TECHNO-ECONOMIC FEASIBILITY STUDY OF SOLAR WATER PUMPING FOR PUBLIC FACILITIES IN NIGERIA

By

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ABSTRACT

TECHNO-ECONOMIC FEASIBILITY STUDY OF SOLAR WATER PUMPING FOR PUBLIC FACILITIES IN NIGERIA

Anamika Singh

This thesis presents a techno-economic feasibility analysis of solar water pumping systems in public facilities located in rural parts of Nigeria. Three different public facilities namely, a primary health care center in Ibwa (PHC, Ibwa), a comprehensive health care center in Kwali (CHC, Kwali), and the LEA Primary School in Mapa (LEA School, Mapa), all located in Federal Capital Territory (FCT) of Nigeria, were analyzed. The facilities considered in the study have varying levels of water demand (micro, small, and medium), and they are used as cases to establish the techno-economic suitability of solar water pumping systems to deliver water at such sites. This study provides a review of challenges associated with the provision of clean water in public facilities in Nigeria and a step-by-step guide to design a solar water pumping system that can be used to provide this water. It also provides a method to optimize the cost of installing these systems with the help of a model and compares the cost of systems in cases where the sizing is determined by a standard design procedure with the cost of systems when sizing is based on an optimization model.

The optimization results identify that the upfront cost of the systems can be reduced by 1.5%, 9%, and 23% for PHC, Ibwa, CHC Kwali and LEA School Mapa,

respectively. Results of the economic analysis indicate that the cost of water from the solar water pumping system is half of the cost of purchasing water (if these facilities were to procure water from the local water distributors to fulfill their water demand) for CHC Kwali, and four times less for the LEA School, Mapa. However, due to its smaller size, the cost of water from the solar pumping system for PHC Ibwa is about twice the cost of purchased water. A sensitivity analysis on storage capacity, PV array size, and cost of the system highlights the importance of optimizing the relationship between PV array size and storage tank size for a given level of water demand. A system designed and analyzed through a modeling tool can therefore enhance the cost-effectiveness of solar pumping systems at public facilities in rural areas.

DEDICATION

I dedicate this work to my beloved Mom and Dad, who always taught me the importance of imbibing the following four values. These values greatly shaped my life, made me the person I am today, and why I understood it is worth contributing to the good efforts in the world to make it a better place to live.

1. Be always useful for the community and society, and have gratitude towards it.
2. Help yourself first to be able to help others.
3. Comfort is stagnant; challenges keep you moving. Invite them!
4. There is no substitute for hard work because sooner or later it always pays off.

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CHAPTER 1: INTRODUCTION

More than 50% of the population in Nigeria lives in rural areas (World Bank, 2018a). People living in rural Nigeria frequently experience insecurity and vulnerability due to insufficient infrastructure to support delivery of services such as electricity, water, sanitation, and health care (International Energy Agency, 2017; Energy and Water Department, World Bank, 2005). Many communities in rural areas do not have access to electricity to pump water. It is estimated that only 26.5 percent of the population use improved potable water sources and sanitation facilities (UNICEF, 2018).

Inadequate access to clean drinking water and sanitation facilities in public institutions of rural areas causes adverse health impacts. Poor water quality contributes to increased morbidity and mortality rates, especially in children under five (UNICEF, 2018). Inadequate water supply, sanitation, and hygiene in schools impacts the learning environment and capabilities of school children (WHO, 2009). The problems related to the availability of clean water in public institutions that serve most community members must be solved through better provision of safe water.

Presently, in public institutions in rural Nigeria, water is commonly pumped using diesel or electricity-based water pumps to access groundwater in a well. Another common approach to accessing water is through paid delivery (tanker truck) services (Onyenechere et al., 2012). The cost of water delivery in Nigeria varies from $0.002/gallon to $0.006/gallon (Onyenechere et al., 2012; Schatz Center, 2018). Various

factors influence the cost of water in Nigeria, such as location, water demand, seasonal variations, type of water delivered (e.g., well water used for cooking and washing purposes versus pipe borne water used exclusively for drinking) (Onyenechere et al., 2012). For sites where it is possible, electricity-driven pumps could be good alternatives to diesel or delivered water to ensure affordable clean water availability. However, lack of access and/or intermittent access to grid electricity and poor durability due to regular maintenance limit their utility in rural areas (UNICEF, 2016b). For public facilities located in rural areas, a reliable, consistent, and low-cost water supply source can only provide a realistic solution. Solar water pumping systems can represent an option for providing a reliable source of water. North, northcentral, northwest, and northeast Nigeria have abundant solar resources, and solar water pumping can be a reliable and cost-effective technology, especially for small scale operations in rural areas (Fidelis Abam, 2014). These systems have many advantages over the conventional (diesel and grid electric) pumping systems for rural usage where grid accessibility and/or reliability are a question. Some advantages include low pumping cost, easy installation, and unattended operation (Muhammadu, 2015).

The objective of this research study is to assess the techno-economic feasibility of solar water pumping for public facilities such as schools and health clinics in rural areas of Nigeria. This study considers three specific sites for analysis. They are (i) “Ibwa PHC,” a primary health care center located in Ibwa village, Gwagwalada Area Council, (ii) “Kwali CHC,” a comprehensive health care unit in Kwali Area Council, and (iii)

"LEA Primary School Mapa," a primary school in Bwari Area Council. All sites belong to the Federal Capital Territory (FCT) of Nigeria. The three sites were chosen out of the eleven sites in Nigeria for which data are available from a project led by the Schatz Energy Research Center at Humboldt State University. The study involved collaboration between the Schatz Center and the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), the Federal Ministry of Power, Works, and Housing of Nigeria, and the World Bank's Lighting Africa program (ECREEE, 2017).

Data, which include information about hydrology, site facilities, existing infrastructure, site layout, site usage, number of users, and other key details for the analysis, were obtained from detailed audit survey questionnaires (Appendix A), and well pumping tests (Appendix B) collected during fieldwork carried out in November 2017 through the project in Nigeria managed by the Schatz Center. The sites are considered to capture different demand scenarios and to analyze how demand can affect the design and performance of the system. The overall water demand of the sites is estimated using two methods. The first method relied on data from the Schatz Center study, while the second method utilized per capita consumption estimates provided in other sources such as World Health Organization (WHO) reports (WHO, WEDC, 2011; WHO, 2005). Using water demand data and other information, the analysis presented in this document determined solar water pumping system design parameters related to sizing and selecting a suitable submersible pump, photovoltaic array, storage system, and other associated equipment.

Variations in the limiting variables such as aquifer characteristics, water demand, and solar resource availability at different sites have a significant impact on the size, design, and performance of systems, and, thereby, the system's costs. Therefore, this thesis also presents results from the hourly modeling of the pump's performance for the various demand scenarios. Economic analysis of all three facilities, including the life-cycle cost (LCC) of the systems, identified the cost of pumping in terms of dollars per gallon of water pumped. The results of this study indicate that this kind of modeling can be utilized to budget and plan systems for other similar applications. This model analyzes solar resource, water demand, and aquifer characteristics of a system to optimize the cost, as the cost of solar water pumping systems strongly depends on these parameters. Using the insights gained from technical and economic calculations and associated sensitivity analyses, this study makes recommendations related to system design for future installations.

The above-mentioned research and associated findings of this thesis are organized in six chapters. The introduction chapter, Chapter 1, provides an overview of the problem of unavailability of clean water and the potential for solar water pumping in Nigeria. It also explains the scope of the thesis. Chapter 2 includes background information and a literature review, which showcases the status of solar water pumping systems in Nigeria, solar pumping technology and its components, and the availability of water and the solar resource in Nigeria. Chapter 3 describes the methodology used for designing the solar pumping systems at the three sites and for analyzing the performance of the designed

solar pumping systems on an hourly basis. This chapter also includes methods used for the economic analysis of each site. The results of the system design and economic analysis are provided in Chapter 4, which is followed by a discussion of the results in Chapter 5. Finally, Chapter 6 presents the conclusions of the study and recommendations for future work.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

Clean water reflects the health of a country's people (Crowfoot, 2018). A healthy population contributes meaningfully to the economic growth of the country. Fewer water-borne diseases reduces the cost of health care and strengthens the financial situation of countrymen (David E Bloom, 2008). A new photo series released to mark Universal Health Coverage Day 2016 reveals the emergency of erratic or non-existent water supply systems along with poor sanitation and hygiene facilities, which puts the health of patients, staff and surrounding communities at risk (Water Aid, 2016). A photo from the series is shown in Figure 1.

Figure 1: (a) Containers of water lined up for sale (b) A cleaner at Bwari town Primary Health Centre (c) A volunteer nurse washing her hands.
Source (EnviroNews, 2016; Water Aid, 2016)

Figure 1(a) shows containers of water lined up for sale in the Garki Village Primary Health Centre in Abuja, Nigeria. These containers are required because of lack of clean water supply to the center. Figure 1(b) shows a cleaner at Bwari town Primary Health Centre, Abuja, Nigeria, showing the rain water collected that is used to clean the toilets because there is no water supply to the center. They also buy clean water for washing more sensitive cleaning tasks and for patients who need clean water to wash.

Figure 1(c) shows a volunteer nurse washing her hands thoroughly with purchased water before attending to patients at the Zuma Primary Health Centre, Abuja, Nigeria.

Availability of water also plays a critical role in poverty alleviation, as fetching clean water from the far away sources accounts for a considerable amount of time for women and children engaged in this work (UNICEF, 2016). Quality of water is often compromised due to the effort and time required to fetch water from distant places. Sphere’s Minimum Standards in Water Supply, Sanitation and Hygiene notes that people in rural areas often generally prefer to use water from a location that is close to their home (e.g. within 500 meters) even if that water source is unprotected (Sphere, 2004).

Studies also indicate that households can utilize the time consumed in fetching of water wisely and effectively to accomplish other tasks if clean water is available at public facilities (UNICEF, 2016). This chapter discusses the problem of unavailability of clean water in rural Nigeria, the status of solar water pumping systems in Nigeria, solar pumping technology and its components, and the availability of water and the solar resource in Nigeria.

2.1 Problem of Unavailability of Clean Water in Rural Nigeria

Industrial wastes such as industrial effluent discharge, leaking tanks, and debris deteriorate groundwater quality in nearby areas. Pollutants generated from unwise human activities, such as litter, open defecation, and domestic wastes also contribute to the degradation of water quality (E.O. Longe, 2010; McGranahan, 2010). The inability to access clean and safe water leads to deleterious health circumstances, especially in children and elderlies. Waterborne diseases such as diarrhea and typhoid caused due to

contaminated water, are seen as a significant contributor to the high mortality rate. A report from the Water, Sanitation, and Hygiene (WASH) program of Nigeria revealed that the deaths of more than 70,000 children annually are due to diarrhea and other waterborne diseases. The report also indicates that more than 73% of the deaths caused by diarrhea are due to poor water, sanitation, and hygiene services (UNICEF, 2018). Mr. Bassey Uwe, a retired Director of Service for UNICEF's Water Sanitation and Hygiene program, said in an interview held on May 30, 2017 that, "…the level of water supply in rural communities in the country is poor and the situation is pathetic. Waterborne diseases, sometimes in an acute form, are therefore endemic in many of the rural areas" (Vanguard, 2017).

Patients in health care centers are especially sensitive to the quality of water, so health centers must be careful to ensure the quality of their water. Omole and colleagues identified water-borne diseases such as cholera and typhoid as the second most reported class of diseases leading to death, with the leading cause being insect-borne diseases such as malaria (Omole et al., 2015).

Ishaku and team revealed that most of the rural Nigerian population do not have the infrastructure, such as pipeline connections, separate water lines, and community-owned water networks to obtain safe water (Ishaku et al., 2011). Community members sometime prefer water resources such as open surface water and poor-quality water stored in open community tanks. Cases of existing infrastructure being unreliable or low quality are also reported. Low quality of infrastructure is mainly due to poor maintenance and lack of funds for operation and maintenance (Ishaku et al., 2011; Omole et al., 2015).

Lack of infrastructure and distance from good quality water sources can make communities rely on the nearest water source that can be accessed easily even if the water quality is poor. For example, the handpump at Ibwa PHC, a site considered for the analysis in this study, was not functional at the time of the Schatz Center survey. The PHC staff members conveyed that water demand at the site is met either through distributed water services or through a community water pump that is located 2.5 miles away from the site, depending on which one is available. According to data reported in survey forms collected by the Schatz Center, the quality of water obtained from these sources is always compromised.

The Nigerian government has policies (such as the National Water Supply and Sanitation Policy) to ensure the supply of clean water services at the federal, state, and local levels. These policies have resulted in the improvement of water supply in urban areas. However, water supply services are insufficient to meet water demand in rural Nigeria. Table 1, below, shows the situation of urban and rural drinking water sources in Nigeria in the year 2015

Table 1: Use of drinking water sources in Nigeria (percentage of population)

	Improved	**Unimproved**	**Surface water**	**Source**
Urban population	81	16	3	(UNICEF, 2015)
Rural population	57	27	16	(UNICEF, 2015)

More than 80% of the urban population uses improve drinking water sources, whereas only 57% of the rural population have access to it. Only 16% of the urban population uses unimproved sources of drinking water, whereas 27% of the rural

population uses unimproved sources. Approximately 3% of the urban population use surface water for drinking, whereas as high as 16% of the rural population still use surface water.

Out of the 57% of the population that uses improved resources of water in rural Nigeria, only 1% have a piping infrastructure for water delivery. The remaining 56% of the population relies on community or private boreholes and water distribution services (UNICEF, 2015). With this situation, it becomes necessary to provide improved water services to the rural communities and public institutions in Nigeria. Water supply systems designed for rural communities and public institutions need to be cost effective and low maintenance so that they can be operated and maintained by the communities or public institutions easily. The systems are also required to be self-sufficient and sustainable for a longer lifetime. Solar water pumping systems can be a reliable, cost-effective, and self-sufficient option to fulfill these water needs. They have significant long-term advantages over diesel-based water pumping systems (Guda et al., 2015).

The LCC of a solar water pumping system is much less than a diesel-based system (Guda et al., 2015; Rowley, 2010). A report published by GIZ in 2013 reported a payback period of four years for solar water pumping systems installed in the state of Bihar in India. The levelized cost of energy (LCOE) for these systems was estimated to be Rs.8.60 (US$ 0.141) compared to Rs.13.90 (US$0.228) for diesel-based pumping systems (Pullenkav, 2017). The World Bank conducted a study in Tanzania that shows that the life cycle cost (LCC) of a solar water pumping system can be 36% less than for diesel-powered water pumping system (World Bank, 2018b). Additionally, the results of

studies conducted at several locations in Nigeria indicate that the solar resource is sufficient throughout the year to facilitate these systems. Section 2.2 presents the findings of some studies about solar water pumping technology that are relevant to this study.

2.2 Status of Solar Water Pumping in Nigeria

The viability of solar water pumping systems has been evaluated since the 1970s. In 1978 the NASA Lewis research center installed a 3.5 kW solar water pumping system on the Papago Indian Reservation located in southern Arizona. This system was first used to provide water pumping facilities and electricity to the community until 1983. Later it was solely dedicated to extracting water from the community well. This system was the first rural water pumping system powered by solar energy (DOE, 2002).

Moreover, the technical feasibility of solar-powered pumping technology was demonstrated in 1973, but the technology was immature and expensive at that time (Barlow et al., 1993). A total of more than 10,000 solar water pumps were installed by 1991with the support of the World Bank and the United Nations Development Programme (UNDP), in developing countries out of which 30-40% were installed in countries like Kenya, Bangladesh, and the Philippines. These pumps were used for rural and small-scale applications (Barlow et al., 1993). Reduction in the cost of PV modules and other components of the systems allowed reduction in the cost of the technology and increased its market penetration (World Bank, 2018b). Initially, the cost to consumers for installing a solar water pump was reduced with the help of subsidies. However, this technology has recently become cost-effective. Subsidy support for solar water pumping

still exists in many countries, but the technology is becoming more sustainable financially day by day (Climate Technology Center and Network, 2018).

Foster and colleagues established the feasibility of solar water pumping and the appropriateness of solar water pumping application for a rural area in 1998 (Foster et al., 1998). Solar water pumping is also found to be economically viable in comparison to electricity or diesel-based systems for irrigation and water supplies in rural, urban, and remote regions (Chandel et al., 2015). The results indicated that PV water pumping systems have become competitive with diesel-based technologies for small scale applications for the last ten years. Array sizes as low as 50 W can provide affordable water pumping solutions to poor communities living in rural areas (Kunen et al, 2015).

A good amount of literature is available on the performance evaluation, design techniques, cost-effectiveness, environmental impact, and the efficiency improvement of these systems. This section highlights the results of some studies related to the application of solar water pumping in rural areas.

Research conducted by Mohammadu indicates that this technology has improved dramatically in terms of its efficiency and cost-effectiveness in the last three decades. Solar water pumping gained popularity in off-grid, low-income, rural communities in tropical countries such as Nigeria, where the solar resource is available in abundance (Muhammadu, 2014). In addition, these systems were used for small-scale water pumping applications, such as in public health centers and schools (UNICEF, 2016b). Particularly in northern Nigeria, solar water pumping is becoming the preferred technology for pumping groundwater among the people and government (World Bank,

2005). More than 763 PV water pumps have been installed in Nigeria since 2011, benefitting 1,907,500 people (UNICEF, 2016).

A study conducted by Sodiki presented an overview of water availability and feasibility of solar water pumping systems in Nigeria. It briefly described a method for system design and economic analysis required to identify the techno-economic viability of these systems for a particular site (Sodiki, 2014).

Ayodele and fellows presented a techno-economic and environmental analysis of solar water pumping systems in three selected slaughterhouses in Ibadan, Nigeria. They discussed the critical design parameters and environmental benefits of these systems. The results revealed yearly saving in energy and water cost and reduction in carbon dioxide emissions by the installation of solar water pumping systems (Ayodele et al., 2018)

Moreover, case studies from various countries in Africa, such as Uganda, Nigeria, and Kenya, show the successful implementation and adoption of solar water pumping systems. These case studies reflect that solar water pumping systems are an alternative to replace conventional fossil fuel-based systems. The higher investment costs of solar water pumping systems, which are considered as a barrier in their implementation, can be outweighed by the benefits they can provide after installation (Kraehenbuehl et al., 2015).

Bolaji and Adu also demonstrated a design methodology for photovoltaic pumping systems suitable for rural applications in Nigeria. This paper also presented a method of predicting the flow rate of a pump at any given environmental condition. The author suggests that a fourth-degree polynomial model developed by applying linear regression can be used to identify a relationship between PV power, flowrate, and

pressure (head). These models can then be used to predict the pump flow rate at a given power and head. Head is defined in Section 3.1.7 in Chapter 3 of this study. A model is developed in this study by applying the multiple linear regression technique. This model is used to identify the hourly performance (for a model year) of pumps considered for the designs at the three sites.

Odeh and colleagues studied the influence of pumping head, insolation, and PV array size on PV water pumping system performance. They analyzed the effect of insolation frequency distribution, mismatch of pump characteristics, and well characteristics on overall system performance. The study determined the optimum PV size considering the LCC of the system with the help of a model. The authors emphasized the need for analyzing the critical system components such as PV array size, storage size, and insolation that impact the cost-effectiveness of the system (Odeh et al., 2006)

Hadj and the team analyzed the performance of different solar water pumping systems at four locations in Algeria by using the metrological data for a typical year. The analysis considered various scenarios for two pumps and concluded that the cost of the systems can be reduced with a computer-based simulation program that accounts for solar insolation, pumping head, type of pump, and demand profile at a particular site. This type of analysis is conducted in the current study to identify the optimum (cost-effective) combination of storage, size, and array size for the systems designed at the three sites (Hadj Arab et al., 1991)

Chandel and colleagues, in a review of solar photovoltaic water pumping technology for irrigation and community drinking water supplies, claimed solar water

pumping to be an attractive alternative for developing countries in Africa, citing that most of the population lives in rural areas, and the countries have abundant solar insolation available throughout the year (Chandel et al., 2015)

Solar water pumping technology with a provision of a water storage tank does not require battery storage, and this further reduces the cost of the system. Moreover, applying analytical methods described in this chapter can lower the overall system cost further. Low-cost pumping systems can play a crucial role in supplying water to the public institutions of rural Nigeria. However, it requires a complete understanding of the system components and factors that impact the efficiency of components. Sections 2.3 and 2.4 describe solar water pumping technology and its components.

2.3 Solar Water Pumping Technology

A solar water pumping system consists of several components, including a photovoltaic (PV) array, an electric motor, a pump, a storage tank, and pump electronics. A PV array converts solar energy directly into electricity as direct current (DC). PV modules are connected to the electric motor through a DC connection that converts electrical energy into mechanical energy and drives a DC pump. However, DC electricity routes through an inverter before it goes to the pump if the pump is powered through an AC drive. The pump then lifts water from the well using mechanical energy and stores water in the storage tank for its further usage. Pump electronics, which include the pump controller, sensors, interconnection cables, are used to connect the system and ensure the maximum efficiency and protection of the system from failure. A typical solar water pumping system is shown in Figure 2. These components are defined in this section in

detail. Additionally, solar water pumping offers a welcome alternative compared to diesel pumps, and wind pumps to obtain clean water from the ground/surface, especially in sunny locations (World Bank, 2018b; EMCON, 2006; Dankoff, 2016).

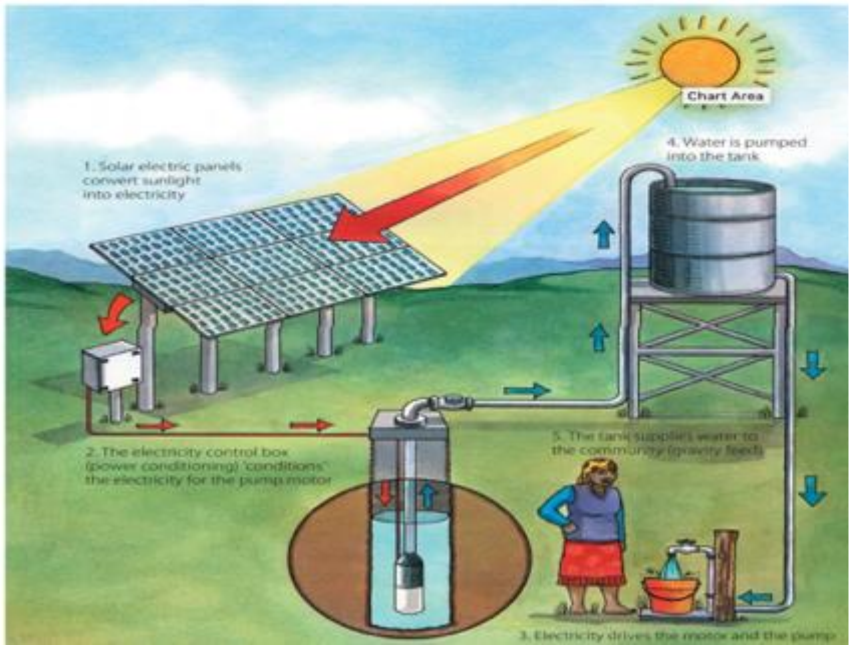


Figure 2: A typical solar water pumping setup.
Source: (Decker, 2015)

The system presented in Figure 2 uses solar-generated electricity to power an electric pump which can then lift water to a storage tank. It is easy to install and can produce effective results. Solar water pumping technology has excellent reliability and a high potential to serve rural communities, especially where grid accessibility is a question. Over the last several years this technology has evolved dramatically (Muhammadu, 2014). The overall cost of the installation, lifetime, and performance parameters, such as the efficiency of solar panels have improved drastically in the last three decades (World Bank, 2018). Figure 3 shows the reduction in the cost of PV

modules in dollars per watt ($/watt) since 1977. The values have not been adjusted for inflation.

Solar water pumps have also become more economical. These pumps can now lift water from a deeper well and deliver higher volumes of water. Figure 4 shows the performance of Grundfos water pumps (one of the credible DC water pump manufacturers) since 1995.

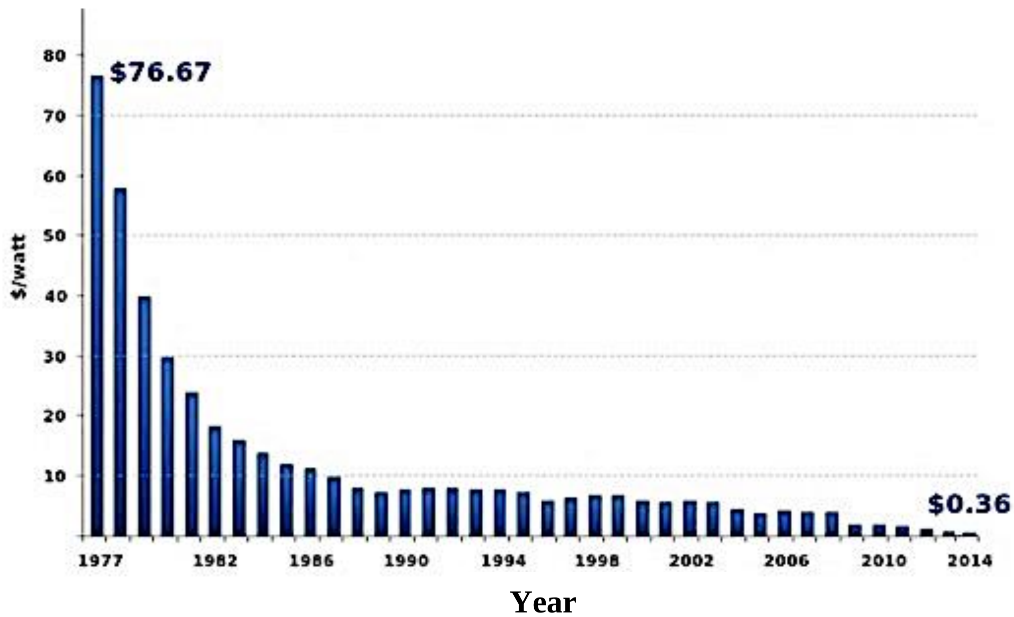


Figure 3: Reduction in overall cost of PV cells ($/watt) with time.
Source (Decker, 2015)

In 1995, the Grundfos pumps included in Figure 4 provided a maximum head of 200 m and 20 $m^{3/}$hr of flowrate. The maximum head and flowrate increased to 550 m and 150 m^3/hr, respectively, by 2017.Markets for solar water pumps are developing in the high solar insolation regions, which include most of Africa, South America, South Asia, and Southeast Asia, and demand for them is highest in institutions located in rural off-grid areas (World Bank, 2018b). The efficiency improvements in PV panels and pumps

have played an important role in reducing the overall cost of the system. The purpose of the individual components is described in the following sections.

