000 THB)
Previous System Water Fee	9 THB/cubic meter*

Appendix H: Observations from Ban Wang Saeng

Observation	Ban Wang Saeng
Population	611 people (174 families)
Type of Pumps	Surface
Pump Models	AC 2 Hp Mitsubishi SuperPump WCM-1505FS (Temple) Calpeda NM 40/20B/A
Installation date	June 2016
Type of Panels	Eight fixed arrays, facing South.
Storage Tank	One large tank in the temple.
Battery	No
Location	In the temple, in the village. It receives water from the grid-powered pump and pumps it into the tank, which filters and distributes it for household use.
Water source	The pond supplies water for 3 villages.
Shade due to obstruction	None, the solar array is well positioned.
Protective structures	The tank and arrays are secure inside the temple.
Village committee gender ratio	We did not see how many women there were, as they did not come forward.
Funding	PDA installed the entire system paid by a sponsor.
PVWPS Use	Household
PVWPS Water fee	7 THB/cubic meter
PVWPS Installation cost	Funded by PDA (200,000-300,000 THB)
Previous System Installation cost	300 THB per household
Previous System Water Fee	7 THB/cubic meter

Appendix I: Average PVWPS use calculations

What follows are calculations of the average amount of time needed to supply each village with all the water it needs per day, based on theoretical data from literature.

Results skew lower than the amount of time that villages currently pump water, which indicates that these villages use more water than the average Thai household. As mentioned in a previous section on water distribution, this may be due to residents using water for small-scale irrigation in their gardens for personal use. There is no evidence that these villages have a higher number of people per household than other regions of Thailand. Further investigation as to the causes behind this discrepancy is required.

Ban Lan

The average Thai person uses 0.22 cubic meters of water per day (Fernquest, 2015). Since there were 679 people in Ban Lan, this meant that the village required 148 cubic meters of water per day. This much water would weigh about 148,000 kilograms. We observed the head distance to be 8 meters. The energy required to lift a mass m of 148,000 kg up a height h of eight meters would be $mgh=148,000(9.81)(8)= 11615040\text{J}$, where g is the acceleration due to gravity.

We wanted to convert Joules to kilowatt-hours: $11615040\text{J}=11615 \text{ KJ}=11615\text{Ws}$
 $=11615/3600\text{kWh}=3.2 \text{ kWh}$. The village used a 1.5 hp pump. 1.5 hp is about 1.1 kW. So dividing 3.2kWh by 1.1kW gives the number of required hours to produce this much power: $3.2\text{kWh}/1.1\text{kW}=2.9$ hours. So the PVWPS would need to run 2.9 hours in order to supply the village with all of the water it needed for one day, which is a realistic requirement since the sun is in the sky for more than 2.9 hours every day in Thailand.

Nong Wang

In Nong Wang, 42 farmers used the PVWPS to irrigate their crops. According to the farmers, the water fee was 3 THB per cubic meter and they spent 117 THB per month, which meant that they each used 39 cubic meters of water per month on average.

Multiplying this number by 42 and dividing by 30 would give the required amount of water needed per day to supply enough water for their crops, and this value is 54.6 cubic meters. This much water would weigh about 54600 kilograms. We observed the head distance to be 8 meters. The energy required to lift a mass m of 54600 kg up a height h of 8 meters would be $mgh=54600(9.81)(8)= 4285008 \text{ J}$, where g is the acceleration due to gravity.

We wanted to convert from Joules to kilowatt-hours: $4285008\text{J}=4285 \text{ KJ}=4285\text{Ws}$
 $=4285/3600\text{kWh}=1.19 \text{ kWh}$. The village used a 2 hp pump. 2 hp is about 1.5 kW. So dividing 1.19kWh by 1.5kW gives the number of required hours to produce this much power: $1.19\text{kWh}/1.5\text{kW}=0.79$ hours. So the PVWPS would need to run 0.79 hours in order to supply the village with all of the water it needed for one day, which is a realistic requirement since the sun is in the sky for more than 0.79 hours every day in Thailand.

Ban Wang Saeng

The average Thai person uses 0.22 cubic meters of water per day (Fernquest, 2015). Since there were 611 people in Ban Wang Saeng, this would mean that the village required 134.1 cubic meters of water per day. This much water would weigh about 134,100 kilograms. We observed the head distance to be 8 meters. The energy required to lift a mass m of 134,100 kg up a height h of eight meters would be $mgh=134,100(9.81)(8)= 10524168\text{J}$, where g is the acceleration due to gravity.

We wanted to convert from Joules to kilowatt-hours: $10524168\text{J}=10524.2 \text{ KJ}=10524.2\text{Ws}$
 $=10524.2/3600\text{kWh}=2.9 \text{ kWh}$. The village used a 2 hp pump. 2 hp is about 1.5 kW. Dividing 2.9 kWh by 1.5 kW gives the number of required hours to produce this much power: $2.9\text{kWh}/1.5\text{kW}=1.9$ hours. So the PVWPS would need to run 1.9 hours to supply the village with all of the water it needed for one day, which is a realistic requirement since the sun is in the sky for more than 1.9 hours every day in Thailand.