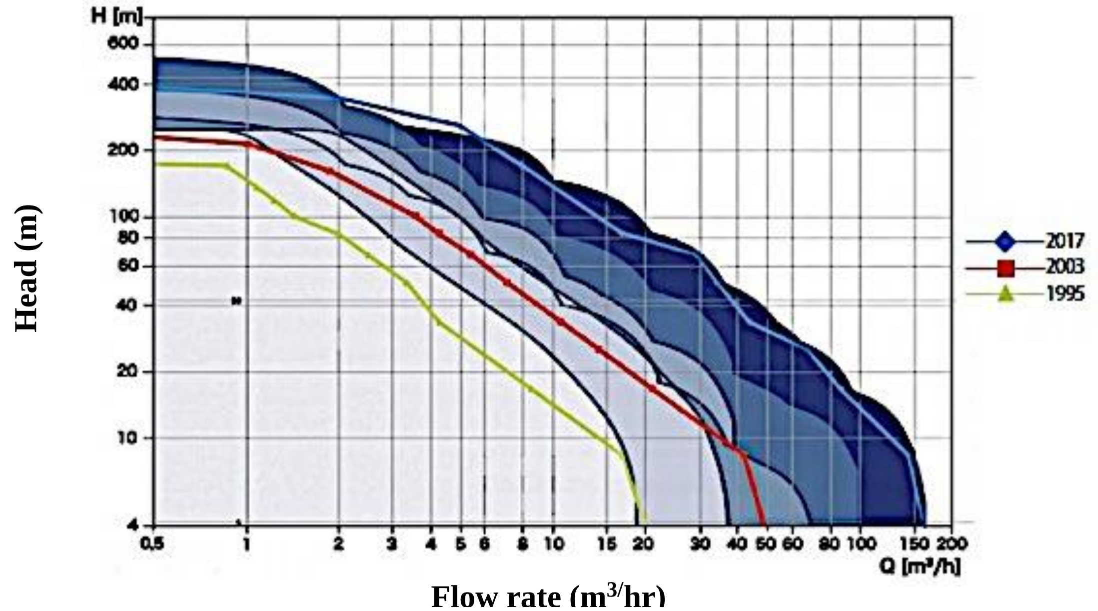


Figure 4: Improvement in Grundfos Solar water pumps since 1995.
Source: (Grundfos Technologies, 2018)

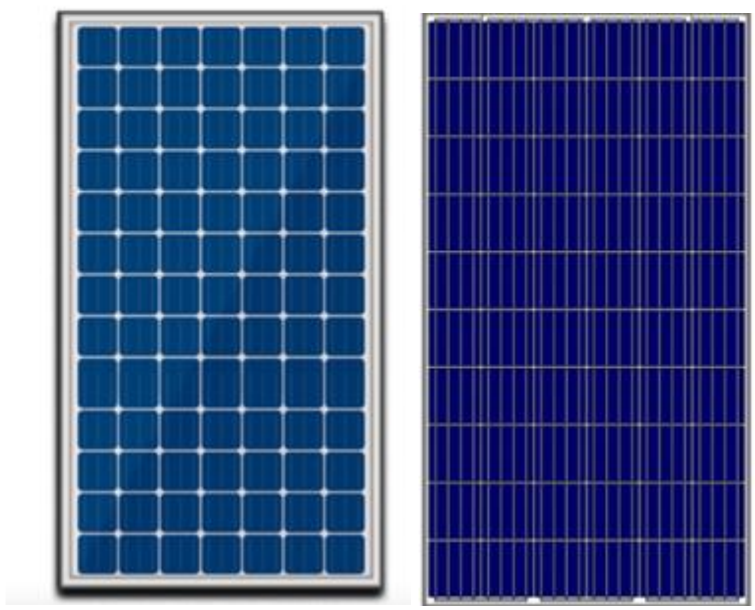
2.4 Components of Solar Water Pumping Technology

This section provides an overview of the components of a solar water pumping system, described in Section 2.3. This section includes a brief description of major system components required to install a DC solar water pump. DC solar water pumps do not need an inverter for the operation. Therefore, the description of an inverter is not included here.

2.4.1: PV modules

PV modules are the power generator for a solar water pumping system. A PV module is made by combining many PV cells together. These cells convert solar radiation

falling on their surface to electrical energy by a process called the photovoltaic effect. (Dankoff, 2016). Different types of modules are present in the market such as monocrystalline, polycrystalline, thin films, and amorphous silicon. However, monocrystalline and polycrystalline modules are used most commonly in solar applications (Energy informatve, 2012). Monocrystalline modules are made by cutting four sides of a monocrystalline silicon cylindrical ingot. The cutting of the rounded edges of cells gives the module its distinctive look and improves its performance by allowing more active cell area to fit in a rectangular area. Polycrystalline modules are made by pouring molten silicon in a square mold, which is then cooled and cut into the shape of a wafer. Figure 5 shows images of monocrystalline and polycrystalline modules.



(a) (b)

Figure 5: (a) Trina solar 250 W Monocrystalline solar panel from Trina solar (b) Amerisolar AS-6P30 265W Polycrystalline Solar Panel.
Source: (Earthenergy, 2019) (Indiamart, 2019)

Thin films modules are made by depositing several layers of photovoltaic material on a substrate module are rated according to metrics such as their power output in peak watts (W_p), their maximum power point voltage (V_{mp}), and their maximum power point current (I_{mp}). For example, the module shown above can produce 275W of power based on a voltage of 31.4 V and a current of 8.76 amps when it is exposed to 1000 wats per square meter of solar radiation and its temperature is 25 degrees Celsius. The module is therefore rated as a 275 W module (Trina Solar, 2017).

The efficiency of a PV module is generally expressed in percentage terms. Monocrystalline PV modules are more efficient than polycrystalline modules. The efficiency of a monocrystalline module ranges from 15–21% as compared to 13–16% of polycrystalline modules. (Energy informatve, 2012). For example, a PV module, capable of converting 1 kWh of energy received from the sun to 0.17kWh of electrical energy, is called 17% efficient module. The performance of a solar water pumping system depends on the performance of the module, which can be identified through its I-V curve. For example, Figure 6 shows an I-V curve of a module.

It is always recommended to identify the performance of a PV module considering the local environmental conditions of a particular installation. For instance, the impact of module temperature and insolation on module performance is depicted in Figure 7. The power production of a module decreases as insolation decreases and temperature increases. The input voltage to the pump also impacts the pump’s performance. Therefore, panel voltage should be more than or equal to the minimum voltage required

for the pump. This improves the pump performance, especially where the array consists of large number of modules connected in series (World Bank, 2018b) (USDA, 2010).

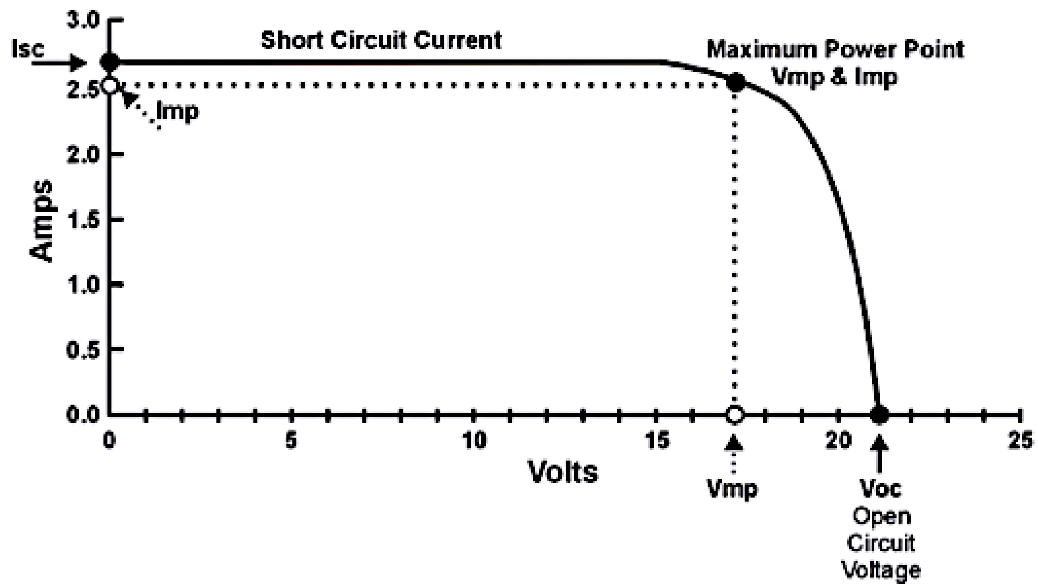
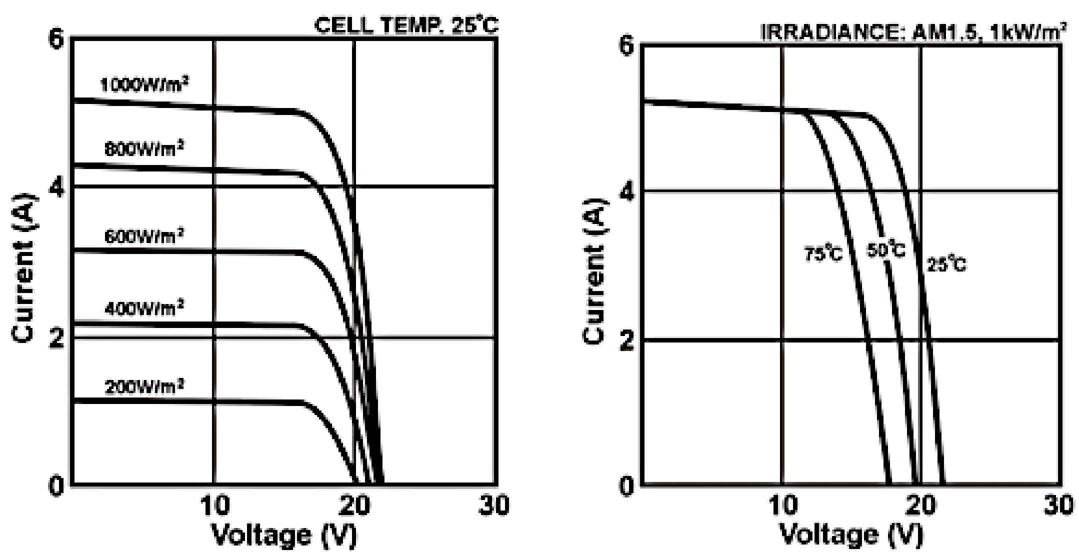


Figure 6: I-V curve of a PV module.
Source: (HKRENet, 2019)



(a) (b)

Figure 7: I-V curve of a module at different (a) Insolation and (b) Temperature values.
Source (HKRENet, 2019)

It is better to choose a module certified by the relevant testing standards such as the International Electrotechnical Commission (IEC) to assure the performance of a module. IEC has testing procedures that can be used to verify the quality and performance of a module, such as IEC 61215, which included methods for evaluating PV module performance. Among other tests, it includes methods to verify the performance of a PV module at Standard Temperature and pressure (STC) and Normal Operating Cell Temperature (NOCT) conditions. PV modules considered in this study are certified to meet requirements set by IEC.

2.4.2 Solar pump

The pump is a crucial element of a solar water pumping system. It lifts water from the well to the point of use/storage. It is powered by an electric motor. With today's technological advancements, various varieties of solar water pumps are available in the market with different lifting capabilities (Grundfos technologies, 2013). Figure 8 below depicts the performance curves of six pumps from and their respective power ratings for different heads and flowrates.

Electric pumps are driven by an electric motor that can be an AC motor or a DC motor. Pumps based on AC motors require an inverter to operate, but DC-based pumps do not. With the technological improvements mentioned in Section 2.3, DC powered pumps are more appealing in the pumping market for selected applications, such as installations with low water demand, as they can reduce the cost of pumping significantly. AC pumps are mostly preferred for large scale applications characterized by

high water demand. For this study, DC solar water pumps are used given the low water demand of the sites. DC pumps are classified as (a) positive displacement pumps and (b) centrifugal pumps.

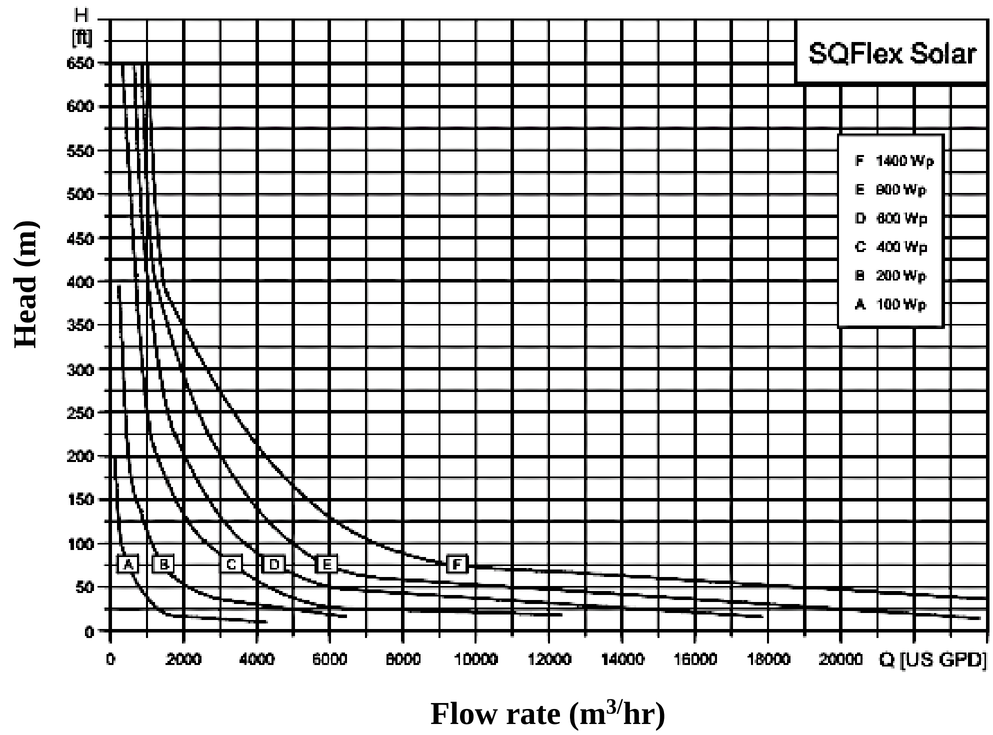
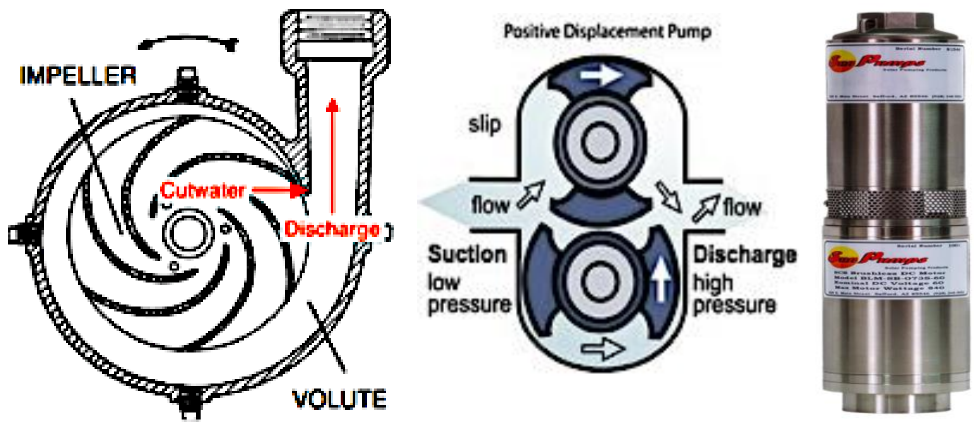


Figure 8: Performance curve of six pumps with different power ratings.
Source: (Grundfos, 2018)

A centrifugal pump operates on the principle of rotation. The impeller in the casing of a centrifugal pump pushes water to the discharge point through rotational energy. Water enters axially through the casing and gets caught up by impeller blades. The impeller blades then whirl the water tangentially and radially outward until it leaves the pump casing from the discharge point. A schematic diagram of a centrifugal pump is shown in Figure 9. They are often used for fixed head applications (Intro to pumps, 2019). A positive displacement pump works on the principle of displacement by force. In

a positive displacement pump, water is forced by a piston in one direction. The piston moves back and forth to deliver water. In each pumping cycle the piston fills the pump's chamber with the suction stroke and then discharge it with pressure, similar to the function of a syringe. In the positive displacement pump, flow remains constant regardless of a pumping head (Saylor, 2019). A conceptual diagram of a typical positive displacement water pump is shown in Figure 9.



(a) (b) (c)

Figure 9: (a) A schematic of a typical centrifugal pump (b) a positive displacement pump c) and a submersible pump.
Sources (a): (Intro to pumps, 2019) (b) (Complete pumps supplies, 2014) (c) (Sun Pumps, 2015)

Pumps can also be classified as surface water pumps and submersible pumps (Saylor, 2019). Surface water pumps are typically designed for low height operations, and they are well suited for pushing a large amount of water at a relatively small elevation gain. They have wide application in crop irrigation and pumping surface water into storage tanks (RPS Solar Pumps, 2019). Solar submersible pumps, as shown in Figure 9, are typically used to pump water from deep wells, as they can lift water over

relatively large elevation gains. DC submersible pumps are considered for the analysis in this study. Because they do not require an inverter and their efficiency can be relatively high, a good quality DC submersible pump can use 20% to 50% less energy per gallon of water pumped for same head compared to an AC pump. They are highly reliable as the maintenance is very low, and they do not require priming (RPS Solar Pumps, 2019; Farm and Livestock, 2018).

2.4.3 Pump controller

A pump controller is a device that is used with a DC pump to enhance to enhance its performance. A controller boosts the current of solar modules by keeping the voltage of the module at the maximum power point. With this feature, the pump starts early in the morning in low sunlight conditions and runs until late evening (Sunpumps, 2019). Pump manufacturers often recommend using a pump controller that is designed for a specific pump and matches its requirements (Lorentz, 2019).

2.4.4 Storage

Most solar water pumping systems include water storage as an integral part of the system. A well-designed water storage tank eliminates the requirement of a battery in the system and reduces its overall cost. An elevated storage tank can ensure water availability on cloudy days and provide flexibility in the functioning of a pump. Figure 10 shows typical storage set up for a solar water pumping system. Elevated storage systems, as shown in Figure 10, are used to deliver water at a constant pressure. They reduce the need for booster pumps to provide water to the point of use (RPS Solar Pumps, 2019). In many

cases solar panels are also put of the roof of storage. Depending on the climate situation and the usage pattern of the site, the capacity of the storage often ranges from three to 10 days of demand fulfilment (Jenkins, 2014). For consistently sunny locations, three or fewer days of storage are often sufficient (UNICEF, 2016b).

Figure 10: A typical storage setup for a water pumping system supported by UNICEF in Anambra state, Nigeria.
Source: (UNICEF, 2016b)

2.4.5 Panel mount

PV modules are mounted on panel mounts. Various types of mount systems are used for holding panels such as ground mounts, roof mounts, pole mounts and tracking systems. Ground mounts are used to attach PV modules on the ground. Roof mounts are

used when PV modules are mounted on the roof. Pole top mounts are used to mount solar panel on the top of a pole. A pole mount keeps the panel away from the ground. However, it can increase the cost of the system significantly (Wholesalesolar, 2019). Panel mounts are also used to orient the panel toward the south side if the system is installed in the northern hemisphere.

In addition to the components of a solar water pumping system, it is important to identify the availability of water in the region to ensure the sustainability of the system. The following section identifies the water availability in Nigeria.

2.5 Water Availability in Nigeria

The Federal Republic of Nigeria, commonly referred as Nigeria, is located in West Africa. It borders Niger in the north, Chad in the northeast, Cameroon in the east, and Benin in the west. It is comprised of 36 states and the Federal Capital Territory (FCT). Figure 11 shows the geographic location of Nigeria on the map of Africa and the location of the FCT on the map of Nigeria. Abuja, capital of Nigeria, is located in the FCT region, which is a territory in central Nigeria.

Nigeria's FCT is made up of six area councils, including Abuja, Abaji, Bwari, Gwagwalada, Kuje, and Kwali. FCT is located north of the confluence of the Niger and Benue rivers, and it falls within the Benue River Basin, which ranges from the Cameroon border to the Nigeria-Benue river confluence (Wikipedia, 2019; British Geological Survey, 2003). The Benue Basin is one of the least exploited water basins in Nigeria. The aquifers in this basin have an enormous potential of groundwater in it (Sodiki, 2014).

(a) (b)

Figure 11: Location of (a) Nigeria on Africa's map and (b) the capital, Abuja, on Nigeria's map. Abuja is located in the Federal Capital Territory (FCT). Source (a) (Flygaytube, 2018) (b) (Kelly-Hope, 2013)

Groundwater remains an important resource of water supply in Nigeria. Groundwater availability in Nigeria is classified into eight hydrogeological areas, including local groundwater resources and aquifers adjacent to major rivers. Three major basins cover most Nigerian land. They are Sokoto Basin, Middle Niger Basin, and Benue Basin. The Sokoto Basin in the northwest part of Nigeria has many unconfined aquifers at a depth of 15m – 75m and a confined aquifer at 75m – 100m. The water yields of this basin are in the range of 3.6 m^3/hr to 20 m^3/hr. The Middle Niger Basin consists of aquifers that can yield water with a flow rate of 2.5 and 20.0 m^3/hr.

The other region is the Chad Basin. It has three main aquifers, the upper, middle, and the lower aquifer. These are identified as having depths of 30-100 m, 40-100 m, and 425-530 m, respectively. The yield from these aquifers are between 4.3 and 5.8m^3/hr (British Geological Survey, 2003; Sodiki, 2014). The Benue Basin, the zone that is

relevant to his study, extends from the Cameroon border to the Niger-Benue confluence. The FCT region of Nigeria falls in this basin. The water table of this basin is higher than the other basins, and it can successfully yield water between 3.6 and 30.0m^3 /hr (Sodiki, 2014; British Geological Survey, 2003).

Groundwater found in most aquifers in Nigeria is fresh with low Total dissolved solids (TDS). However, the surface water and water from shallow aquifers are doubted to contain domestic and industrial pollutants (Sangodoyin, 1993). Approximately, 20%, 40%, and 40% of the country's groundwater has low (< 6.5), medium (6.5 to 6.8) and high pH, and it is very corrosive, moderately corrosive, and not corrosive, respectively (Sodiki, 2014).

The bacterial content in the water is high and declared to be unfit for domestic consumption in many cases (Sangodoyin, 1993). At some sites, high salinity is also recognized as a problem. The concentration of iron and manganese and total dissolved solids (TDS) are common in the Benue Basin, which covers the majority of FCT areas. The presence of Hydrogen Sulphide in some regions has also questioned the acceptability of water for domestic usage (British Geological Survey, 2003).

In conclusion, a sufficient amount of water is present in approximately every part of the country that can be extracted through solar water groundwater pumping technology. The aquifer depths vary from 10m to 800 m, and water yield ranges from 0.5 m^3/hr to 300 m^3/hr. Overall the groundwater quality is good in the FCT region, but in some cases the concentration of iron, manganese, nitrates, and fluoride are high. The presence of arsenic has also been reported in the groundwater in some parts of the Benue

Basin in Nigeria (Sangodoyin, 1993). Therefore, it is essential to identify the hydrological characteristic of water pumped from a borehole by laboratory analysis. Also, it is required to treat water before further usage. For the purpose of this study, water quality at the site will be studied through lab analysis.

The feasibility of a solar water pumping systems also highly depends on the solar resource of a location. If the solar resource is less than 3.0 kWh/m^2 per day (3,000 watt-hours per square meter of area in one day), then the location is not considered feasible for a solar water pumping system (Jenkins, 2014). The solar resource of Nigeria is discussed in Section 2.6.

2.6 Solar Resource in Nigeria

Nigeria is located between latitudes 4◦N to 14◦N and longitudes 3◦E to 15◦E (Wikipedia, 2019). Nigeria is blessed with the abundant solar resources in almost every location of the country. The yearly average solar energy received on a horizontal surface in Nigeria is 2300 kWh/m^2/day, and the annual averages of global solar radiation are as high as 7.0 kWh/m^2/day. Figure 12 shows the solar radiation map of Nigeria (Fidelis Abam, 2014). In the map, Nigeria is divided into three zones, namely, Zone I, Zone II and Zone III. Zone 1, which is north and northeast of Nigeria, is called a high solar insolation zone. Solar radiation in this zone ranges from 6.0- 6.5 kWh/m^2/day on average. Zone II, which includes the central, northwest, and southeast areas, is a moderate solar zone with solar 5.0- 5.5 kWh/m^2/day solar insolation. Zone III is low solar zone with solar insolation 4.0-4.5 kWh/m^2/day.

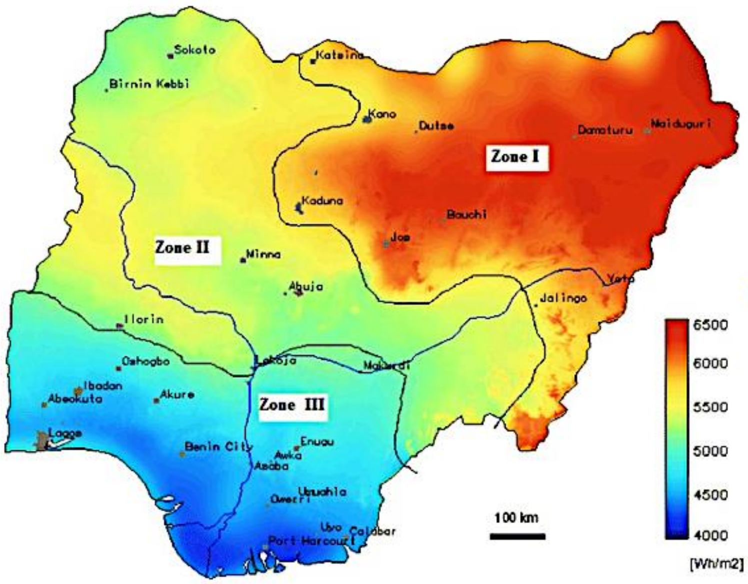


Figure 12: Solar radiation map of Nigeria.
Source: (Fidelis Abam, 2014)

The sites considered in this study are located in FCT Nigeria, where the solar resource ranges from 5.0 to 5.5 kWh/m^2/day (NASA, 2018). The average monthly solar resource of individual sites considered in the study are presented in Chapter 4.

CHAPTER 3. METHODOLOGY

In order to design and successfully implement a solar water pumping system for a particular location, it is important to understand the steps of the design process. For this research study, three public facilities, as mentioned in Chapter 1, are identified as targeted sites for the installation of solar water pumping systems. Three different sites, a primary health center (PHC), a comprehensive health center (CHC), and a primary school, are chosen to capture several different demand scenarios (micro, small, and medium demand).

The PHC at Ibwa is a small rural health center that serves approximately seven patients and three staff persons per day. This PHC has a micro water demand, whereas CHC at Kwali that serves 35 patients in a day and 28 staff members has small water demand. In LEA school at Mapa, 311 students use water per day along with three staff members. LEA School has medium water demand and the highest water demand among the three cases considered. Key information that influences the design of the system, such as the number of people served, daily water demand, and the size of the storage tank, is provided and discussed in Chapter 4. This study involves two broad steps, technical analysis and an economic analysis, for the analysis of the pumping systems. These steps are classified further, as shown below.

Technical Analysis: Technical Analysis is classified into the following seven steps

1. Site information
2. Identification of water requirements
3. Identification of water resources

4. System layouts
5. Storage
6. Solar resource availability
7. Design of solar pump systems

Economic analysis: Economic analysis is classified into the following six steps

1. Cost estimation
2. Cost Optimization
3. Life cycle cost
4. Cost of water
5. Cost benefit analysis
6. Sensitivity analyses

3.1 Technical Analysis

Technical analysis includes identification of the water demand, the water resource, the solar resource, storage requirements, and critical design parameters such as the design flow rate, total dynamic head (TDH), and the electric power required for the pump. These steps are further classified into sub-steps as needed in the following sections. This section also includes system design assumptions, empirical equations and constants used for completing the design and analysis at the three locations.

3.1.1 Site information

IBWA PHC: Ibwa PHC is a small public health center. It serves approximately seven patients per day, seven days a week, with the help of three medical staff. It is a day-

only service which offers approximately nine hours of service each day to the community. Figure 13 shows the location of PHC, Ibwa (Google Maps, 2019). Figure 14 shows the Google Earth image of PHC Ibwa and a picture of the health center taken from outside (Google Earth, 2019). The site is located very near to Abuja and lies in Zone II shown in Figure 12, and it receives solar radiation ranging from 5.0- 5.5 kWh/m^2/day. Detailed solar analysis conducted at the site is shown in Appendix C.

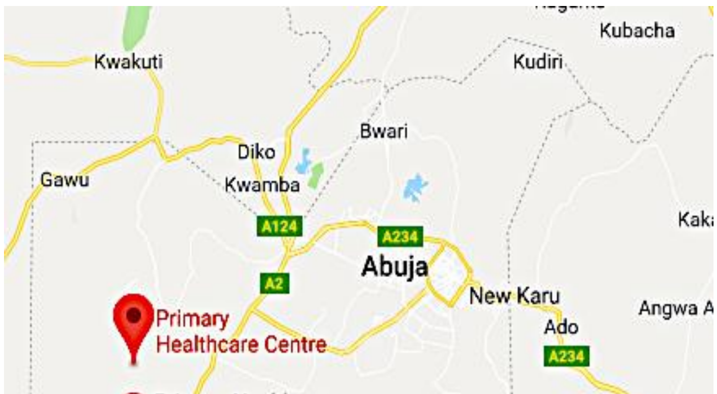


Figure 13: Location of PHC, Ibwa, FCT Nigeria.
Source: (Google Maps, 2019)

Figure 14: PHC, Ibwa, FCT, Nigeria.
Source: (Google Earth, 2019; Schatz Center, 2018)

Three separate, small PV solar systems are currently available at the site that are catering to other electric loads at the site. A hand pump was used for pumping water from the borehole before it became dysfunctional. The inner pipes of the hand pump are broken as reported in the detailed survey. The PHC obtains water from a submersible pump located at a nearby community. Water is used for domestic activities such as cleaning, drinking, cooking, and prayers, as well as for medical activities such as lab testing, maternal deliveries, and vaccinations. Key information that influences water demand at the site was obtained from the detailed audit survey forms and is presented and discussed in Chapter 4.

CHC, KWALI: Kwali is a district in Nigeria. This health center is also a day only service and opens for almost 10 hours a day to serve approximately 35 patients. CHC is connected to the electric grid, but the reliability of the grid is abysmal. Figure 15 shows the location of CHC at Kwali (Google Maps,2019).

Figure 15: Location of CHC, Kwali.
Source: (Google Maps, 2019)

CHC, Kwali, as shown in Figure 16 is a fairly big health care facility comprised of eight small buildings (Google Earth, 2019; Schatz Center, 2018). This site also has a small solar system installed that supports the electrical loads of the health center, such as a vaccine refrigerator. A borehole is available at the site which is equipped with a non-functioning submersible water pump. The health center gets water from a nearby community borehole. The site is located very near to Abuja and lies in Zone II, as shown in Figure 12, and it receives solar radiation ranging from 5.0- 5.5 kWh/m^2/day. The detailed solar analysis is also conducted at the site is shown in Appendix C.

Figure 16: CHC, Kwali, FCT Nigeria.
Source: (Google Earth, 2019; Schatz Center, 2018)

LEA SCHOOL, MAPA: This site is a day boarding school with approximately 311 students. It operates in one building with approximately 18 teachers (three are full time). Figure 17 shows the location of LEA School (Google Maps, 2019).

The site is a large facility, as shown in Figure 18 (Google Earth, 2019; Schatz Center, 2018). Important information about the school and its water consumption activities are tabulated in Chapter 4. The site also lies in Zone II and receives solar

radiation ranging from 5.0 to 5.5 kWh/m^2/day. Detailed solar analysis for the site is shown in Appendix C.

Figure 17: Location of LEA School at Mapa.
Source: (Google Maps, 2019)

Figure 18: LEA, School, Mapa, Nigeria.
Source: (Google Earth, 2019; Schatz Center, 2018)

The school does not have access to the electric grid. It produces electricity through a generator supplied by UBEB. Water at the site comes from the nearest borehole or sometimes from a water pump on the site powered by the generator.

3.1.2 Identification of water requirements

The first step in designing a solar-powered water pumping system for a particular site is to identify the overall water demand for the system. A reasonable estimate of the water demand is essential to achieve a reliable system performance. Water demand can be defined as an aggregate of the various types of water usage at the site and expressed in terms of gallons/day. Two methods can be used to do this. First, by using the estimated demand according to an audit, such as the one carried out by the Schatz Center team. Second, by using the average per capita water consumption estimates recommended by agencies such as WHO for various types of usages (WHO, 2015). The amount of water consumed in each activity per day is identified by multiplying the average per capita water consumption estimates recommended WHO for various types of usage (WHO, 2015) by the number of people. The water demand estimates of WHO are provided in Table 2, and the number of people considered in this study for each site are listed in Chapter 4.

Table 2: Average per capita water consumption estimates for rural areas

Activities	WHO Estimate	Source
Basic Hygiene (Hand washing, Toilet, Bathing)	6 l/day/person)	(WHO, 2005)
Drinking	3 (l/day/ person)	(WHO, 2005)
Cooking	6 l/day/person	(WHO, 2005)
Cleaning	3 litres/day	(WHO, 2005)
Operating Theater/ Maternity	300 (L/ intervention)	(WHO, 2005)
Cleaning medical equipment	3(l/day)	(WHO, 2005)
Lab Testing	0.25 (l/patient/ day)	(WHO, 2005)
Laundry	5 (l/day/ person)	(WHO, 2005)
Prayers/ Mosque	5 l/per day /per person	(WHO, 2005)
School (Drinking and handwashing)	3 l/pupil/day	(WHO, 2005)
School toilets	5 l/user/ day	(WHO, 2005)

To apply the first method, the overall demand as given by the site users is identified from the detailed audit survey forms. In the second method, the estimates from Table 2 are multiplied by the number of users/patients/students and then aggregated to identify the total water requirement.

$$Daily\ water\ demand\ per\ activity\ per\ person\ =\ Water\ demand\ per\ activity\ (l/per\ person/day)\ *\ number\ of\ persons \quad (1)$$

For a conservative estimate, both methods are used for each site, and the larger of the two values is used in further design calculations. The maximum demand is then adjusted for potential demand growth and a storage factor of safety to identify total water demand for the site. The growth factor is intended to account for any future growth in the demand. The storage factor of safety is intended to account for the excess storage need to bridge the gap in supply that may be due to poor weather conditions or equipment failure. In this study, it is also used as a factor to account for any uncertainties in the assumptions about demand (Sullivan, 2018)**.**

3.1.3 Water resource

The configuration for a water pumping system depends highly on the source of water and the hydrogeology of the location. For example, a water system designed for a well is different from a surface water pumping system. Systems designed for wells require the following additional information about the well.

1. Static water level,
2. Maximum pumping rate and drawdown

The quality of water is also required to be tested. Water quality is discussed in Section 3.1.3.3 of this document.

3.1.3.1 Static water level: Static water level refers to the level of water in a well under normal, undisturbed, and no-pumping conditions. It can be determined as the depth of water in the well when water is not pumped several hours before the measurements (Water Systems Council, 2014). For this study, the well characteristics such as static water level, and total well depth are taken from the reports of pumping tests conducted at the sites (Appendix B). The static water level is shown in Figure 19.

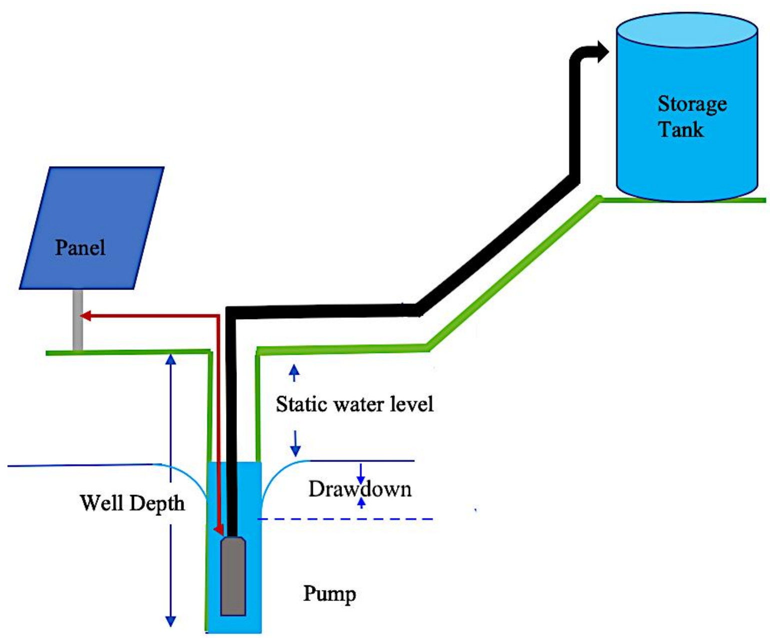


Figure 19: Parameters identifying the water availability.

3.1.3.2 Pumping rate and drawdown: The pumping rate and drawdown can be identified by performing a pump test. A pump test is an experiment that provides a practical and reliable method of estimating the well performance, yield, drawdown, and aquifer characteristics. This test identifies two main parameters of interest for any solar water

pumping system, drawdown, and recovery rate. In the test, water is pumped out of the well at a controlled rate, and the water level is measured manually in regular intervals of time. Careful measurements of water level, time, and flowrate are recorded in the test. These measurements should continue until the water level comes to a steady level. The steady water level is an indicator of the water replenishment potential of the aquifer after pumping at a particular flowrate. For this research, the data recorded at the time of the pump test conducted at the sites were used to identify the maximum flow rate and drawdown water depth. Drawdown is defined as the difference between the static water level and the deepest steady state water depth attained during the pump test. The maximum flow rate during the pump test was also recorded, the flowrate at which the water level became steady. If the maximum flowrate that the aquifer can provide is less than the designed flowrate, then it can be concluded that a single well is not adequate to fulfill the water demand of the site. Regression analysis is conducted on the water level and pumping time recorded during the pump test to identify the number of days the maximum flow rate can be sustained. The regression model used to identify the number of days for the sites is presented in Table 3. The details of the regression analysis conducted for each site are provided in Appendix C.

Table 3: Model used to identify the number of days the maximum flow rate can be sustained

Site	**Model**
Ibwa, PHC, Borehole	H = -19.819*D + 581.64 ft
Kwali, CHC Borehole	H = -92.488*D + 779.3 ft
LEA School Mapa Borehole.	H = -14.371*D + 1994 ft

Where, H is the water elevation from sea level in ft and D is the number of days.

A monitored recovery test is conducted to identify the recovery rate. Water pumping from the well was stopped, and the water level and time are recorded to perform the recovery test. Careful measurements of water level and time, are recorded in the test until the well reached to the static water level. The recharge/recovery rates are calculated from the obtained data with the help of a formula shown in Equation 2.

$$Recovery\ rate\ = Volume\ (gal)\ /\ (Start\ Time - End\ time\ of\ recovery\ test \qquad (2)$$

Where,

$$Volume\ (gal) = \ Area\ of\ the\ well\ (ft^2) * height\ of\ water\ displaced.(ft) \qquad (3)$$

The difference in the time is calculated by subtracting the start time and the end time of the recovery test. Time is calculated by converting minutes to hours. For example, 4:35 is converted to hours by converting 35 minutes to hours and adding 4 hours to it (4+35/60).

3.1.3.3 Water quality: The water extracted during the pump test was also tested in a laboratory to identify the quality of the water from the wells. Water samples were taken during the pumping test conducted at PHC, Ibwa, CHC, Kwali, and LEA School Mapa. Several physicochemical and microbiological tests were performed that identifies the conductivity, total dissolved solids (TDS) concentration, dissolved CO_2, free chlorine, aerobic bacterial content, and E.coli, etc. The results are summarized in Chapter 4. A detailed water quality analysis report is placed in Appendix D.

3.1.4 System layout

The system layout is a crucial step in the system development process. It outlines

the complete layout of the system. System layout gives an idea of the location of the PV modules, the location of the storage tanks, elevation in the system, and the length of pipelines required for pumping water from the well to the storage tanks and delivering it from the tanks to the delivery point. The method described in this study only considers the extraction of water from the well and delivery to the storage point. Water delivery from the storage tanks to the delivery point is excluded from the scope of this thesis, as shown in Figure 20 below. For convenience, the pipeline network for the entire system is divided into two sections, Section 1 and Section 2. Section 1 includes the pipes inside the well; these are referred to as L1 in Figure 20. Section 2 includes the pipes outside the well.

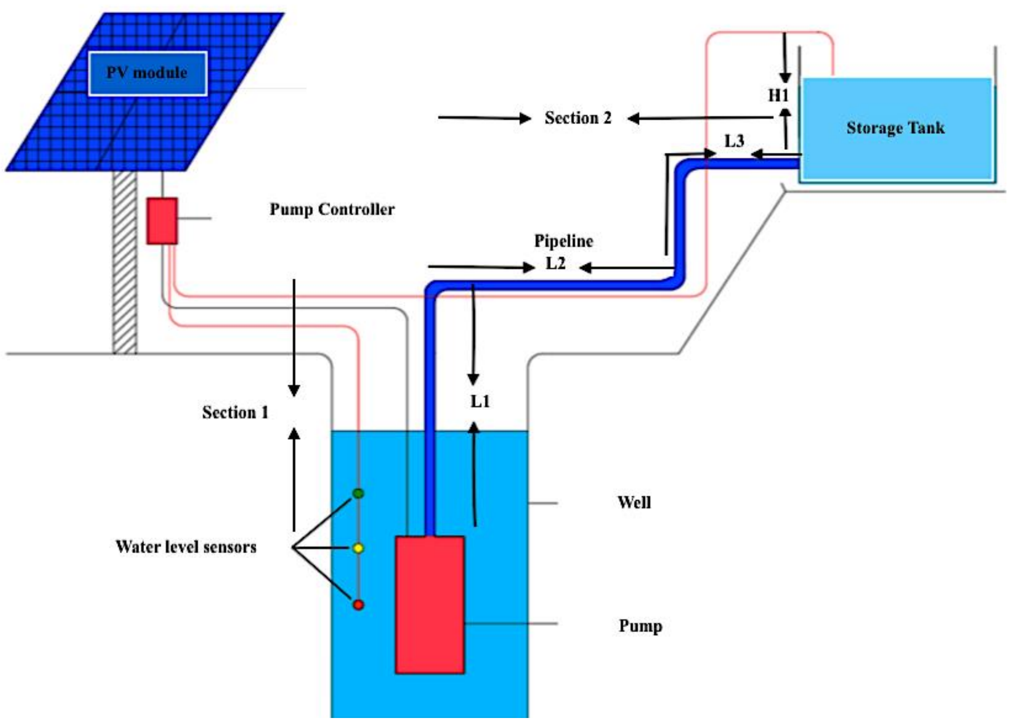


Figure 20: System layout for the solar water pumping system designs

The pipelines outside the well include the pipe from the head of the well to the bottom of the storage tank foundation, referred as L2 in the system layout. The pipeline from the bottom of the elevation to the top of elevation is referred to as L3, and the height of the tank labeled H1. Based on the site-specific data for the systems, it was identified that the solar PV modules should be oriented toward the south. Additionally, the pumps can be fit on the existing boreholes the pipeline line lengths are available for these sites.

3.1.5 Water storage

A water storage tank is usually an essential element in an economically viable solar-powered water pump system. The use of a storage tank improves the reliability of the solar water pumping system by storing enough water during peak energy production to meet water needs at night and in the event of cloudy weather and during maintenance periods. The design storage capacity is calculated by considering three days of autonomy as an initial assumption. However, the actual storage that optimizes the system performance and cost can be identified through calculations considering the profile of water demand and availability of solar insolation over a model year. The recommended storage tank size for each of the three systems is presented in Chapter 4.

3.1.6 Solar resource feasibility

Monthly average solar data for PHC Ibwa, CHC Kwali, and LEA school in Mapa were downloaded from the solar resource database of NASA with the help of longitude and latitude coordinates of the sites. The data is presented in Table 4. It includes the average daily solar energy incident on a horizontal surface without shading

(kWh/m^2/day) for each month obtained from the Power Single Point Data Access tool of NASA.

Table 4: Average monthly Solar Data of the sites.

Month	**Insolation incident on a horizontal surface without shading (kWh/m^2/day)**			
	Ibwa PHC	Kwali CHC	LEA School Mapa	Source
Jan	5.88	5.89	5.88	(NASA, 2018)
Feb	6.90	6.07	6.09	(NASA, 2018)
Mar	6.27	6.11	6.27	(NASA, 2018)
Apr	6.06	5.77	6.06	(NASA, 2018)
May	5.56	5.40	5.58	(NASA, 2018)
June	5.06	4.89	5.06	(NASA, 2018)
July	4.44	4.51	4.44	(NASA, 2018)
Aug	4.19	4.26	4.19	(NASA, 2018)
Sep	4.73	4.59	4.73	(NASA, 2018)
Oct	5.31	5.12	5.31	(NASA, 2018)
Nov	5.98	5.81	5.98	(NASA, 2018)
Dec	5.86	5.82	5.86	(NASA, 2018)
Minimum	4.19	4.26	4.19	(NASA, 2018)

For a conservative estimate, the month which receives the smallest quantity of daily solar energy was used for the design calculations. For example, PHC, Ibwa receives the smallest quantity of solar energy in August, and this resource was used to calculate the design flowrate.

3.1.7 System design

Design of a solar water pumping system broadly depends on two important parameters: TDH and design flow rate. The method of calculating TDH and design flow rate are described in this section.

3.1.7.1 Design flowrate**:** The design flowrate is calculated by dividing the daily water demand by the available solar resource of the site using Equation 4.

$$Q = \frac{Daily\ water\ demand\ \ (Gallons)}{Solar\ Hours * 60\ (\frac{min}{hr})} \qquad (4)$$

Where, daily water demand is the total demand in the site, and solar hours are the minimum solar insolation in kWh/m^2/day that implies a number of hours of available sunlight in a day at 1000 W/m^2 of incoming radiation. This study uses the minimum monthly average solar resource to make a conservative estimate.

3.1.7.2 Total dynamic head: In addition to the flowrate, TDH is another critical parameter that defines the design of a system. TDH is a concept that relates the energy of an incompressible fluid to the height of an equivalent static column of that fluid. For water pumping systems, it is the pressure required to overcome the depth of well, the velocity of the fluid in a pipe, and friction in the pipe and fittings converted into the height of an equivalent water column (USDA, 2010). In general, TDH is the “equivalent” total vertical distance that the pump needs to lift the water from the well to the storage facility or another delivery point. It can be measured in the units of distance. Since it needs to incorporate the amount of head loss due to the velocity of fluid in the pipe and to overcome the friction in the pipe and fittings, it can be calculated by adding static head, friction head, velocity head, and the friction losses that are created by the fittings such as joints, couplings, and valves. It can be calculated from Equation 5 given below:

$$TDH = Static\ head\ (ft) + Drawdown + Velocity\ head(ft) + Friction\ head\ (ft) + Friction\ loss\ due\ to\ fittings\ (ft) \qquad (5)$$

(USDA, 2010)

Static Head: Static head or vertical lift is typically the most significant contributor to TDH. It is the vertical distance from the water level to the pump discharge point. In the design process, the static head is calculated by adding the static water level (the vertical distance from the ground to the water level), and system elevation (vertical distance from the ground to the discharge point), as given in Equation 6 and shown in Figure 21. During fieldwork carried out by the Schatz Center team, static water level and drawdown were recorded at the time of pumping test, and system elevation is measured.

$$Static\ Head\ (ft) = Static\ water\ level + \ system\ elevation. \qquad (6)$$

(Jenkins, 2014)

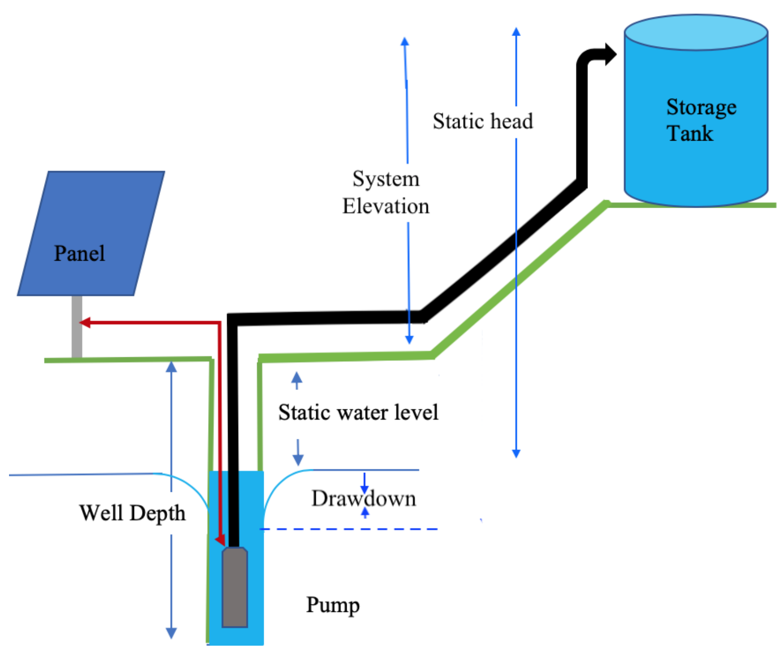


Figure 21: Schematic diagram of a solar water pumping system.

Velocity Head: When a fluid flows in a pipe, it also experiences various resistance to its flow. Velocity head is the head created due to the flow of water in the pipe. It can be calculated by using Equation 7.

$$Velocity\ Head\ (ft) = \frac{V^2}{2g} \qquad (7)$$

Where V is velocity of fluid in the pipe in ft/s, can be calculated with the help of Equation 8, and g is acceleration due to gravity in ft/s

$$V = \frac{Q}{A} \qquad (8)$$

Where Q = flow rate (cfs)

A = Area (ft^2)

Friction Head: The other resistance is called friction loss. Loss in pressure due to friction near the surface of the pipe creates friction head in the pipe. It is also referred as friction head loss and expressed in (ft H_2O/unit (ft) of Pipe length). Friction head depends on the type of pipe (roughness), the total length of pipe, the flow rate of the fluid in the pipe, pipe diameter, and number and type of fittings and joints in the pipe. Friction head is expressed in terms of the equivalent length of pipe. Friction head can be calculated by using Hazzen–Williams formula given in Equation 9. Various forms of the Hazzen–Williams formula are available in the literature. However, the form indicated in Equation 9 is used for site designs in this thesis.

$$\boldsymbol{H_l = \frac{10.472}{C^{1.852}} * \frac{Q^{1.852}}{D^{4.871}} * L} \qquad (9)$$

Where, C: Roughness coefficient variable; it depends on the type of the pipe (PVC pipe, C = 150)

Q: Flow rate in gpm.

D: Pipe inside diameter in inches

L: Length of the pipe in feet.

For the designs in this study, a 3/4 - inch (0.75 -inch) diameter PVC pipe is used. This relatively small pipe size is acceptable due to the low water demand and low flow rate of the systems. Table 5 below shows roughness coefficient and diameter used in the designs. The other component of friction head is the friction losses due to fittings, which is also calculated in terms of the equivalent length. Friction losses due to fittings depend on the number and type of fittings used in the system. This study calculates friction losses due to fittings as a part of friction head losses instead of calculating them separately. Several fittings are used in the systems to connect the pipelines. Several fittings used in the designs and equivalent length added by them is shown in Table 6. Pressure loss contributed by these fittings is equal to the head created by the equivalent length of the pipe. The equivalent length shown in Table 6 is obtained from Table E.1 in Appendix E.

Table 5: Pipes used in the system designs

Pipe details	**Section 1**	**Section 2**
Material type	PVC	PVC
Roughness coefficient	150	150
Size of pipe (in)	0.75	0.75
Cross sectional area (ft^2)	0.0031	0.0031

Equivalent lengths added due to fittings in Sections 1 and 2 of the pipelines are then added to the length of the pipeline in Sections 1 and 2 to obtain total pipe lengths. For example, in Section 1, the total length is identified by adding the equivalent length in Section 1, as shown in Table 6 and L1. Similarly, for Section 2 total length is calculated by adding equivalent length in Section 2, L2, L3, and H1. The total pipeline length is then used in the Hazzen-Williams Equation to calculate the friction head loss that also includes friction loss due to fittings. Since the friction losses are highly

dependent on flow rate, length of pipe, size, and type of pipe, as seen in Equation 9 above, they are calculated at different flow rates ranging for the minimum to maximum. Similarly, velocity head loss also depends on flowrate, and it is calculated at different flowrates between the minimum and maximum flow rate points.

Table 6: Number of fittings used in the pipes and their corresponding equivalent length

	Section 1		Section 2	
Fittings	**Count (nos)**	**Eq. length (ft)**	**Count (nos)**	**Eq. length (ft)**
Coupling	2	0.42	2	1.84
Long radius 90- screwed	1	2.2	0	0
Check valve screwed	1	8	0	0
Gate valve screwed	1	0.56	0	0

Static head, friction head, and velocity head are then added to identify TDH, as shown in Equation 5. A system curve is plotted to show the variation in TDH with different flow rates. System curves show TDH as a function of flowrate. TDH values corresponding to the minimum, maximum, and design flowrate, TDH_{min}, TDH_{max}, and TDH_{des}, respectively, are calculated and highlighted on the system curve. The next step in the design process is the identification of a water pump that can provide the design flowrate at the design TDH.

3.1.7.3 Pump and PV power requirement: Two methods can identify a pump. (i) Selecting a pump that can provide the hydraulic energy that is required to run a pump (Jenkins, 2014); (ii) By looking at the pump performance curves of a pump provided by the manufacturer. A pump curve identifies the power that is required to provide the design flow rate and TDH for a particular pump (USDA, 2010).

Pump curves indicate the power required by a pump to produce water at various flow rates and head values. An example of a pump curve is shown in Figure 22. The pump represented by the curves shown in Figure 22 requires approximately 400 W of power to lift water with 60ft of TDH at 10 gpm. Alternatively, some suppliers have computer programs and web-based utilities for selecting and sizing pumps for specified values of available solar radiation, pump flow rate, and pumping head.

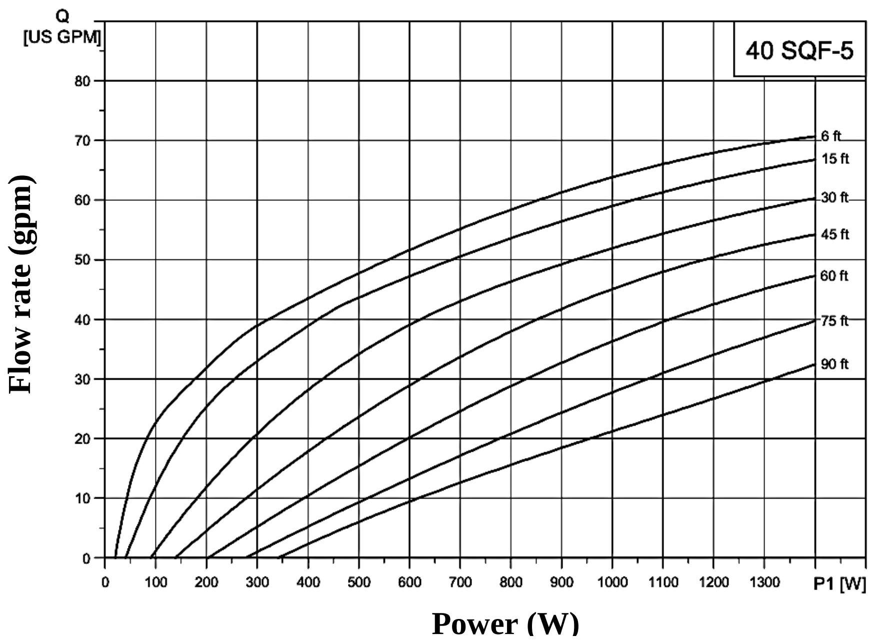


Figure 22: Pump curve for identification of power.
Source: (Grundfos, 2018)

This research relied on the second method to identify pump power and the selection of pumps. Pump curves of different pump models from manufacturers such as Grundfos, Lorentz, and Aquatec were compared to identify a suitable pump. These curves are provided in Appendix F. These manufacturers have better credibility than the other manufacturers of the pump, and they are already established in the Nigerian market

(UNICEF, 2016b). A report from UNICEF indicated that preference was given to the Grundfos SQ Flex and Lorentz PS pump models based on their proven durability, output, and long-term cost-effectiveness in Nigeria (UNICEF, 2016b). Many government, NGO, and private sector partners identify Grundfos and Lorentz as the most common pumps installed in Nigeria (EED, 2018). For the three systems designed in this study, a lowest power consuming pump model for the designed flow rate and TDH is selected out of the several models available from the credible manufacturers.

Solar water pumps are powered by DC and AC current. Solar water pumps with DC motors use power directly produced from PV modules. Pumps with AC motors require an inverter that converts the DC current produced by a PV module to AC current in addition to the other system components. PV modules are selected such that they are able to meet the power requirement of the pumping system. In addition to the power required by the pumping system, the PV modules must also have additional capacity to account for potential reduction in power due to high temperature, dust, age, and other efficiency losses. In order to account for the power loss, it is recommended to increase the minimum power required by the pump value by 25%. One or more PV panels are selected such that their electrical characteristics (voltage and current) meet the specifications of the pump. The panels selected in this thesis are able to provide the voltage and current required for efficient functioning of the selected pumps.

3.2 Economic Analysis

Solar water pumps can be used to provide clean water to rural communities. When this is done effectively, the resulting clean water can help alleviate illnesses and deaths

caused by unsafe water. However, this technology has far to go in terms of its complete deployment in the rural areas (UNICEF, 2016b). Two main barriers prohibit their wider deployment in the rural communities: (i) high initial investment cost, and (ii) surety of their continual operation. According to a report from UNICEF, operational problems in the systems are mostly due to poor borehole identification and inaccurate system design that include errors in demand assessment and system sizing (UNICEF, 2016b). This section of the study identifies the methods followed to identify the cost of the systems designed at the three sites.

This section also describes a method used for optimizing the cost of the system by identifying the PV power and storage capacity required to meet the demand of the site. The method used to estimate the life cycle cost (LCC) and the cost-benefit analysis of the systems designed in this study are also presented in this section.

3.2.1 Cost estimation

The initial cost of the system designed in this research study is calculated by adding the costs of individual system components along with the installation and balance of systems (BOS) costs as described in Equation 10.

$$Total\ initial\ cost\ =\ PV\ Array\ Cost\ +\ Pump\ system\ cost\ +\ Mount\ +$$
$$Storage\ system +\ piping\ cost + Installation\ and\ BOS\ cost \qquad (10)$$

Where, Array cost = the cost of the solar array calculated by using Equation 11.

$$Array\ Cost\ (\$) = Array\ size\ (W) *\ Array\ cost\ (\frac{\$}{watt}) \qquad (11)$$

The pump system cost includes the cost of the pump, pump controller and its accessories calculated by Equation 12. The storage tank cost is calculated by Equation 13. The estimated total cost of the system calculated by Equation 10 is based on the design requirements and assumption made at various stages of design.

$$Pump\ system\ cost\ =\ Cost\ of\ Pump\ +\ Controller\ +\ Accessories \qquad (12)$$

$$Storage\ Cost\ =\ Tank\ (gallon) * \ Cost\ \left(\frac{\$}{gallon}\right) \qquad (13)$$

This study strives to optimize the system cost with the help of a mathematical model which considers the relationship between design parameters and system cost. If the cost of creating the borehole or well is excluded (e.g. because it is already in place), the cost of a solar water pumping system is influenced by three main parameters, including the cost of the pump, the cost of the solar array, and the cost of the storage tank(s). Out of these, the cost of the pump selected to lift water from a particular TDH usually remains relatively constant for the designs considered in this thesis. Moreover, it is set by the manufacturer and it does not influence the optimization tool used in this thesis. Only the array size and storage play an important role in optimizing the system performance and its cost effectiveness. The solar array cost usually remains fixed in the cost estimation. Therefore, this model tries to maximize its utilization by varying storage tank volume to enhance the cost effectiveness of the system. Various trials of different array size and storage tank volumes are evaluated using the model to identify the optimum cost of the system.

3.2.2 Cost optimization model

As noted above, the cost of a solar water pumping system depends on the array size, storage size, and pump size. Selection of a pump that can meet the water demand of the site and size of storage are important to ensure a reliable system.

The flowrate of a pump varies widely with the power input, and it is important to analyze. To identify the relationship between the power and flowrate of a pump, this study adopts a curve fitting approach using a multiple linear regression method.

For DC-powered systems, power input to the pump depends on the power produced by the array, which varies according to the amount of solar insolation available throughout the day. The systems designed in this thesis were analyzed through an hourly simulation model that utilizes solar insolation data for a model year. This section presents the method used to identify the relationship between power input to the pump and flowrate. It also covers calculations used to simulate the performance of the selected pump over a year and to identify a cost-effective combination of array size, pump, and storage size.

A curve fit is used to identify a fourth-degree polynomial model that can predict the flowrate of the pump at a given power and TDH. Pump data were obtained for the pump curves provided by the manufacturers. These pump curves were digitized using the Graph Click software and analyzed. Digitized data for the pumps selected for the three sites are presented in Chapter 4. This data is used to carry out a regression to develop a fourth-degree polynomial model for the designs, presented in Equation 14, below.

$$Q = B_0 + B_1 * P + B_2 * P^2 + B_3 * P^3 + B_4 * TDH + B_5 * TDH * P + B_6 * P^2 * TDH \tag{14}$$

Where, P: Input power (modeled hourly for a year with PVGIS tool of European commission), H is the total dynamic head and $B_0 - B_6$ are constants. Values of these constants are identified for the pumps selected in the designs. The values of these constants for different pump models used in this thesis are presented in Table 7 below. The closeness of the predicted flow rates from the model developed for the three designs to the actual flowrates is ensured by finding the residual values (difference between the actual flowrate values and the corresponding estimated values).

Table 7: Constants for the pumps selected for the designs

Model Variables	Lorentz PS2	Grundfos 6 SQF-2
B_0	-9.97×10^{-2}	-9.97×10^{-2}
B_1	1.26×10^{-2}	9.54×10^{-3}
B_2	-3.45×10^{-5}	-1.22×10^{-5}
B_3	-6.61×10^{-11}	4.73×10^{-9}
B_4	-3.51×10^{-3}	-1.95×10^{-3}
B_5	-1.07×10^{-4}	-1.12×10^{-5}
B_6	4.32×10^{-7}	1.55×10^{-8}

Results of the regression analysis are shown in Chapter 4. The standard deviation and confidence intervals are also determined to estimate the accuracy of the models. With the help of the model presented above, the flowrate of a given pump can be simulated with the TDH and power values for each hour in a year.

During modelling, the hourly pump performance is simulated for a year to identify the suitability of pump in meeting the demand with the power produced by the solar arrays at the respective sites. For the designs considered in this study, the value of TDH remain constant (TDH_{des}) in the model, and the flowrate of the pump is predicted for hourly power

produced by a PV module. With the help of the hourly flowrate and hourly demand, this model calculates the net water volume in the tank added by the pump in that particular hour and the total water volume in the tank by using Equations 15 and 16 with a constraint that the total volume of the tank should never be more that the maximum storage capacity.

The model then uses an Excel program that identifies the minimum volume of storage and PV array size required to minimize the overall system cost that can meet the water demand of the site without allowing the storage tank to run dry at any moment in the year. The algorithm works on the concept represented in the Equation 17, below.

$$N_n = Q_n - D_n \qquad (15)$$

$$T_n = N_n + T_{n-1} \qquad Tn \leq \text{Max (storage capacity)} \qquad (16)$$

Where, N_n is the net water in tank at n^{th} hour. Q_n is the flow rate at n^{th} hour, D_n is water demand at n^{th} hour and T_n is the total water in the tank at n^{th} hour.

$$\text{Min (C)} = \text{F (T, S); Min } (T_n) > 0 \qquad (17)$$

Where, n ranges from 1 to 8760 hours, C is the cost of the system as calculated in Equation 10, T is the storage volume, and S is the array size.

The objective of the Excel program was to vary the storage volume (V) and solar array size (S) with the constraint that the minimum volume of the tank should always be greater than zero. This algorithm runs various trials of combination of storage volume and PV array size to identify the optimized combination of storage volume and array size at which storage has some amount of water at any instant, and the total cost of the system remains minimum. This cost is called the total optimized cost of the system. It is pertinent

to note that this model is generally valid for most pumps, but the value of the constants can vary significantly from the pump to pump, as seen in Table 7, above.

3.2.3 LCC analysis

A life-cycle cost analysis is also conducted on the system cost to identify its price over the system lifetime. The lifetime of the system is assumed to be 25 years. The life cycle cost is calculated by adding the capital cost (including installation costs), equipment replacement costs, operation and maintenance costs, and energy/fuel costs. The optimized cost, as identified in Section 3.2.2, above, is considered as the capital cost in the LCC calculation. Energy (fuel) charges for the systems are considered nil. Annual operation and maintenance costs are considered to be 2.5% of the upfront cost (Solar Electric Light Fund, 2008; Foster et al., 1998). The net present value (NPV) of these costs are calculated to identify the cost today. The discount rate is assumed to be 12% per year (Central Bank of Nigeria, 2018). The pump and controller device are considered to be replaced every 10 years (UNICEF, 2016b). The NPV of the costs is added to calculate the LCC of the system. The life time cost is then used to identify the cost of water by using Equation 18.

$$Cost\ of\ water = \ Life\ Cycle\ cost/\ Water\ pumped\ in\ 25\ years \tag{18}$$

3.2.4 Cost-Benefit analysis

A cost-benefit analysis is conducted to identify the benefit before and after the installation of the solar water pumping system. The cost of water per gallon before and after the installation of the solar water pumping systems are identified for the analysis. The facilities considered in this thesis reported at the time of a detailed survey that water

is collected on site from free resources such as community boreholes, streams, or rainwater. However, the free water is not enough to meet the water demand at the facilities, as the water consumption reported by the facilities during the survey is less than the water consumption prescribed for health clinics and schools by WHO (WHO, 2005; WHO, WEDC, 2011). This could occur because the facilities are not able to access sufficient water through their existing channels. If the public facilities want to have the water volume that fully meets their demand according to the recommended water estimates by the WHO, then facilities will probably need to purchase the water from other commercial sources such as water truck vendors.

The public facilities considered in this thesis did not report any cost-related data for water purchases, as they obtain water from nearby community boreholes for free. However, this study relied on the cost of water data reported by a few other facilities considered in the detailed survey to identify the cost of water that the public facilities would pay if they decide to procure water from commercial sources to fulfill their water demand completely. Very few public facilities (4 of the 11 clinics and 1 of the 10 schools surveyed) reported paying for water, and the cost they paid for water was negligible ($0.002/gallon) (Schatz Center, 2018). However, the cost of water obtained from the borewell by the rural communities in Nigeria reported in some literature sources is slightly higher than the cost of water reported by the facilities ($0.006/gallon) (Onyenechere et al., 2012).

Given the variability in the cost data in Nigeria, this study analyses low cost and high-cost scenario for the range of price of water ($0.002/gallon-$0.006/gallon). In the low-cost scenario, the cost of water is considered $0.002/gallon, whereas, for the high-cost

situation, the cost of water is regarded as \$0.006/gallon. With the low and high-cost estimates daily, yearly, and cost of water in 25 years is calculated by using Equations 19, 20, and 21, respectively. An interest rate of 12% is considered to identify the discounted cost of water in 25 years. The cost identified by Equation 18 is considered as the cost of water after the installation of solar water pumping system. The cost before and after the installation of solar water pumping systems are compared and discussed in Chapter 4 and 5, respectively.

$$\frac{Cost\ of\ water\ (\$)}{Day} = Cost\ of\ water\left(\frac{\$}{gallon}\right) * Water\ demand\ \left(\frac{gallon}{day}\right) \qquad (19)$$

$$\frac{Cost\ of\ water\ (\$)}{Year} = \frac{Cost\ of\ water\ (\$)}{Day} * 365\ \ Days \qquad (20)$$

$$\frac{Cost\ of\ water\ (\$)}{25\ Years} = Discounted\ cost\ of\ water\ in\ 25\ years \qquad (21)$$

CHAPTER 4: RESULTS

This chapter outlines the results of the technical and economic analysis conducted in the study. The methods described in the technical and economic analysis sections in Chapter 3 are used to obtain the results presented in this chapter.

4.1 Technical Analysis

This section presents the result of technical analysis based on methods from Section 3.1.

4.1.1 Site information

Site information gathered at the time of the Schatz Center field survey is summarized and reproduced in Table 8, below.

Table 8: Site information of PHC, CHC and School. Source (Schatz Center, 2018)

Site name	**PHC, Ibwa**	**CHC, Kwali**	**LEA, School**
State	FCT	FCT	FCT
District	Gwagwalada	Kwali	Bwari
Country	Nigeria	Nigeria	Nigeria
Latitude	9.06371	8.8174	9.15971
Longitude	7.05874	7.03242	7.48049
Number of days open in a week	7	7	5
Holidays closed per year	0	0	9
Hours open per day	9	10	5
Hours open per week	63	70	25
Hours of operation per year	3285	3650	1271
Existing Source of Water supply	Hand pump	Borehole	Borehole
Number of full-time staff members	3	28	3 (on site)
Number of support staff members	2	7	2
Number of pupils	n/a	n/a	311
Average number of patients served/day	7	35	n/a
Number of beds	4	8	n/a
Number of deliveries per month	3	3	n/a

Table 8 also shows the geographical coordinates of the sites, location, operating hours of the facilities, water demand, and other relevant information. The information provided in Table 8 is used as inputs for the design of solar water pumping systems for the sites.

4.1.2 Water requirement

Water demand at the sites is mainly due to water consumption in various activities such as drinking, cleaning, and basic hygiene, as described in Table 9. Table 9 mentions the type of actions performed on a site that makes for water demand. This information is collected from the detailed survey forms. Table 9 also presents the current approximate daily water demand at the sites.

Table 9: List of water consuming activities at the three sites

Name	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
Basic Hygiene (Hand washing, Toilet, Bathing)	Yes	Yes	Yes
Drinking	Yes	Yes	Yes
Cooking	Yes	Yes	Yes
Operating Theater/ maternal deliveries	Yes	Yes	No
Cleaning medical equipment	Yes	Yes	No
Lab Testing	Yes	Yes	No
Laundry	Yes	Yes	Yes
Prayers/ Mosque	Yes	Yes	Yes
Cleaning	Yes	Yes	Yes
Water demand at the facility (gal/day)	50	265	528
Total number of persons using water	10	63	314

The water demand at the sites was calculated by two methods, described in Section 3.1.2, and varies considerably. The current approximate daily water demand values at PHC Ibwa, CHC Kwali, and LEA School Mapa determined from the survey are

50 gallons/day, 265 gallons/day, and 528 gallons/day, respectively. The second method involves calculating water demand by aggregating water per activity per person for various activities listed in Table 9.

Activity-specific water demand is calculated by the formula given in Equation 1. The number of people at the sites (used in Equation 1) are listed in Table 10, and water estimates recommended by the WHO reproduced in Table 11.

Table 10: Number of users at PHC, Ibwa, CHC, Kwali, and LEA School Mapa

Types of users	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
Patients/Pupils*	7	28	311
Staff	3 (on site)	35 (off site)	3 (off site)
Total users	10	63	314

*Patients for health clinic and pupil for school.

Table 11: Activity specific water demand

Activities	**Activity specific demand of site**			
	WHO estimates	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
Basic Hygiene (Hand washing, Toilet, Bathing) (L/day/Person)	6	60	378	0
Drinking (L/day/Person)	3	30	189	0
Cooking (L/day/Person) *	6	18	0	0
Cleaning (L/day/person) *	3	9	84	0
Operating Theatre/ Maternity (L/per intervention per month)	300	30	30	0
Cleaning medical equipment (l/day)	3	3	3	0
Lab Testing (l/patient/ day)	0.25	1.75	8.75	0
Laundry (L/day /person) **	5	50**	175	0
Prayers/Mosque	5	50	315	0
School (Drinking/handwashing) (l/pupil/day)	3	0	0	942
School toilets(l/user/day)	5	2500	0	1570
Total water demand (l/day)		250	1190	2500
Total water demand (gal/day)		66	310	663

***** staff lives on site
**Patients and onsite staff only

Some activities such as cooking and cleaning are considered for only staff members that live on site. It is assumed that only on-site staff and patients consume water for laundry. Activity specific water demand as shown in Table 11 is then added to identify the total water demand. The total water demand estimated for the sites by the second method is 66 gal/day, 310 gal/day, and 663 gal/day, respectively. Out of the demand estimates identified by the two different methods, the greater water demand (identified using the second method) is considered for the design calculations. This value was then adjusted for potential demand growth and a storage factor of safety to identify the total system water demand as described in Section 3.1.2. The total water demand for systems are found to be 120 gal/day, 560 gal/day, 1190 gal/day and are shown in Table 12.

Table 12: Total water demand at Ibwa PHC, Kwali CHC, and LEA School

Site	Water demand (gal/d)	Storage factor of safety	Potential demand growth	System Water demand (gal/d)
Ibwa PHC	66	1.5	1.2	120
Kwali CHC	310	1.5	1.2	560
LEA School	663	1.5	1.2	1190

4.1.3 Water resource

Sites considered for solar water pumping system installations in the study have borewells in the premises. As described in Section 3.1.3 in Chapter 3, additional details required to design solar water pumping systems for wells such as static water level, the inner diameter of well, and total well depth are presented in Table. 13. Analysis conducted on the pumping test data to determine well drawdown depth from the ground,

minimum and maximum pump flow rates, the well recovery rate, and an estimation of the number of days a well can sustain the maximum flow rate are shown in Table 14.

Table 13: Details of the boreholes identified from the pump test

Parameter	PHC, Ibwa	CHC Kwali	LEA School
Static water level (ft)	24	21	20
Well inner diameter (ft)	0.52	0.5	0.66
Total Well Depth (ft)	107	104	118

The estimated number of days are identified by using the regression model shown in Table 3 for the sites. This analysis indicates that the boreholes can meet the water demand of the sites. Water collected during the pumping test is analyzed in a laboratory, as explained in Section 3.1.3.3, to identify its appropriateness for drinking. The quality of water is tested for the parameters shown in Table 15.

Table 14: Parameters identified from the pumping test results

Parameter	PHC, Ibwa	CHC Kwali	LEA School
Drawdown well depth from ground (ft)	42	36	27
System elevation (ft)	32	26	32
Minimum Pump Flow Rate (gpm)	0	0	0
Maximum Pump Flow Rate (gpm)	13.6	19	20.
Recovery flow rate (gpm)	0.5	0.6	0.1
Predicted elevation (ft)	543	691	1933
Number of days the well can sustain the maximum flow rate	2	1	4

Table 15: Results of test conducted on water obtained from the boreholes

Parameter	PHC, Ibwa	CHC Kwali	LEA School
Alkalinity	High	High	Acidic
Total dissolved solids	High	High	Low
Conductivity	High	High	No
Bacteria contamination	Yes	Yes	Yes
Suitability for drinking	No	No	No

Tests results presented in Table 15 indicates that the quality of water was not suitable for drinking at any of the three sites as per the report of analysis.

4.1.4 System layout

System layout is one of the critical steps in the design of the proposed systems. The pipeline length required for the sites was identified for both sections as described in Section 3.1.4 of Chapter 3. The lengths of the pipelines in Sections 1 and 2 were calculated for the systems from data obtained by survey forms and are shown in Table16.

Table 16: Length of pipeline considered in site designs

Site	**System Section 1**	**System Section 2**		
	L_1 (ft)	**L_2 (ft)**	**L_3 (ft)**	**H_1 (ft)**
Ibwa PHC	107	30	27	6
Kwali CHC	104	250	20	6
LEA School at Mapa	117	30	27	6

4.1.5 Water storage

Three days of autonomy were considered to identify the volume of the storage tank required for the designs. The estimated storage volumes for the sites are presented Table17.

Table 17: Additional storage required to be added for the designs

Site	**Storage required for 3 days of autonomy (Gallons)**
Ibwa PHC	338
Kwali CHC	1,690
LEA School at Mapa	3,583

The required storage that should be added to the sites to provide three days of autonomy to the sites is 338 gallons, 1,690 gallons, and 3,583 gallons, respectively, for Ibwa PHC, Kwali CHC, and LEA School at Mapa.

4.1.6. Solar resource feasibility

The sites considered in this study are found to have an abundant solar resource. Solar insolation at the sites varies from 4.2 $kWh/m^2/day$ to 6.5 $kWh/m^2/day$ as shown in Figure 23.

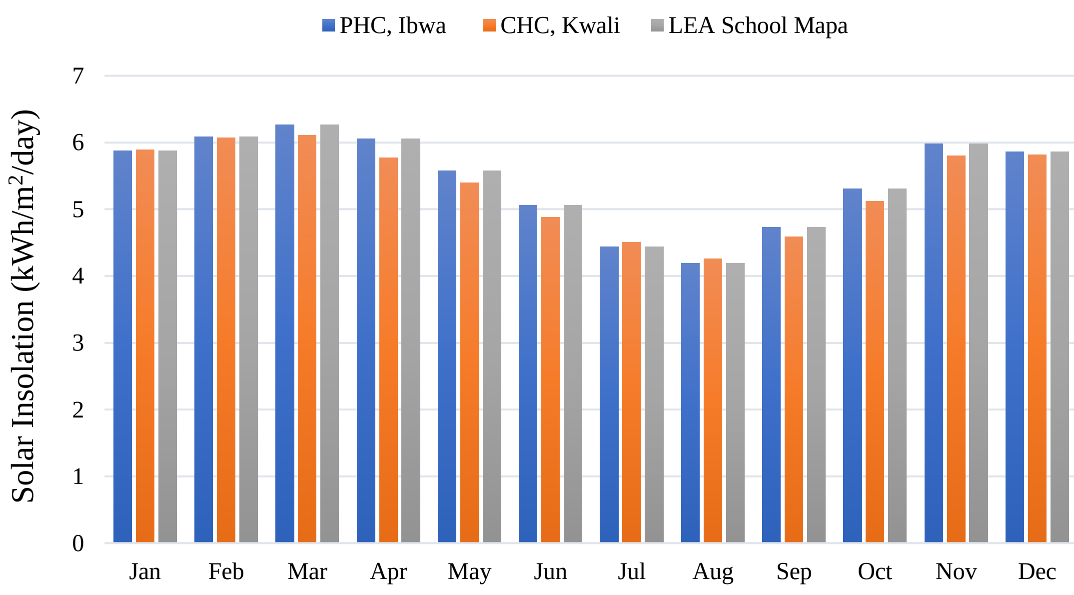


Figure 23: Average monthly solar insolation at the sites.

The data shown in Table 4 presents the number of sun hours that can be used to design the solar water pumping systems. To ensure fulfillment of water demand in the month of August (the month of year when there is least sun available during the day), the solar resource for that month is used for the design calculations.

4.1.7 System design

Design of a solar water pumping system depends on some critical parameters such as the flow rate, TDH, power requirement of pump, and sizing of PV array. This section shows design parameters calculated in this study.

4.1.7.1 Design flowrate: The design flow rate for the systems is calculated with the help of Equation 4. The system water demand as determined in Table 12, above, and the design solar resource as identified in Table 3 are used to calculate the design flow rate for the sites (see Table 18).

Table 18: System water demand and designed flow rate

Site	**System Water Demand (Gallons)**	**Solar hours (hr)**	**Design flow rate (gpm)**
Ibwa PHC	117	4.19	0.46
Kwali CHC	563	4.26	2.20
LEA School	1194	4.19	4.75

4.1.7.2 Total dynamic head: TDH of the system is calculated by using Equation 5. Each component such as static head, drawdown, velocity head, and friction head are calculated separately to obtain the TDH value. Static head values for the sites are calculated by using Equation 6 and are shown in Table 19. The sum of static head and drawdown for different sites is shown in Figures 24, 25, and 26. Velocity head depends on the flowrate in the system, and it varies over the range of flowrates. Therefore, it is calculated for a range of flowrates (Q_{min} to Q_{max}). Velocity head values for the three sites are shown in Figures 24, 25, and 26.

Similarly, friction head also varies with flow rate. It is therefore calculated for a range of flowrates (Q_{min} to Q_{max}) and is shown in Figures 24, 25, and 26. As described in Section 3.1.7.2, friction head due to fittings is included in the friction head loss values and is calculated by adding an equivalent pipe length to account for friction loss in fittings. The pipe line length in each section and the equivalent length due to fittings in each section are added to calculate the total length of pipe. The total pipeline length in sections 1 and 2, shown in Table 19, below, is then used to calculate the friction head loss in the section of pipe.

Table 19: Total pipeline length to calculate friction losses

Parameters	**PHC, Ibwa**		**CHC Kwali**		**LEA School**	
	Section 1	Section 2	Section 1	Section 2	Section 1	Section 2
Pipe length (ft)	107	63	104	276	117	63
Eq. Length (ft)	11	2	11	2	11	2
Total Length (ft)	118	65	115	278	128	65

Velocity head loss at the design flow rate (V_{des}) and friction head loss (F_{des}) at the design flow rate are calculated and shown in Table 20. These values (V_{des} and F_{des}) are also highlighted in Figures 24, 25 and 26. With varying velocity head and friction head values, TDH (the sum of all three head values mentioned above) is calculated for a range of flowrates (Q_{min} to Q_{max}) to plot the system curve as shown in Figures 24, 25, and 26. Figures 24, 25, and 26 highlight the minimum and maximum design flowrates and the corresponding TDH values for all three designs. The value of the TDH_{des} and Q_{des} is used to select a pump among competing options.

Table 20: Design parameters for PHC, CHC and school

Site	PHC, Ibwa	CHC Kwali	LEA School
Static head (ft)	56	46	52
Designed flow rate Q_{des} (gpm)	0.46	2.2	4.6
Minimum Flowrate Q_{min} (gpm)	0	0	0
Maximum Flowrate Q_{max} (gpm)	13.6	19.1	20.1
Velocity head at V_{des} (ft)	0	0.08	0.38
Velocity head at V_{min} (ft)	0	0	0
Velocity head at V_{max} (ft)	3.00	5.92	6.50
Friction head at F_{des} (ft)	0.1	6.6	13.8
Friction head at F_{min} (ft)	0	0	0
Friction head at F_{max} (ft)	90	363	194
TDH at Q_{des} (TDH_{des}) (ft)	74.2	68.9	73.49
TDH at Q_{min} (TDH_{min}) (ft)	74	62	59
TDH at Q_{max} (TDH_{max}) (ft)	167.2	432	260

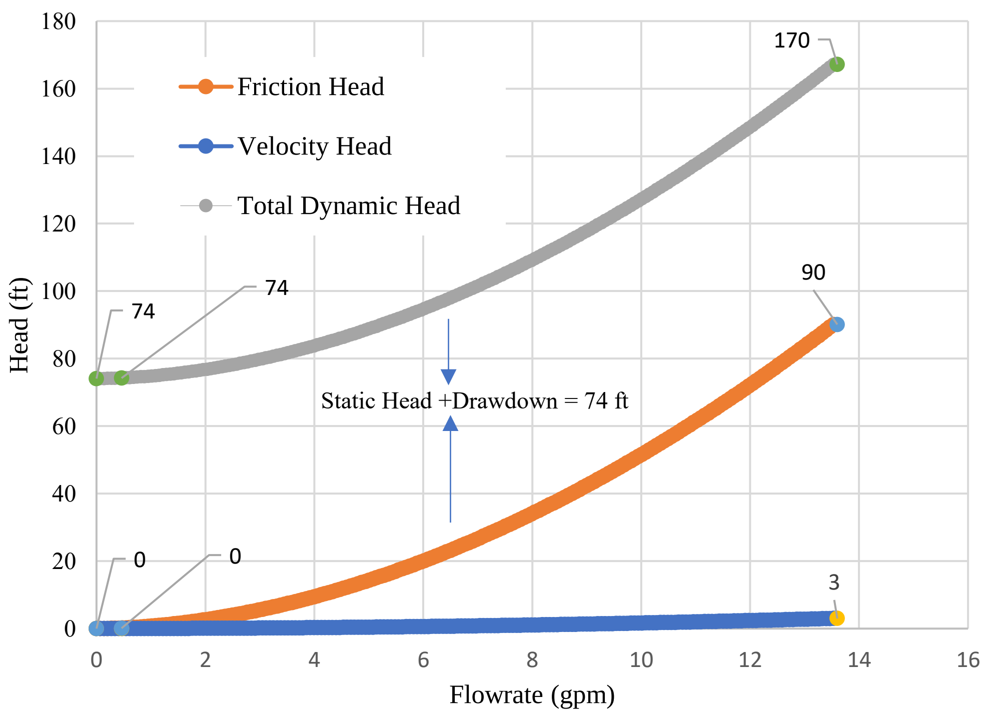


Figure 24:Velocity head, Friction head, and Total dynamic head, for PHC, Ibwa

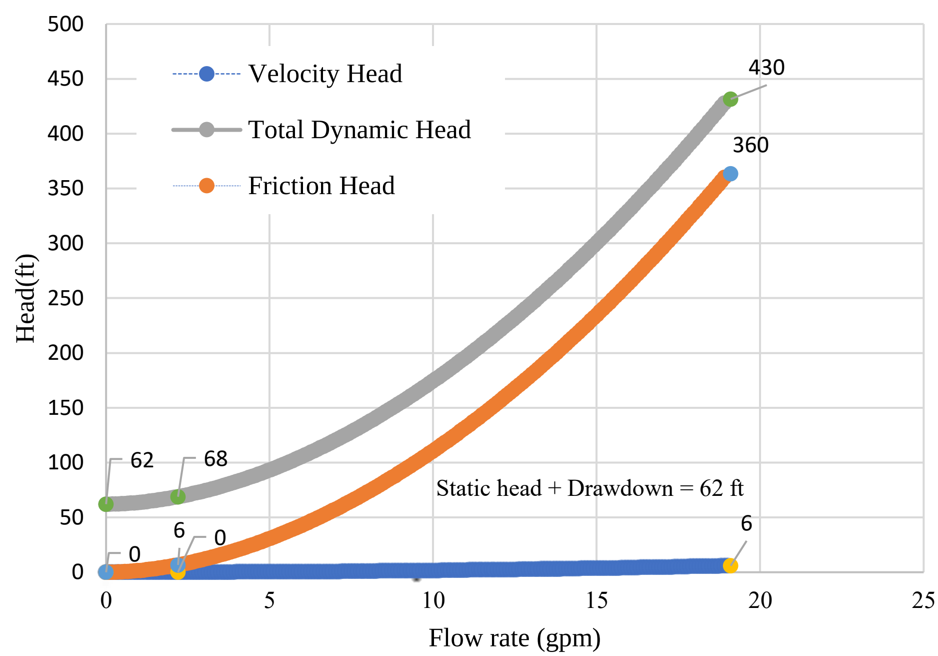


Figure 25: Velocity head, Friction head, Total dynamic head, for CHC, Kwali

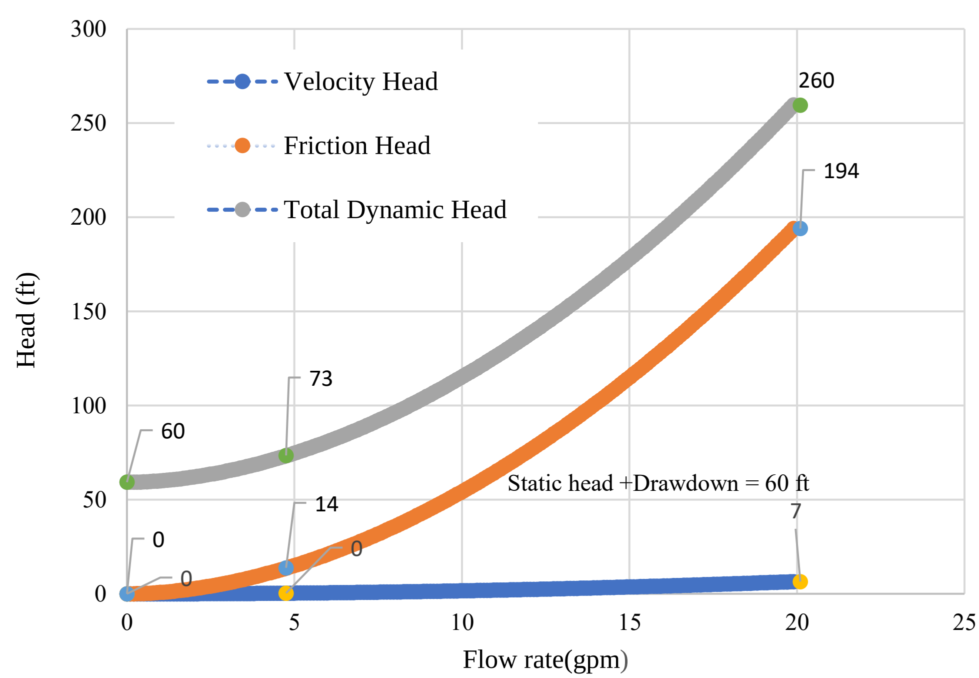


Figure 26: Velocity head, Friction head, Total dynamic head, for LEA School Mapa

4.1.7.3 Pump power: As described in Section 3.1.7.3, this study looked at pump curves of several pump models from different manufacturers and selected three pumps for the design of the systems and identified the power required by those pump models to deliver the design flow rate at the design TDH. Table 21 shows the minimum input power to operate the pump and the size of the solar module/array for PHC Ibwa, CHC, Kwali and LEA School Mapa. The minimum input power for PHC, Ibwa, CHC Kwali, and LEA School Mapa are identified as 30 W, 78 W, and 200 W, respectively, as shown in Figures 27 and 28.

Table 21: Pump and PV power required at the three sites

Site	**PHC, Ibwa**		**CHC Kwali**		**LEA School**	
Q_{des}	0.46 gpm	0.10 m^3/hr	2.2 gpm	0.50 m^3/hr	4.6 gpm	1.1 m^3/hr
TDH_{des}	74 ft	23 m	69 ft	21 m	74 ft	22 m
Pump Power	30 W	0.03 kW	78 W	0.08 kW	200 W	0.2 kW
Size of PV array	37.5 W	0.04 kW	98 W	0.1kW	250 W	0.3 kW

The Lorentz PU150 HR-04S-3 Submersible Pump Unit is selected for the PHC Ibwa and CHC Kwali, and the Groundfos-6SQF-2 pump is chosen for LEA School Mapa. These pump models are preferred due to their credibility in the market, ease of operation, and low power consumption at the estimated values of TDH_{des} and Q_{des}. Lorentz and Grundfos are the most preferred and most successful pumps in the Nigerian market (UNICEF, 2016b). Pump curves of several pumps considered for the designs are shown in Appendix F. The pump curve for the selected pumps are shown in Figures 27 and 28. The design flowrates and TDH values for PHC, Ibwa, and LEA School, Mapa are

highlighted in the Figure. 27 and 28. As described in Section 3.1.7.3, the PV panels are sized to account for the losses.

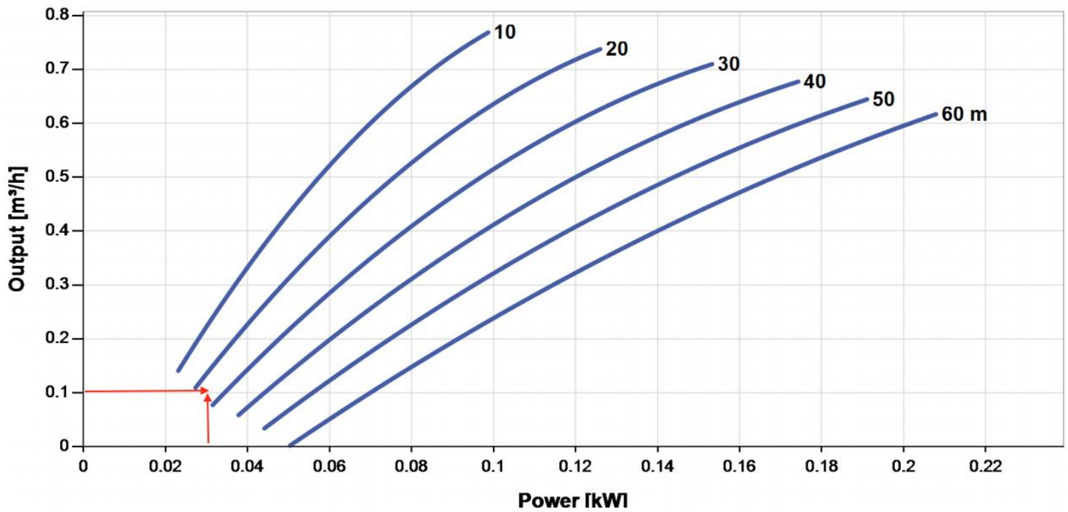


Figure 27: Pump curve of Lorentz PU150 HR-04S-3 submersible pump unit identified for PHC, Ibwa and CHC, Kwali.
(Power requirement of PHC, Ibwa is highlighted in red)

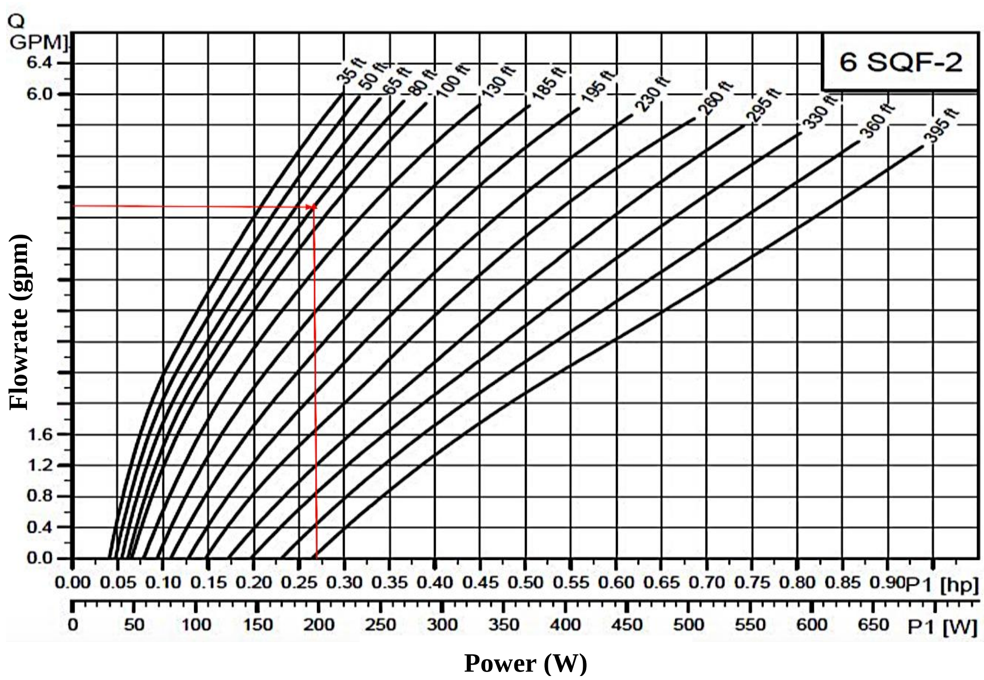


Figure 28: Pump curve of Groundfos-6SQF- 2 identified for LEA School, Mapa.
(Power requirement of LEA, School is highlighted in red)

The size of the PV array is calculated by adding 25% more power to the minimum input power required for the pump (30 x 1.25) for PHC, Ibwa (USDA, 2010).

To minimize the probability of system or component failure over the lifetime of the project, certified components from credible manufacturers are used in the designs. This ensures minimal replacement and maintenance costs for the system. The sizes of PV panels for all sites are also mentioned in Table 21.

4.2. Economic Analysis

This section presents, the summary of the cost of the systems estimated by using two methods as described in Section 3.2.1. One where the system is designed by following a standard design procedure and other when the system is optimized by a model.

4.2.1 Cost estimation

The cost of the system is calculated by adding the cost of the individual components of the system when the system is designed by following a standard procedure. Each system is comprising of a PV module, roof mount, submersible pump, and its accessories, piping, and a storage tank. In addition, the installation and BOS cost also considered to determine the total cost. This cost is assumed to be 40% of the sum of the cost of all components (World Bank, 2018b). . This cost includes the cost of wiring, cable and accessories. Two types of PV modules are selected for the sites, one is used for the cost estimation in the standard design, the other where the system is optimized by the model. This is because the model varies the array size for cost

optimization and the PV module selected for the standard designs are smaller for the array size calculated by the model. In all cases, the modules are selected on the basis of their cost-effectiveness and reliability.

As discussed in the previous section, Lorentz PS2-150 AHR-04S pump is selected for PHC Ibwa and CHC, Kwali as this pump can fulfill the water demand of the sites and can cater more need if required. This is also the smallest pump unit offered by the Lorentz.

Roof mount racking system is considered for the three sites for mounting solar panels. An adequate amount of space is available on the roof of all the PHC, Ibwa and CHC, Kwali as shown in Figure 29, therefore panels will be mounted on the roof of the health center for these two sites

(a) (b) (c)

Figure 29: Proposed area for solar PV installation at (a) PHC, Ibwa (b) CHC, Kwali, (c) LEA School

Panels will be installed on the roof on the storage tank foundation in LEA school Mapa as shown in Figure 29. A Unirac solar mount flush roof mount system is selected for mounting solar panels at all three sites. Roof mounting systems are designed through the Unirac racking system design tool (Detailed design report is at Appendix H). Storex storage tanks are used for providing the storage at the site. A list of all the

system components and their costs are presented in Tables 22, 23, and 24.

Table 22: Cost of components of solar water pumping system for PHC, Ibwa (Including tax and delivery charges)

Component	**Model/type**	**Source**	**Price**
Solar Module	Rich Solar SKU RS-M50W	(Richsolar, 2019)	$74
	Rich Solar 100 W SKURS-M100 W *	(Richsolar, 2019)	$ 90
Pump and Accessories	PS2-150 AHR-04S	Quotation from Lorentz pumps (Appendix H)	$ 1900
Roof mount	Unirac Solar flush mounting system	(UNIRAC, 2019)	$ 85
Piping	PVC	(Frakem, 2018a)	$ 0.23/ft
Storage	Storex, 1500 liters (395 gallons) tank	(Frakem, 2018b)	$ 0.24 /gallon
	Storex, 500 liters (132 gallons) **	(GeePee, 2019)	$0.37/gallon

*Module used in the optimized design for PHC, Ibwa
**Storage tank used in optimized designs

Table 23: Critical design parameters of the system for CHC, Kwali (Including tax and delivery charges)

Component	**Model/type**	**Source**	**Price**
Solar Module	Rich Solar 100 W SKURS-M100 W	(Richsolar, 2019)	$90
	Trina Solar TSM-DDO5A-05 II 305*	(Webosolar, 2019)	$189
Pump and Accessories	PS2-150 AHR-04S	Quotation from Lorentz pumps (Appendix J)	$1900
Roof mount	Unirac Solar flush	(UNIRAC, 2019)	$85
Piping	PVC	(Frakem, 2018a)	$ 0.23/ft
Storage	2 Storex, 3000 liters, 1 GeePee 500 liters (1717 gallons)	(Frakem, 2018b), (GeePee, 2019)	$ 0.24 /gallon
	1 Storex 2000 liters (570 gallons) **	(Frakem, 2018b)	$0.19 gallon

*Module used in the optimized design at CHC Kwali
**Storage tank used in optimized designs

Table 24: Cost of components of solar water pumping system for LEA School Mapa (Including tax and delivery charges)

Component	**Model/type**	**Source**	**Price**
Solar Module	Trina Solar TSM-DDO5A-05 II 305	(Webosolar, 2019)	$189
	Seraphim Solar SRP-340-6MA*	(altestore, 2019)	$295
Pump and Accessories	Grundfos 6 SQF-2	(Solarhome, 2019)	$2054
Roof mount	Unirac Solar flush	(UNIRAC, 2019)	$85
Piping	PVC	(Frakem, 2018a)	$ 0.23/ft
Storage	2 GeePee, 7500 liters (3960 gallons) tank	(Frakem, 2018b)	$ 0.29 /gallon
	Storex 4000 L (1000) gallons) **	(Frakem, 2018b)	$0.22/gallon

*Module used in the optimized design at CHC Kwali
**Storage tank used in optimized designs

The cost of individual components as provided in Tables 22, 23, and 24 are used to determine the initial cost of the system, presented in Table 25. System installation and BOS charges, 40% of the initial cost are included to identify the total cost of the system. The total initial cost of the system is shown in Table 25.

Table 25: Cost estimates of the system considered for standard designs (Inclusive of tax and delivery charges)

Components	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
PV array size (W)	37.5 W	97.5W	250 W
PV array cost ($)	$ 74	$ 90	$189
Pump ($)	$ 1900	$ 1900	$2054
Pole mount cost ($)	$ 85	$ 85	$85
Piping cost ($)	$ 43	$ 90	$44
Storage volume (gallons)	395	1717	3960
Storage cost ($)	$ 97	$378	$1150
Initial cost	$ 2,188	$ 2,543	$ 3,522
Installation and BOS	$ 875	$1018	$1408
Total initial Cost ($)	**$ 3,100**	**$ 3,600**	$ **4,900**

4.2.2 Cost optimization model

As described in Section 3.2.2, this study strives to optimize the cost of the systems by optimizing the sizing of parameters that impact costs, such as the array size and storage tank volume. The model optimizes the storage volume and PV array size to minimize the initial investment cost. The optimized array size and storage volume allow the fulfillment of water demand at the site at any hour during a year. The optimized array size and optimized storage volume as shown in Table 26 are used to identify the optimized total initial cost.

Table 26: Cost estimates of the system considered for optimized designs (Inclusive of tax and delivery charges).

Components	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
Optimized PV array size (W)	100	226	324
Optimized Array Cost ($)	$ 90	$189	$ 295
Optimized storage volume (gallons)	118	570	1000
Optimized Storage cost ($)	$ 46	$ 112	$ 224
Pump cost ($)	$ 1,900	$ 1,900	$ 2,054
Pole mount ($)	$ 84	$ 84	$ 84
Piping ($)	$ 43	$ 90	$ 44
Installation ($)	$ 861	$ 926	$ 1080
Optimized total initial cost ($)	**$ 3000**	**$ 3300**	**$ 3800**

The model increases the array size and reduces the storage volume and the cost of storage. A bigger solar module is used to meet the increase in the array size for the optimized system. The cost of a larger solar module is slightly higher; however, the price per watt is less. More power produced through a larger module increases the flowrate and reduces the size of storage. System installation charges are added to

identify the optimized total cost of the system. This cost is further used for the life cycle cost estimation and the cost-benefit analysis of the pumping systems.

4.2.3 LCC analysis

A life cycle cost analysis is also conducted to identify its cost over life time as described in Section 3.2.3. The life cycle cost identified by adding replacement cost, capital cost, O&M cost, etc. is presented in Table 27. The life cycle cost of the system is used to identify the cost of water as described in Section 3.2.3 is tabulated in Table 27.

Table 27: Life cycle cost of the system

Components	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
Capital cost including installation ($)	$ 3031	$ 3326	$ 3781
Replacement cost ($)	$ 3211	$ 3211	$ 3471
Operation and Maintenance cost ($)	$ 594	$ 652	$ 740
Energy cost ($)	0	0	0
Discount rate	12%	12%	12%
Life cycle cost of water ($)	$ 6,800	$ 7,200	$ 8,000
Cost of pumping water ($/gallon)	0.00624	0.0013	0.0007

4.2.4 Cost-Benefit analysis

For the cost-benefit analysis, before and after solar water pumping installation scenarios are used. The actual cost of water before the installation is zero for these public facilities. However, as discussed above in Section 3.2.4, their current supply does not fully meet their needs. For the analysis presented here, a range of water costs is considered to show low-cost and high-cost scenarios for purchased water that fully meets the needs of the facilities according to recommended values provided by WHO and

discussed in Section 3.2.4. The cost of water, as shown in Table 27, is regarded as the cost of water after the installation of a solar water pumping system.

Based on recommended values from WHO and field survey data from the Schatz Center, it is assumed that the PHC, Ibwa, CHC, Kwali, and LEA School Mapa purchase 120 gallons/day, 560 gallons/day, and 1190 gallons/day of water, respectively, which is their present water demand as identified in Table 12. The price of purchased water varies from $0.002/gallon to $ 0.006/gallon; where, the low cost ($0.002/gallon) is calculated from the cost data reported by other public facilities in Nigeria in the Schatz Center data set and the high cost ($0.006/gallon) is identified from literature (Onyenechere et al., 2012; Schatz Center, 2018). The daily, yearly, and 25-year costs of water are calculated in both low-cost and high-cost scenarios and shown in Table 28 and 29.

Table 28: Cost of purchasing water in the low-cost scenario

	PHC, Ibwa	**CHC, Kwali**	**LEA, School**
Gallons/day	117	563	1194
Cost of commercial water ($/gal)	0.002	0.002	0.002
Daily cost of Water ($)	$ 0.23	$ 1.12	$ 2.38
Yearly cost of water ($)	$ 85.4	$ 411	$ 872
Cost of Water in 25 years ($)	$ 2,800	$ 13,500	$ 28,600

Table 29: Cost of purchasing water in the high-cost scenario

	PHC, Ibwa	**CHC Kwali**	**LEA School**
Gallons/day	117	563	1194
Cost of commercial water ($/gal)	0.006	0.006	0.006
Daily cost of Water ($)	$ 0.702	$ 3.37	$ 7.16
Yearly cost of Water ($)	$ 250	$ 1230	$ 2610
Cost of Water in 25 years ($)	$ 8,400	$ 40,500	$ 85,900

The cost of water in the low-cost scenario, high-cost scenario, and cost with the solar water pumping system is compared and shown in Table 30.

It is seen that, if these public facilities decide to purchase water to meet their water demand completely, the cost of water for PHC Ibwa, CHC Kwali, and LEA School Mapa will vary from $2,800 to $8,400, $13,500 to $40,500, and $28,600 to $85,900, respectively. Whereas, the cost of water with the solar pumping system in 25 years will be $6,800, $7,200, and $8,000, respectively, as presented in Table 27.

Table 30: Results of Cost-Benefit analysis.

Cost of water in 25 years	**PHC, Ibwa**	**CHC Kwali**	**LEA School**
Low cost scenario	$ 2,800	$ 13,500	$ 28,600
High cost scenario	$ 8,400	$ 40,500	$ 85,900
Solar water pumping	$ 6,800	$ 7,200	$ 8,000

The cost of water after the installation of solar water pumping system for CHC Kwali and LEA School Mapa is less than the price of water sourced from commercial channels, and the installation of solar water pumping systems can be financially attractive for these two public facilities. However, the solar water pumping system might not be the preferred alternative to meet the water demand at PHC Ibwa from a financial perspective, as the cost of purchasing water in a low-cost scenario is lower than the solar water pumping system life cycle cost. In the high-cost scenario, the cost is somewhat higher than the solar water pumping life cycle cost. However, the realistic/ actual cost of water for PHC, Ibwa might vary between the cost of water in low-cost and high-cost scenario.

CHAPTER 5: DISCUSSION

This chapter discusses the findings of the solar water pumping system designs for the three public facilities in Nigeria. The results of the analysis indicated that public facilities at CHC Kwali and LEA School Mapa can be equipped with solar water pumping systems, as the cost of water for CHC Kwali, and LEA School Mapa is less after the installation of the solar pumping system. The analysis indicated that the cost of water in 25 years in the low-cost cost scenario for CHC Kwali is $13,500, which is approximately double the life cycle cost of a solar water pumping system. In the high-cost situation, this cost is five times the solar system life cycle cost. Similarly, for LEA School Mapa, the price of water in 25 years in the low-cost cost scenario is $28,600, which is approximately four times the life cycle cost of the solar system. For the high-cost scenario, this cost is ten times the solar system life cycle cost. From the results of this analysis, solar water pumping systems can be recommended for the CHC Kwali and LEA School Mapa sites.

However, this is not the case of PHC, Ibwa. The solar water pumping system may not be the preferred alternative to meet the water demand at PHC Ibwa from a financial perspective, as the cost of purchasing water in a low-cost scenario is less than the cost of a solar water pumping system. In the high-cost situation, the cost of water purchases does exceed the solar system life cycle cost. Although there is some uncertainty due to the range of prices reported for water purchases, procuring water from the nearby

community borehole or purchasing water from other commercial sources may be more economically attractive for PHC, Ibwa.

This study seeks to minimize the barriers of high upfront costs, and borehole failure, as these are key causes of system failures (UNICEF, 2016b). First, the barrier of the high upfront cost of the system is considered. To address this barrier, the design completed in this thesis is based on computer modeling. The cost of the solar water pumping system based on the standard design procedure and the cost based on the optimization model are calculated and compared to ensure the cost-effectiveness of the designs. In the system design completed in this thesis, the difference in the cost of the system based on standard design procedure and the system designed through modeling signifies that appropriate due diligence can enhance the cost-effectiveness of the system.

The model used in the analysis optimized the cost of the system by varying the size of the array and storage capacity and ensuring that the storage never gets empty in a model year. For example, the costs of the systems as per the adopted design method are estimated to be $3,100 $3,600 and $4,900 for PHC Ibwa, CHC Kwali, and LEA School at Mapa, respectively, whereas the optimized costs are $3,000, $3,300 and $3,800, respectively. In other words, the modeling reduces the capital cost of the designs by 1.5%, 9 %, and 23% for the respective systems.

This study also conducts a sensitivity analysis to identify the cost-effectiveness of the designed systems so that the systems can be maintained by the public health facilities. The sensitivity analysis was carried out to identify the impact of storage size on system design and its cost. It suggests that the size of the storage tank impacts the PV system

size. Adding storage capacity can enable a reduction in the size of the solar array, but increasing the storage size beyond its optimum value has a diminishing effect on the PV array size as shown in Figure 30.

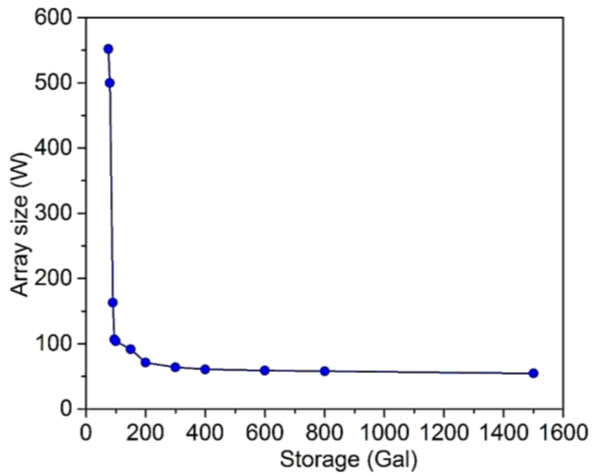


Figure 30: Impact of storage capacity on the PV array size at the PHC Ibwa.

As noted in Figure 30, the PV array size for PHC Ibwa was 550 W for a storage size of 75 gallons. It reduced significantly from 550W to 75 W with an increase in storage size from 75 gallons to 200 gallons. However, the capacity of the PV array is not reduced markedly as the storage size increases from 200 gallons to 1500 gallons. At the upper end of the storage size (1500 gallons), the solar module size is 55 W, and at the lower end (200 gallons) it is 75W. The difference in the PV array size for an increase in storage size from 75 gallons to 200 gallons (an extra 125 gallons) was 479 W, whereas the difference is only 15 W for an additional 1300 gallons.

A similar relationship between storage tank size and PV array size was observed for the other two sites, CHC Kwali and LEA School Mapa (see Figures 31 and 32). An increase in storage capacity at these two sites allowed a substantial reduction in the PV

array size. However, upon reaching the inflection point in the curve, the incremental storage capacity does not have a significant effect on the PV array size.

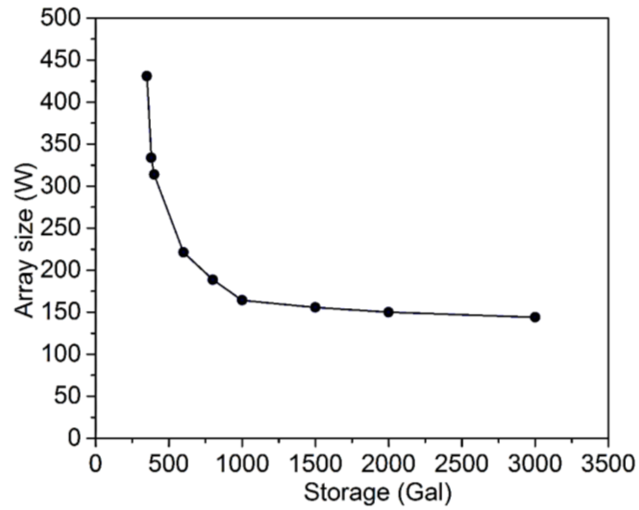


Figure 31: Impact of storage capacity on the PV array size at the CHC Kwali.

This analysis indicates that it is best to have a PV array size that is well matched with the storage size, considering the solar resource and water demand at the site, to ensure the cost-effectiveness of the system according to the needs of the site.

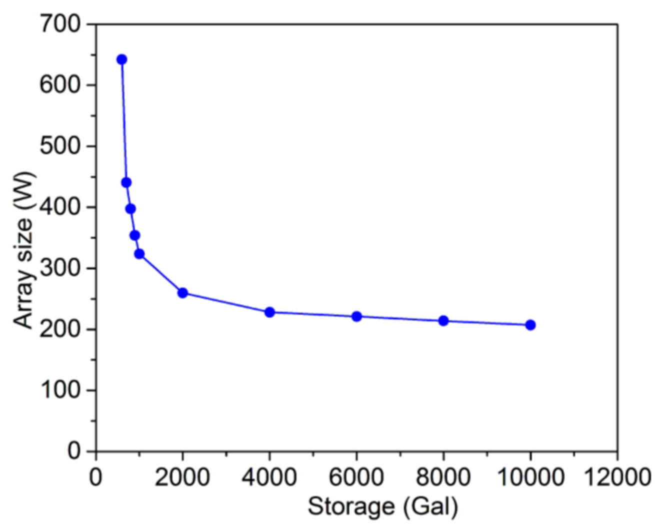


Figure 32: Impact of storage capacity on the PV array size at the LEA School Mapa

The cost-effectiveness of the system is also examined by estimating the cost of the system for different combinations of PV array capacity and storage size as shown in Figures 33, 34, and 35. For example, in PHC Ibwa, a combination of storage capacities of 95gal, 100gal, and 150 gal with PV array sizes of 106W, 103W, and 91 W, respectively, can be the most cost-effective combinations of PV array and storage size. Other combinations such as 600 gal of water storage and 75 W of PV array, 800 gallons of storage and PV array size of 62 W can work, but they will be more expensive. Therefore, the best combination can be defined with the help of the total cost of the system. Figures 33, 34, and 35 indicate that the cost of the system decreases with the increase in storage size. However, after achieving the optimum point, the cost starts increasing with further increases in storage size.

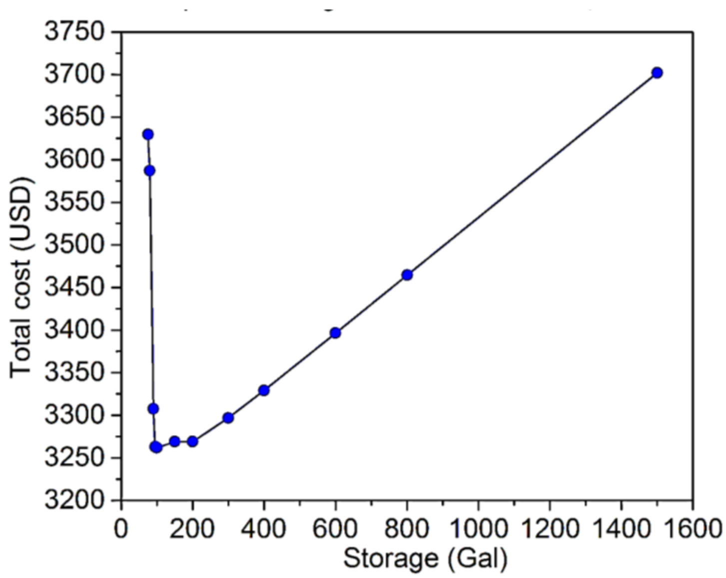


Figure 33: Impact of storage capacity on system cost at PHC, Ibwa.

The system can be designed for any combination of storage and PV size on this curve, but the least cost option is the most cost-effective design combination. For

example, the cost of the system for PHC, Ibwa with storage capacities of 600 gallons and a PV array size of 75 W is estimated to be $3,390. However, the most cost-effective design will have a storage capacity of 118 gallons and a PV size of 100W with a total cost of $3,030.

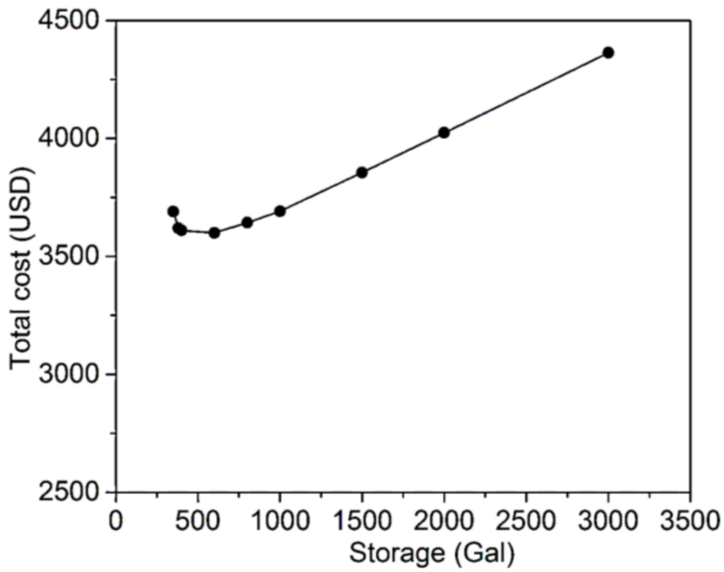


Figure 34: Impact of storage capacity on system cost at CHC, Kwali.

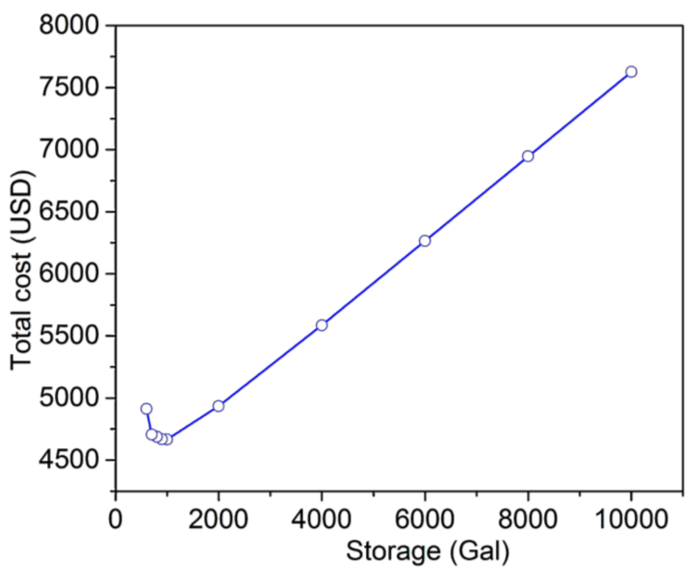


Figure 35: Impact of storage capacity on system cost at LEA School, Mapa

Similarly, for CHC Kwali and LEA School, Mapa, the most cost-effective combinations of storage capacity and PV array size are identified as 226 W and 570 gallons and 324 W and 1000 gallons, respectively.

Second primary cause of water pumping system failures in Nigeria is failure of boreholes (UNICEF, 2016b). The yield of the boreholes considered for the facilities in this design is calculated and analyzed. The thesis verifies the suitability of each borehole and its capabilities to provide enough water for the sites. The relevance of boreholes is also dependent on the size of the pump and the expected volume of water to be pumped. The design ensures that the expected amount of water needed to be pumped to meet the demand of the sites is considerably less than the maximum flow rate the borehole can sustain for a few days based on pump test results presented in Table 14.

The analysis indicates the facilities may choose to opt for the installation of a solar water pumping system instead of deciding to buy water through commercial sources to meet their water demand completely. However, PHC, Ibwa, with its low water demand, might not want to invest in a solar water pumping system as the cost of purchased water is significantly less than the price of water from the solar water pumping system. The relationship between the cost per gallon of water from a solar system and the water demand for the sites considered in the study is shown in Figure 36.

Apart from the cost of the storage tank and array size, the cost of the water pump also plays an important role. The pumps selected for the particular designs are chosen specifically for the sites according to their water demand and borehole characteristics. Since the water demand values for PHC Ibwa and CHC Kwali are shallow and can be

met with a small design flow rate given the solar resource available at the sites, small pumps were chosen for the sites.

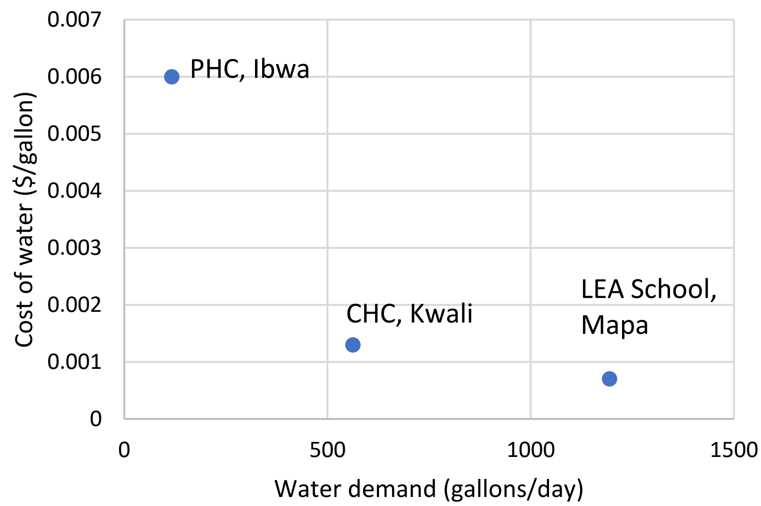


Figure 36: Impact of water demand on the cost of water ($/gallon) for solar water pumping

The Lorentz pump chosen for both sites is the smallest pump by Lorentz. This pump is the smallest model made by the pump manufacturing companies such as Grundfos, Lorentz, and Shurflo. This pump can easily provide the designed flow rate of 0.46 gpm and 2.2 gpm from the required head of 74 ft and 167 ft for PHC Ibwa and CHC Kwali, respectively. It can obtain up to 3.5 gpm of water from 200 ft of head. This pump can easily produce more water if the facility decides to provide water to the nearby community members by adding extra storage capacity. Similarly, the Grundfos pump chosen for the LEA School at Mapa can produce 6.5 gpm of flowrate from 300ft of water in comparison to the design flowrate of 4.75 gpm and the design TDH of 80 ft.

CHAPTER 6: CONCLUSION

The findings of the study show that the public facilities in rural locations in the FCT region of Nigeria can be equipped with the solar water pumping systems to fulfill their water needs from a technical perspective. From a financial perspective, solar water pumping is an excellent alternative to meet the water demand of the public facilities with small and medium water demands, but it may not be the preferred approach for facilities with very low (micro) water demand such as PHC, Ibwa.

Facilities with small and medium water demand can choose to invest in a solar water pumping system rather than purchasing water through a commercial source, as the water purchases may be more expensive over time than getting water from the solar water pumping system. This is mainly due to the availability of abundant sunshine and groundwater throughout the year. With the high solar insolation, solar-powered water pumps can be considered an appropriate option for water delivery systems in public facilities located in rural locations of the state.

From the results of the cost-benefit analysis, it is identified that if the facilities decide to buy water to meet their demand completely, the cost of purchasing water from vendors in 25 years will be $13,500 for CHC, Kwali and $28,600 for LEA School Mapa. This cost is more than double and three times the cost of getting water from a solar water pumping system for the two sites, which had life cycle costs of $7,200 and $8,000, respectively. However, for PHC Ibwa with a micro level water demand, the cost of water

purchased from commercial sources at $2,800 is approximately half of the life cycle cost of a solar water pumping system, $6,800.

It is evident from the results that the cost of water decreases with the increase in system size and with increased demand up to a medium level. Since large systems are not analyzed in this thesis, it is beyond the scope of this thesis to comment on solar water pumping solutions for sites with large water demand.

The systems designed and modeled in the thesis can be used as a reference for replication at other rural public facilities. However, the modeling conducted is specific to a specific location, pump model, and system configuration. The fourth power polynomial model used to identify the flow rate of the pump at a given TDH and input power can be used, but the constants used in the model should be updated for each case as the performance of different pumps varies significantly. The hourly performance of a pump identified in the hourly modeling also varies with the solar insolation. As a result, hourly solar insolation for the location under study must be determined to use this model. Since the system designs in the study are aligned with the National Water Supply and Sanitation Policy of the Nigerian Government, policymakers, and appropriate water authorities in FCT State may decide to provide solar water pumping facilities to one or more of these public facilities.

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APPENDICES

APPENDIX A: Detailed site survey forms

This appendix contains detailed site survey forms for PHC Ibwa, CHC, Kwali and LEA School Mapa. These forms are used to obtain information related to the sites such as number of staffs at the site, number of days the facilities open in a week, number of hours it remains open in a day, number of maternal deliveries it handles and what type of activities take place in a general day in the facilities. Tables A.1, A.2, and A.3, below, show the required information about PHC Ibwa, CHC Kwali, and LEA School Mapa. The data were collected by the Schatz Energy Research Center with support from the Federal Ministry of Power, Works, and Housing of Nigeria during fieldwork in 2017 and 2018.

Table A.1. Detailed site survey for PHC, Ibwa

Auditing Team Record				
Name of auditor(s)	Olakunle Owoeye Edward Micah			
Date of audit	18.12.2017			
Time start of audit/interview	11:10AM			
Time end of interview/audit	1:35PM			
Basic Information				
Facility type	Health Clinic			
Location of facility	**Country**	**State**	**District**	**Nearest trade center**
	Nigeria	FCT	Gwagwalada	Dukpa market
Name(s) of people contacted prior to site visit	Mr. Aliyu Haruna			
Corresponding people's titles	In Charge			

Auditing Team Record				
Facility name	Ibwa 1 PHC			
Facility level/tier/type	Primary Health Care			
Dust conditions (Observe the environment/ask if it's rainy season)	Not significant			
GPS coordinates (Detect with device upon arrival)	**Latitude (record as many digits as possible, at least 5 decimals)**		**Longitude (record as many digits as possible, at least 5 decimals)**	
	9.06371		7.05874	
Name(s) of respondent	Mr. Aliyu Haruna			
Corresponded during current visit or past visit?	Current visit			
Respondent(s) relationship(s) with facility (Title /Position)	In Charge			
Contact email				
Contact phone number	2348118305931			
Name and title of staff in charge if different from respondent	NA			
Number of buildings in the facility complex	1			
Number of staff present	**Full Time/ Permanent Staff**	**Support Staff**	**Number of staffs present at time of site visit**	**Number of staff that live on site**
	3			
Opening time of facility per day	7:00 AM			
Closing time of facility per day	4:00 PM			
Is the facility staffed and open for emergencies at night?	Yes			
Number of days open in a week	7			
Holidays closed per year	0			
Hours open per day	9			
Hours open per week	63			
Hours of operation per year	3285			
FOR SCHOOLS:				
Is it a day or boarding school?				
Number of pupils present				

Auditing Team Record				
If boarding, how many pupils live on site?				
What entity is responsible for the school affairs?				
FOR HEALTH CLINICS:				
Service(s) provided (Choose all that apply)	**Yes/No**			
Antenatal (ANC)	**Yes**			
Delivery	**Yes**			
Family Planning	**Yes**			
Health Education	**No**			
HIV Testing	**Yes**			
HIV Treatment	**No**			
Immunization	**Yes**			
Laboratory	**Yes**			
Malaria	**Yes**			
Minor Ailment / Injury	**Yes**			
Nutrition / Food	**No**			
STD Testing	**Yes**			
Tuberculosis (TBL Center)	**No**			
Average number of patients served per day (average over last quarter)	7			
If available: How many people live within approx. 5 km (1 hour walk) of the facility?	3000			
Number of beds present	4			
If offer maternal services, number of deliveries per month	3			
FOR OTHER FACILITIES:				
Number of people served				
What entity is responsible for the facility?				
Other general notes on facility size and scope				

Table A.2 Detailed site survey for Kwali, CHC

Auditing Team Record				
Name of auditor(s)	Olakunle Owoeye and Edward Micah Maku			
Date of audit	20-Feb-18			
Time start of audit/interview	11:15 AM			
Time end of interview/audit	3:10 PM			
Basic Information				
Facility type	Health Clinic			
Location of facility	**Country**	**State**	**District**	**Nearest trade center**
	Nigeria	FCT	Kwali	
Name(s) of people contacted prior to site visit	Gideon			
Corresponding people's titles	Doctor			
Facility name	Kwali CHC			
Facility level/tier/type	Comprehensive Health Care			
Dust conditions (Observe the environment/ask if it's rainy season)	not significant			
GPS coordinates (Detect with device upon arrival)	**Latitude (record as many digits as possible, at least 5 decimals)**		**Longitude (record as many digits as possible, at least 5 decimals)**	
	8.8174		7.03242	
Name(s) of respondent	Hussaini Lawal	mrs elizabethh gakwoi		
Corresponded during current visit or past visit?	Past visit	Current visit		
Respondent(s) relationship(s) with facility (Title /Position)	Consultant CHO and BSC Environmental	In charge		
Contact email	princelhussaini@gmail.com			
Contact phone number	8069835959	8036930987		
Name and title of staff in charge if different from respondent				
Number of buildings in the facility complex	8			

Auditing Team Record				
Number of staff present	**Full Time/ Permanent Staff**	**Support Staff**	**Number of staff present at time of site visit**	**Number of staff that live on site**
	28	7	20	
Opening time of facility per day	8:00 AM			
Closing time of facility per day	6:00 PM			
Is the facility staffed and open for emergencies at night?				
Number of days open in a week	7			
Holidays closed per year	0			
Hours open per day	10			
Hours open per week	70			
Hours of operation per year	3650			
FOR SCHOOLS:				
Is it a day or boarding school?				
Number of pupils present				
If boarding, how many pupils live on site?				
What entity is responsible for the school affairs?				
FOR HEALTH CLINICS:				
Service(s) provided (Choose all that apply)	**Yes/No**			
Antenatal (ANC)	**Yes**			
Delivery	**Yes**			
Family Planning	**Yes**			
Health Education	**Yes**			
HIV Testing	**Yes**			
HIV Treatment	**No**			
Immunization	**Yes**			
Laboratory	**Yes**			
Malaria	**Yes**			
Minor Ailment / Injury	**Yes**			
Nutrition / Food	**Yes**			
STD Testing	**Yes**			
Tuberculosis (TBL Center)	**No**			
Other				

Auditing Team Record				
Average number of patients served per day (average over last quarter)	35			
If available: How many people live within approx. 5 km (1 hour walk) of the facility?	4000			
Number of beds present	8			
If offer maternal services, number of deliveries per month	3			
FOR OTHER FACILITIES:				
Number of people served				
What entity is responsible for the facility?				
Other general notes on facility size and scope				

Table A.3 Detailed site survey of LEA School Mapa

Auditing Team Record					
Name of auditor(s)	Olakunle Owoeye Edward Micah				
Date of audit	27-Nov-17				
Time start of audit/interview	10:35AM				
Time end of interview/audit	12:35 PM				
Basic Information					
Facility type	School				
Location of facility	**Country**	**State**	**District**	**Nearest trade center**	
	Nigeria	FCT	Bwari	Mbape mini market	
Name(s) of people contacted prior to site visit					
Corresponding people's titles					
Facility name	LEA Primary School Mapa				
Facility level/tier/type	Primary School				
Dust conditions (Observe the environment/ask if it's rainy season)	significant in the area				
GPS coordinates (Detect with device upon arrival)	**Latitude (record as many digits as possible, at least 5 decimals)**		**Longitude (record as many digits as possible, at least 5 decimals)**		
	9.15971		7.48049		
Name(s) of respondent	Mrs Benedict Ofuegbu				
Corresponded during current visit or past visit?	Current visit				
Respondent(s) relationship(s) with facility (Title /Position)	Head Teacher				
Contact email					
Contact phone number	XXXXXXXXXXX				
Name and title of staff in charge if different from respondent					
Number of buildings in the facility complex	7				
Number of staff present	**Full Time/ Permanent Staff**	**Support Staff**	**Number of staff present at time of site visit**	**Number of staff that live on site**	
	3	2	5	0	

Auditing Team Record				
Opening time of facility per day	8:30 AM			
Closing time of facility per day	1:30 PM			
Is the facility staffed and open for emergencies at night?	No			
Number of days open in a week	5			
Holidays closed per year	9			
Hours open per day	5			
Hours open per week	25			
Hours of operation per year	1271			
FOR SCHOOLS:				
Is it a day or boarding school?	Day			
Number of pupils present	311			
If boarding, how many pupils live on site?				
What entity is responsible for the school affairs?	UBEB,Community/PTA			
FOR HEALTH CLINICS:				
Service(s) provided (Choose all that apply)	**Yes/No**			
Antenatal (ANC)				
Delivery				
Family Planning				
Health Education				
HIV Testing				
HIV Treatment				
Immunization				
Laboratory				
Malaria				
Minor Ailment / Injury				
Nutrition / Food				
STD Testing				
Tuberculosis (TBL Center)				
Other				
Average number of patients served per day (average over last quarter)				

Auditing Team Record				
If available: How many people live within approx. 5 km (1 hour walk) of the facility?				
Number of beds present				
If offer maternal services, number of deliveries per month				
FOR OTHER FACILITIES:				
Number of people served				
What entity is responsible for the facility?				
Other general notes on facility size and scope				

APPENDIX B: Pumping test results

This appendix contains the details of the boreholes, the pumping tests performed at the site, and the results of regression analysis conducted on the pump test data to identify the number of days the borehole can sustain the maximum flow rate. This appendix also shows the calculation of recovery rates for the boreholes. Tables B.1, B.4, and B.7 show the information about the borehole for PHC, Ibwa, CHC, Kwali and LEA School Mapa respectively. Tables B.3, B.6, and B.9 show the pumping test results for PHC Ibwa, CHC Kwali, and LEA School Mapa.

Table B.1 Site Parameters of PHC, Ibwa

Site Name:	**IBWA 1 Hand Pump**
Date:	14-02-2018
Type of test	Draw down and recovery test
GPS coordinates of well (latitude, longitude):	9.0637, 7.106
Well depth	111
Static Water level	24
Surface Elevation	614
Well inner diameter	o.5
Pump Used	0.5hp, 1hp, and 1.5hp

Recovery Flowrate calculation for PHC Ibwa

Recovery flow rate is calculated are using the equation given below. Table B.2 presents the time of the day and water elevation measured at that time of recovery test conducted at PHC, Ibwa. The water level estimated by regression models presented in Table 3 in chapter 3 are also shown in the table below.

Table B.2. Recovery test results from the regression model for PHC, Ibwa

Days	Time of day	Water elevation	Estimated water elevation
0.5938	2:15:00 PM	570	569.87
0.5972	2:20:00 PM	569.7	569.8
0.6076	2:35:00 PM	569.5	569.6
0.6146	2:45:00 PM	569.4	569.46

Table B.3. Pumping test results of PHC, Ibwa

Time		**Water level**	**Type of pump**	**Flow rate**		**Remarks**
HR	Min	ft	HP	L/s	gpm	
1	20	24	0.5	0.68	10.8	Started with 0.5hp looking at the well-being shallow, the water was very dirty with rusty color
1	25	34	0.5	0.65	10.3	Carried out another flow metering, measured draw down after 5 mins from start of pumping
1	30	44	0.5	0.66	10.5	Measured with flow meter attached to riser pipe
1	35	44	0.5	0.66	10.5	Steady level
1	40	44.2	0.5	0.66	10.5	Steady level
1	48	44.5	0.5	0.66	10.5	
1	50	44.3	0.5	0.66	10.5	
2	15	44	1	0.86	13.6	Still steady
2	20	44.3	1	0.86	13.6	Still steady
2	35	44.5	1	0.86	13.6	Still steady
2	45	44.6	1	0.86	13.6	Still steady
2	50	44.5	1	0.86	13.6	Still steady
3	0	44	1	0.86	13.6	Still steady
3	10	44.3	1	0.86	13.6	Still steady, semi clean water
3	20	44.2	1	0.86	13.6	Still steady, semi clean water
3	30	44.3	1	0.86	13.6	Still steady, semi clean water
3	45	44.3		0.86	13.6	Steady, semi clean water, sample water taken to lab
4	0	29.7	1.5	1	15.9	Just before pump was started
4	10	48	1.5	1	15.9	Water a bit rusty
4	15	47.5	1.5	1	15.9	Semi clean
4	20	44.5	1.5	1		Generator stopped, pump capacity too much for it.
4	25	40	1.5	1		Recovery test started
4	30	33	1.5	1		Continued recovery measurement
4	35	30	1.5	1		Continued recovery measurement
4	45	29	1.5	1		Continued recovery measurement
5	0	28.3	1.5	1		Stopped recovery measurement

Recovery Flow rate: Volume /change in time, Volume = Area * Change in height

Area = $\pi * r^2$; Change in height = (Water level at the start of recovery test- Water level at the end of recovery test.)

Change in time = time at the start of recovery test- time at the end of recovery test

Minimum water elevation = Surface elevation – Depth of well +Screen height

= 614-111+40 = 543ft

No of days = (543-581.64)/ 19.819 = 2 days

Screen height is the level of water until the water extracted (Water extracted during test until within 40 ft of bottom of well).

Table B.4 Site parameters of CHC, Kwali

Site Name:	**Kwali CHC**
Date:	20-02-2018
Type of test	Draw down and recovery test
GPS coordinates of well (latitude, longitude):	8.80112,7.072
Well depth(ft)	105
Static Water level(ft)	21.8
Surface Elevation(ft)	756
Well inner diameter (ft)	0.5
Pump used	1.5HP

Recovery calculation for CHC, Kwali

Table B.5 presents the time of the day and water elevation measured at the time of the recovery test conducted at CHC, Kwali. The water elevation estimated with the help of regression models presented in the Table 3 in chapter 3 are also shown in the Table B.5.

Table B.5. Recovery test results from regression model for CHC, Kwali

Days	Time of day	Water elevation (ft)	Estimated water elevation (ft)
0.6153	2:46:00 PM	722.5	722.39419
0.625	3:00:00 PM	722.1	721.495
0.6271	3:03:00 PM	721.6	721.30232
0.6285	3:05:00 PM	721.1	721.17386
0.6306	3:08:00 PM	721	720.98118
0.6319	3:10:00 PM	721	720.85272
0.6333	3:12:00 PM	720.6	720.72427
0.6354	3:15:00 PM	720.35	720.53158
0.6368	3:17:00 PM	720.1	720.40313
0.6389	3:20:00 PM	719.9	720.21044
0.641	3:23:00 PM	719.75	720.01776
0.6424	3:25:00 PM	719.6	719.88931
0.6444	3:28:00 PM	719.45	719.69662
0.6458	3:30:00 PM	719.43	719.56817
0.6479	3:33:00 PM	719.26	719.37548
0.6493	3:35:00 PM	719.2	719.24703
0.6514	3:38:00 PM	719.1	719.05434
0.6528	3:40:00 PM	718.9	718.92589
0.6549	3:43:00 PM	718.8	718.73321
0.6563	3:45:00 PM	718.61	718.60475
0.6583	3:48:00 PM	718.55	718.41207
0.6604	3:51:00 PM	718.5	718.21938
0.6618	3:53:00 PM	718.44	718.09093

Minimum water elevation = Surface elevation – Depth of well +Screen height.

Table B.6 shows the pumping test results for CHC, Kwali

Table B.6 Pumping test results of CHC, Kwali

Time		**Water level**	**Pump type**	**Flowrate**		**Remarks**
Hr	Min	ft	HP	L/s	gpm	
2	22	22	1.5	1.24	20	Water is clean.
2	27	23	1.5	1.24	20	static water level reduced
2	32	25	1.5	1.24	20	static water level reduced
2	41	31	1.5	1.24	20	static water level reduced
2	43	31	1.5	1.24	20	static water level reduced
2	44	32	1.5	1.24	20	static water level reducing at small rate
2	45	32	1.5	1.24	20	static water level reducing at small rate
2	46	34	1.5	1.24	20	static water level reducing at small rate
3	0	34	1.5	1.24	20	static water level reducing at small rate
3	3	34	1.5	1.24	20	static water level reducing at small rate
3	5	35	1.5	1.24	20	static water level reducing at small rate
3	8	35	1.5	1.24	20	static water level reducing at small rate
3	10	35	1.5	1.24	20	static water level reducing at small rate
3	12	35	1.5	1.24	20	static water level reducing at small rate
3	15	36	1.5	1.24	20	static water level reducing at small rate
3	17	36	1.5	1.24	20	static water level reducing at small rate
3	20	36	1.5	1.24	20	static water level reducing at small rate
3	23	36	1.5	1.24	20	static water level reducing at small rate
3	25	36	1.5	1.24	20	static water level reducing at small rate
3	28	37	1.5	1.24	20	static water level reducing at small rate
3	30	37	1.5	1.24	20	static water level reducing at small rate
3	33	37	1.5	1.24	20	static water level reducing at small rate
3	35	37	1.5	1.24	20	static water level reducing at small rate
3	38	37	1.5	1.24	20	static water level reducing at small rate
3	40	37	1.5	1.24	20	static water level reducing at small rate
3	43	37	1.5	1.24	20	static water level reducing at small rate
3	45	37	1.5	1.24	20	static water level reducing at small rate
3	48	37	1.5	1.24	20	static water level reducing at small rate
3	51	38	1.5	1.24	20	static water level reducing at small rate
3	53	38	1.5	1.24	20	static water level reducing at small rate
3	55	36	1.5		0	Stopped draw down test
4	0	31	1.5		0	Started recovery test measurement
4	3	30	1.5		0	Continued recovery test measurement
4	4	29	1.5		0	Continued recovery test measurement

Time		Water level	Pump type	Flowrate		Remarks
4	5	29	1.5		0	Continued recovery test measurement
4	6	28	1.5		0	Continued recovery test measurement
4	7	27	1.5		0	Continued recovery test measurement
4	8	25	1.5		0	Continued recovery test measurement
4	13	25	1.5		0	Continued recovery test measurement
4	18	25	1.5		0	Continued recovery test measurement
4	23	24	1.5		0	Continued recovery test measurement

Table B.7 Site parameters of LEA School, Mapa

Site Name:	**LEA School Mapa**
Date:	16-02-2018
Type of test	Draw down and recovery test
GPS coordinates of well (latitude, longitude):	8.80112,7.481
Well depth(ft)	118
Static Water level(ft)	20.4
Surface Elevation(ft)	2011
Well inner diameter (ft)	0.66
Pump used	1.5HP

Recovery calculation for LEA School Mapa

This section presents the detailed calculation performed to identify the recovery rate of the boreholes at the sites. Table B.8 presents the time of the day and water elevation measured ate the time of the recovery test for LEA School Mapa.

Table B.8 Recovery test results from regression model for LEA School, Mapa

Days	**Time of day**	**Water elevation (ft)**	**Estimated Water elevation (ft)**
0.5486	1:10:00 PM	1986.10	1986.12
0.5500	1:12:00 PM	1986.10	1986.10
0.5514	1:14:00 PM	1986.08	1986.08
0.5521	1:15:00 PM	1986.05	1986.07
0.5556	1:20:00 PM	1986.03	1986.02
0.5576	1:23:00 PM	1986.00	1985.99
0.5611	1:28:00 PM	1985.95	1985.94
0.5639	1:32:00 PM	1985.90	1985.90
0.5660	1:35:00 PM	1985.85	1985.87
0.5694	1:40:00 PM	1985.82	1985.82
0.5729	1:45:00 PM	1985.78	1985.77
0.5764	1:50:00 PM	1985.74	1985.72
0.5799	1:55:00 PM	1985.70	1985.67
0.5833	2:00:00 PM	1985.66	1985.62
0.5903	2:10:00 PM	1985.45	1985.52
0.5972	2:20:00 PM	1985.30	1985.42
0.6042	2:30:00 PM	1985.26	1985.32
0.6111	2:40:00 PM	1985.13	1985.22
0.6181	2:50:00 PM	1985.00	1985.12
0.6250	3:00:00 PM	1984.83	1985.02
0.6319	3:10:00 PM	1984.70	1984.92
0.6389	3:20:00 PM	1984.65	1984.82
0.6458	3:30:00 PM	1984.61	1984.72
0.6493	3:35:00 PM	1984.59	1984.67
0.6563	3:45:00 PM	1984.54	1984.57

Minimum water elevation = Surface elevation – Depth of well +Screen height

= 2011-118+ 40 = 1933 ft

No of days = (1933- 1994)/ (- 14.37) = 4 days.

Table B.9 Pumping test results of LEA School, Mapa

Time		Water level	Pump type	Flowrate		Remarks
Hr.	Min		(HP)	L/S	gpm	
1	5	20.4	1.5	1.38	22	
1	7	22.3	1.5	1.38	22	static water level reduced
1	10	24.9	1.5	1.38	22	static water level reduced
1	12	24.9	1.5	1.38	22	static water level reduced
1	14	24.92	1.5	1.38	22	static water level reduced
1	15	24.95	1.5	1.38	22	static water level reduced
1	20	24.97	1.5	1.87	30	static water level reduced
1	23	25	1.5	1.87	30	water level kept reducing at a proportional way
1	28	25.05	1.5	1.87	30	water level kept reducing at a proportional way
1	32	25.1	1.5	1.87	30	water level kept reducing at a proportional way
1	35	25.15	1.5	1.87	30	water level kept reducing at a proportional way
1	40	25.18	1.5	0.68	11	water level kept reducing at a proportional way
1	45	25.22	1.5	0.68	11	water level kept reducing at a proportional way
1	50	25.26	1.5	0.68	11	water level kept reducing at a proportional way
1	55	25.3	1.5	0.68	11	water level kept reducing at a proportional way
2	0	25.34	1.5	0.68	11	water level kept reducing at a proportional way
2	10	25.55	1.5	0.68	11	water level kept reducing at a proportional way
2	20	25.7	1.5	0.68	11	water level kept reducing at a proportional way
2	30	25.74	1.5	0.68	11	water level kept reducing at a proportional way
2	40	25.87	1.5	0.68	11	water level kept reducing at a proportional way
2	50	26	1.5	0.68	11	water level kept reducing at a proportional way
3	0	26.17	1.5	0.68	11	water level kept reducing at a proportional way
3	10	26.3	1.5	0.68	11	water level kept reducing at a proportional way
3	20	26.35	1.5	0.68	11	water level kept reducing at a proportional way
3	30	26.39	1.5	0.68	11	water level kept reducing at a proportional way
3	35	26.41	1.5	0.68	11	water level kept reducing at a proportional way
3	45	26.46	1.5	0.68	11	water level kept reducing at a proportional way
3	50	26.49	1.5	0.68	11	water level kept reducing at a proportional way
4	0	26.52	1.5	0.68	11	water level kept reducing at a proportional way
4	10	26.62	1.5	0.68	11	water level kept reducing at a proportional way
4	15	26.66	1.5	0.68	11	water level kept reducing at a proportional way
4	20	26.73	1.5	0.68	11	water level kept reducing at a proportional way
4	25	26.76	1.5	0.68	11	water level kept reducing at a proportional way
4	30	26.8	1.5	0.68	11	water level kept reducing at a proportional way
4	35	26.84	1.5	0.68	11	water level kept reducing at a proportional way
4	40	26.97	1.5	0.68	11	water level kept reducing at a proportional way
4	45	27.04	1.5	0.68	11	water level kept reducing at a proportional way

Time		Water level	Pump type	Flowrate		Remarks
4	50	27.15	1.5	0.68	11	water level kept reducing at a proportional way
4	55	27.28	1.5	0.68	11	water level kept reducing at a proportional way
5	5	23.82	1.5		0	Started recovery test measurement
5	6	23.8	1.5		0	Started recovery test measurement
5	7	23.77	1.5		0	Started recovery test measurement
5	9	23.6	1.5		0	Started recovery test measurement
5	10	23.5	1.5		0	Started recovery test measurement
5	20	23.2	1.5		0	Started recovery test measurement
5	25	23.1	1.5		0	Started recovery test measurement
5	30	23.05	1.5		0	Stopped recovery test measurement

APPENDIX C: Solar resource feasibility report

Appendix C includes solar resource feasibility reports for PHC Ibwa, CHC Kwali, and LEA School Mapa. The reports identify the solar insolation at the sites. The solar access averages in two skylines identified by Solometric Suneye tool are included in the reports shown in this section.

C.1 Solar Resource feasibility at PHC, Ibwa

This section shows the solar feasibility of PHC Ibwa. The feasibility is recorded with the help of Solometric Suneye tool for two skylines as shown in this section.

Session Properties

Name	IBWA PHC GWAGWALADA
Creation Date	10/9/2017 16:50
Note	sunny sky
Location	9.1°N, 7.1°E Mag Dec: 0.8°W Time Zone: GMT-12:00

Solar access averages of 2 skylines in this session

Skylines Averaged: Sky01, Sky02

Annual	May-Oct	Nov-Apr
97%	98%	96%

Sky01 -- 10/9/2017 16:59 -- south

Panel Orientation: Tilt=21° -- Azimuth=206° -- **Skyline Heading=301°**
GPS Location: Latitude=9.06362°N -- Longitude=7.05858°E
Solar Access: Annual: 99% -- Summer (May-Oct): 99% -- Winter (Nov-Apr): 99%

Sky02 -- 10/9/2017 17:02 -- East

Panel Orientation: Tilt=21° -- Azimuth=206° -- **Skyline Heading=153°**
GPS Location: Latitude=9.06370°N -- Longitude=7.05864°E
Solar Access: Annual: 95% -- Summer (May-Oct): 97% -- Winter (Nov-Apr): 93%

C.2 Solar Resource feasibility at CHC Kwali

This section shows the solar feasibility of CHC, Kwali. The feasibility is recorded with the help of Solometric Suneye tool for two skylines as shown in this section.

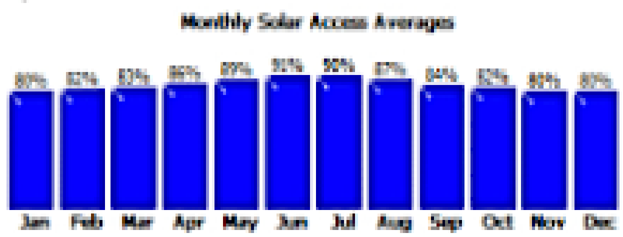
Session Properties

Name	kwali chc
Creation Date	9/29/2017 22:09
Note	evening clear sky
Location	8.8°N, 7.0°E Mag Dec: 0.9°W Time Zone: GMT-12:00

Solar access averages of 2 skylines in this session

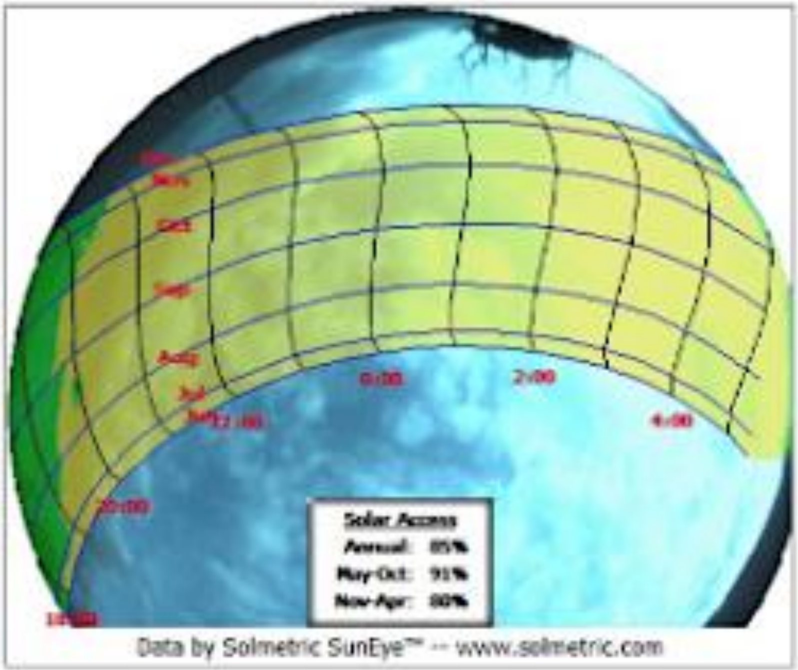
Skylines Averaged: Sky01, Sky02

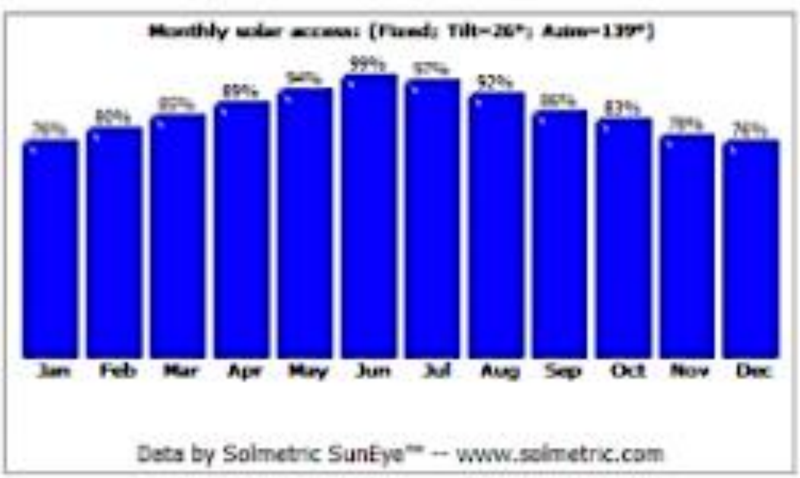
Annual	May-Oct	Nov-Apr
84%	87%	82%



Sky01 -- 9/29/2017 22:30 -- south

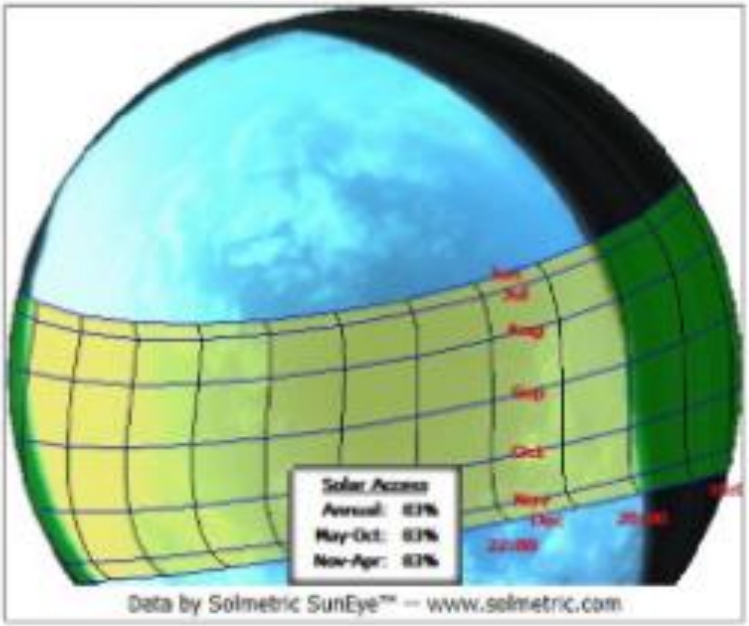
Panel Orientation: Tilt=26° -- Azimuth=139° -- **Skyline Heading=194°**
GPS Location: Latitude=8.81738°N -- Longitude=7.03244°E
Solar Access: Annual: 85% -- Summer (May-Oct): 91% -- Winter (Nov-Apr): 80%

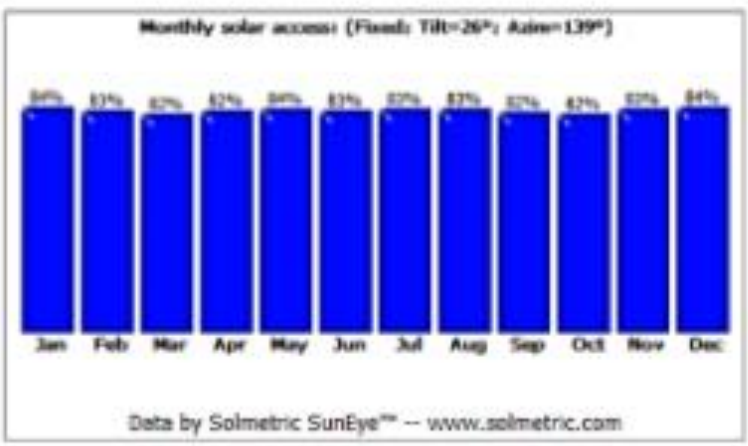




Sky02 -- 9/29/2017 22:39 -- west

Panel Orientation: Tilt=26° -- Azimuth=139° -- **Skyline Heading=10°**
GPS Location: Latitude=8.81736°N -- Longitude=7.03254°E
Solar Access: Annual: 83% -- Summer (May-Oct): 83% -- Winter (Nov-Apr): 83%





C.3 Solar Resource feasibility at LEA School, Mapa

This section shows the solar feasibility of LEA School Mapa. The feasibility is recorded with the help of Solo metric Sun eye tool for two skylines as shown in this section.

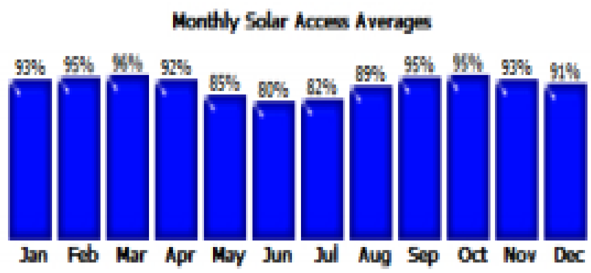
Session Properties

Name	MAPA PHC and LEA
Creation Date	11/27/2017 11:54
Note	(none)
Location	9.2°N, 7.5°E Mag Dec: 0.7°W Time Zone: GMT+01:00

Solar access averages of 4 skylines in this session

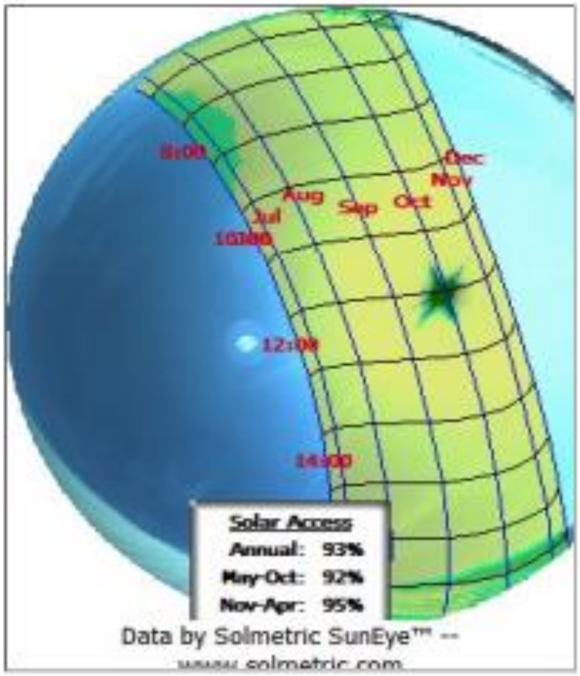
Skylines Averaged: Sky01, Sky02, Sky03, Sky04

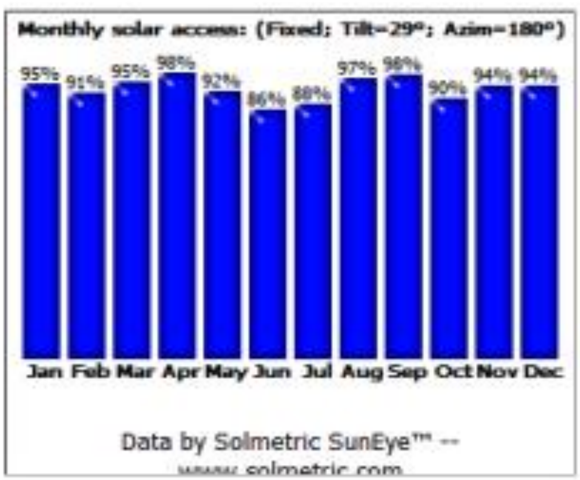
Annual	May-Oct	Nov-Apr
91%	89%	93%



Sky01 -- 11/27/2017 12:11 -- LEA due south

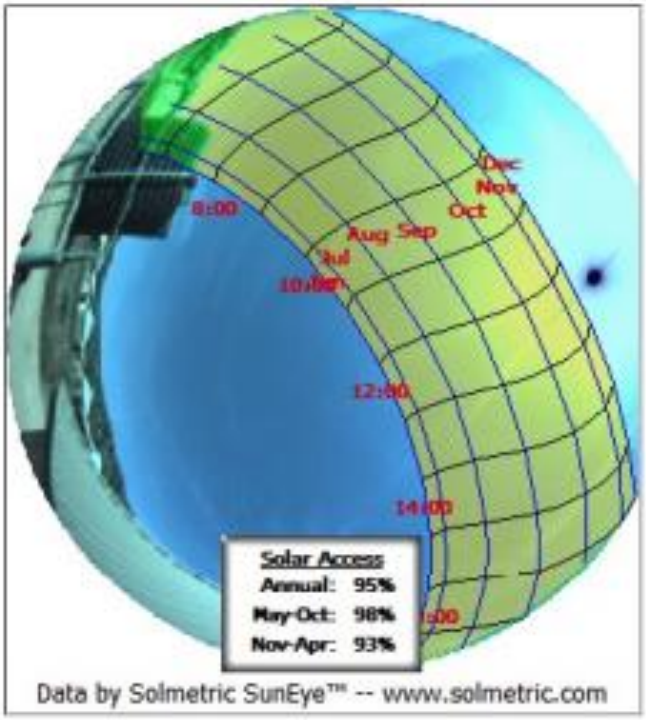
Panel Orientation: Tilt=29° -- Azimuth=180° -- **Skyline Heading=107°**
Solar Access: Annual: 93% -- Summer (May-Oct): 92% -- Winter (Nov-Apr): 95%

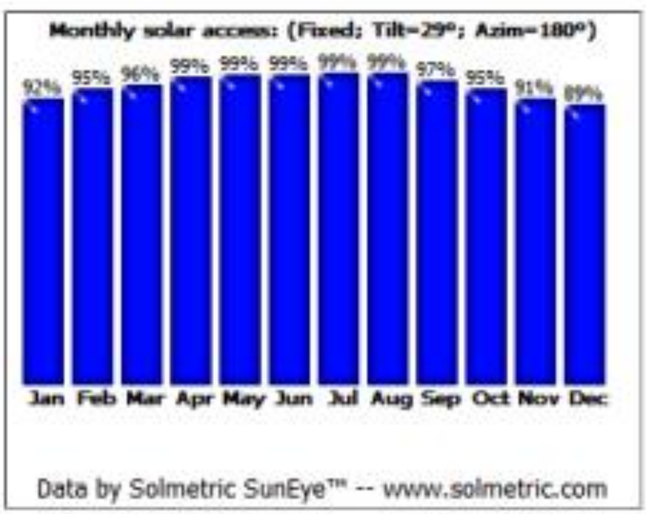




Sky02 -- 11/27/2017 12:12 -- clinic due south

Panel Orientation: Tilt=29° -- Azimuth=180° -- **Skyline Heading=117°**
Solar Access: Annual: 95% -- Summer (May-Oct): 98% -- Winter (Nov-Apr): 93%

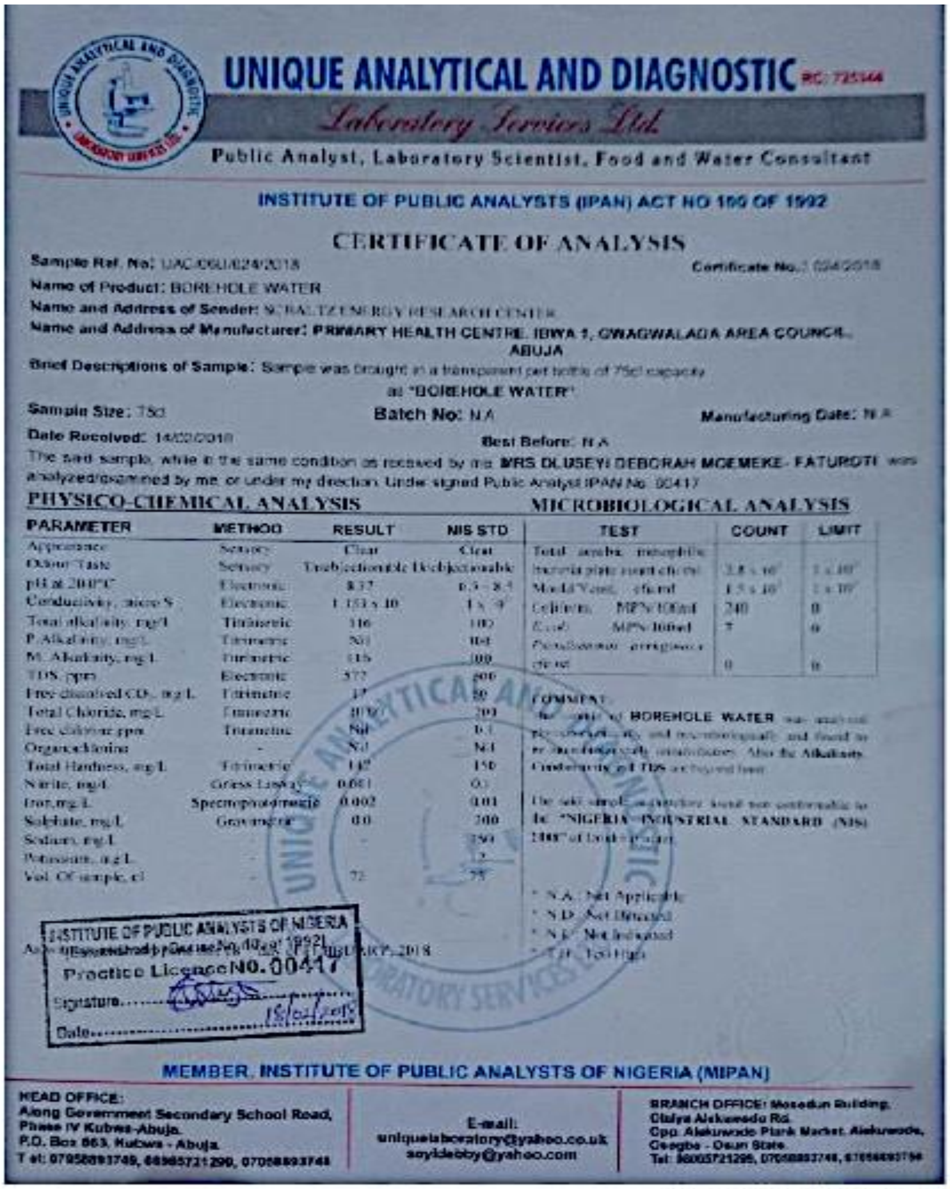




APPENDIX D: Water quality reports

Water quality results for the respective water sources are shown in this appendix. Sections D.1 and D.2 show the reports for PHC Ibwa and LEA School Mapa.

D.1 Water Quality report for PHC, Ibwa



UNIQUE ANALYTICAL AND DIAGNOSTIC RC: 725344

Laboratory Services Ltd.

Public Analyst, Laboratory Scientist, Food and Water Consultant

INSTITUTE OF PUBLIC ANALYSTS (IPAN) ACT NO 100 OF 1992

CERTIFICATE OF ANALYSIS

Sample Ref. No: UAC/D6U/624/2018 Certificate No.: [illegible]

Name of Product: BOREHOLE WATER

Name and Address of Sender: SCHALTZ ENERGY RESEARCH CENTER

Name and Address of Manufacturer: PRIMARY HEALTH CENTRE, IBWA 1, GWAGWALADA AREA COUNCIL, ABUJA

Brief Descriptions of Sample: Sample was brought in a transparent pet bottle of 75cl capacity as "BOREHOLE WATER"

Sample Size: 75cl Batch No: N.A Manufacturing Date: N.A

Date Received: 14/02/2018 Best Before: N.A

The said sample, while in the same condition as received by me MRS OLUSEYI DEBORAH MGEMEKE- FATUROTI was analyzed/examined by me or under my direction. Under signed Public Analyst IPAN No. 00417

PHYSICO-CHEMICAL ANALYSIS

PARAMETER	METHOD	RESULT	NIS STD
Appearance	Sensory	Clear	Clear
Odour/Taste	Sensory	Unobjectionable	Unobjectionable
pH at 20.0°C	Electronic	8.37	6.5 - 8.5
Conductivity, micro S	Electronic	1.153 x 10	1 x 10
Total alkalinity, mg/l	Titrimetric	116	100
P. Alkalinity, mg/l	Titrimetric	Nil	Nil
M. Alkalinity, mg/l	Titrimetric	115	100
TDS, ppm	Electronic	577	500
Free dissolved CO_2, mg/l	Titrimetric	17	50
Total Chloride, mg/l	Titrimetric	[illegible]	200
Free chlorine ppm	Titrimetric	Nil	0.1
Organochlorine	-	Nil	Nil
Total Hardness, mg/l	Titrimetric	142	150
Nitrite, mg/l	Griess Ilosvay	0.001	0.2
Iron, mg/l	Spectrophotometric	0.002	0.01
Sulphate, mg/l	Gravimetric	0.0	200
Sodium, mg/l	-	-	250
Potassium, mg/l	-	-	[illegible]
Vol. Of sample, cl	-	72	75

MICROBIOLOGICAL ANALYSIS

TEST	COUNT	LIMIT
Total aerobic mesophilic bacteria plate count cfu/ml	2.8 x 10	1 x 10
Mould/Yeast, cfu/ml	1.5 x 10	1 x 10
Coliform, MPN/100ml	240	0
E.coli, MPN/100ml	7	0
Pseudomonas aeruginosa cfu/ml	0	0

COMMENT:

The sample of BOREHOLE WATER was analysed physicochemically and microbiologically and found to be microbiologically unsatisfactory. Also the Alkalinity, Conductivity and TDS are beyond limit.

The said sample is therefore found not conformable to the "NIGERIA INDUSTRIAL STANDARD (NIS) 2007" of Drinking water.

* N.A.: Not Applicable
* N.D.: Not Detected
* N.I.: Not Indicated
* T.H.: Too High

INSTITUTE OF PUBLIC ANALYSTS OF NIGERIA (Established by Decree No. 100 of 1992)
Practice Licence No. 00417
Signature......
Date...... 15/02/2018

MEMBER, INSTITUTE OF PUBLIC ANALYSTS OF NIGERIA (MIPAN)

HEAD OFFICE: Along Government Secondary School Road, Phase IV Kubwa-Abuja. P.O. Box 863, Kubwa - Abuja. Tel: 07058893748, 08065721299, 07058893748

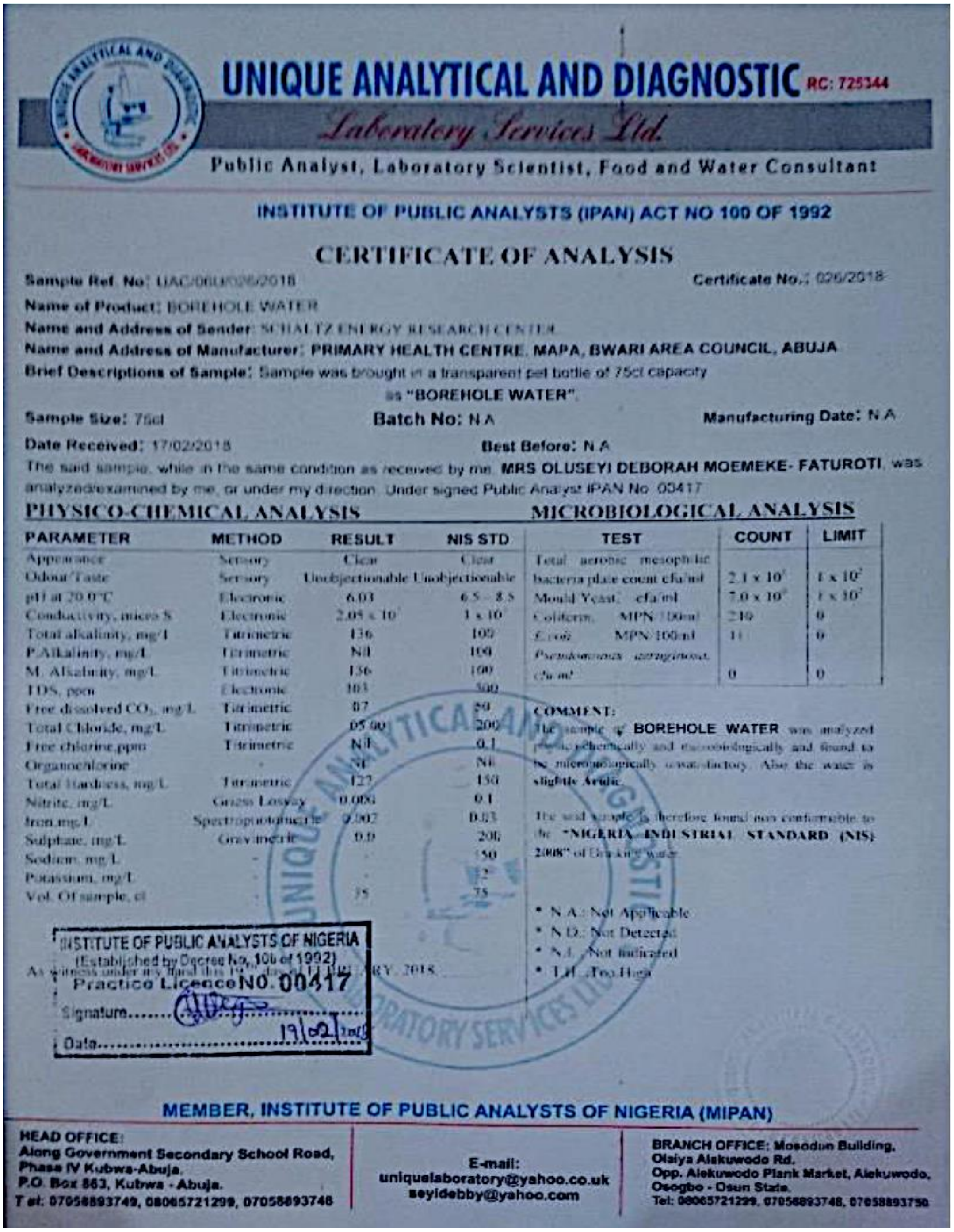
E-mail: uniquelaboratory@yahoo.co.uk, seyidebby@yahoo.com

BRANCH OFFICE: Mosadun Building, Olaiya Alekuwodo Rd. Opp. Alekuwodo Plank Market, Alekuwodo, Osogbo - Osun State. Tel: 08065721299, 07058893748, 07058893748

Scanned by CamScanner

D.2 Water Quality report for LEA School, Mapa

Report for LEA School Mapa is as follows.



UNIQUE ANALYTICAL AND DIAGNOSTIC RC: 725344

Laboratory Services Ltd.

Public Analyst, Laboratory Scientist, Food and Water Consultant

INSTITUTE OF PUBLIC ANALYSTS (IPAN) ACT NO 100 OF 1992

CERTIFICATE OF ANALYSIS

Sample Ref. No: UAC/06U/026/2018 **Certificate No.:** 026/2018

Name of Product: BOREHOLE WATER

Name and Address of Sender: SCHALTZ ENERGY RESEARCH CENTER

Name and Address of Manufacturer: PRIMARY HEALTH CENTRE, MAPA, BWARI AREA COUNCIL, ABUJA

Brief Descriptions of Sample: Sample was brought in a transparent pet bottle of 75cl capacity as "BOREHOLE WATER".

Sample Size: 75cl **Batch No:** N A **Manufacturing Date:** N A

Date Received: 17/02/2018 **Best Before:** N A

The said sample, while in the same condition as received by me, **MRS OLUSEYI DEBORAH MOEMEKE- FATUROTI**, was analyzed/examined by me, or under my direction. Under signed Public Analyst IPAN No. 00417

PHYSICO-CHEMICAL ANALYSIS

PARAMETER	METHOD	RESULT	NIS STD
Appearance	Sensory	Clear	Clear
Odour/Taste	Sensory	Unobjectionable	Unobjectionable
pH at 20.0°C	Electronic	6.03	6.5 – 8.5
Conductivity, micro S	Electronic	2.05×10^{2}	1×10^{3}
Total alkalinity, mg/l	Titrimetric	136	100
P.Alkalinity, mg/L	Titrimetric	Nil	100
M. Alkalinity, mg/L	Titrimetric	136	100
TDS, ppm	Electronic	103	500
Free dissolved CO_2, mg/L	Titrimetric	87	50
Total Chloride, mg/L	Titrimetric	05.00	200
Free chlorine, ppm	Titrimetric	Nil	0.1
Organochlorine	-	[illegible]	Nil
Total Hardness, mg/L	Titrimetric	127	150
Nitrite, mg/L	Griess Losvay	0.086	0.1
Iron, mg/L	Spectrophotometric	0.007	0.03
Sulphate, mg/L	Gravimetric	0.9	200
Sodium, mg/L	-	-	150
Potassium, mg/L	-	-	12
Vol. Of sample, cl	-	75	75

MICROBIOLOGICAL ANALYSIS

TEST	COUNT	LIMIT
Total aerobic mesophilic bacteria plate count cfu/ml	2.1×10^{2}	1×10^{2}
Mould/Yeast, cfu/ml	7.0×10^{2}	1×10^{2}
Coliform, MPN/100ml	210	0
E.coli MPN/100ml	11	0
Pseudomonas aeruginosa, cfu/ml	0	0

COMMENT:

The sample of **BOREHOLE WATER** was analyzed physicochemically and microbiologically and found to be microbiologically unsatisfactory. Also the water is slightly Acidic.

The said sample is therefore found non conformable to the "NIGERIA INDUSTRIAL STANDARD (NIS) 2008" of Drinking water.

- N.A.: Not Applicable
- N.D.: Not Detected
- N.I.: Not Indicated
- T.H.: Too High

As witness under my hand this 19th day of FEBRUARY, 2018.

INSTITUTE OF PUBLIC ANALYSTS OF NIGERIA (Established by Decree No. 100 of 1992) Practice Licence NO. 00417

Signature.......

Date....... 19/02/2018

MEMBER, INSTITUTE OF PUBLIC ANALYSTS OF NIGERIA (MIPAN)

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E-mail: uniquelaboratory@yahoo.co.uk seyidebby@yahoo.com

BRANCH OFFICE: Mosodun Building, Olaiya Alekuwodo Rd. Opp. Alekuwodo Plank Market, Alekuwodo, Osogbo - Osun State. Tel: 08065721299, 07058893746, 07058893750

APPENDIX E: Equivalent Length considered for fitting in pipe

This appendix shows Table E.1, which is used to identify the equivalent length considered for the pipe.

Table E.1 Equivalent Length of straight pipe for various generic fittings (Linderburg, 2011).

Size (in)	**1/4**	**3/8**	**1/2**	**3/4**	**1**
Name of Fitting	**Equivalent Length (ft)**				
Fitting	**0.25**	**0.375**	**0.5**	**0.75**	**1**
Ball valve flanged	NA	NA	NA	NA	NA
Gate valve flanged	NA	NA	NA	NA	NA
T line flow flanged	NA	NA	0.69	0.82	1
Long Radius 90 flanged	NA	NA	1.1	1.3	1.6
45 Elbow flanged	NA	NA	0.45	0.59	0.81
T branch flow flanged	NA	NA	2	2.6	3.3
Regular 90 screwed	2.3	3.1	3.6	4.4	5.2
45 Elbow screwed	0.34	0.52	0.71	0.92	1.3
Ball valve screwed	0.32	0.45	0.56	0.67	0.84
Check valve flanged	NA	NA	3.8	5.3	7.2
Check valve screwed	7.2	7.3	8	8.8	11
Coupling	0.14	0.18	0.21	0.24	0.29
Gate valve screwed	0.32	0.45	0.56	0.67	0.84
Globe valve flanged	NA	NA	38	40	45
Globe valve screwed	21	22	22	24	29
Long Radius 90 screwed	1.5	2	2.2	2.3	2.7
Regular 90 flanged	NA	NA	0.92	1.2	1.6
T branch flow screwed	2.4	3.5	4.2	5.3	6.6
T line flow screwed	0.79	1.2	1.7	2.4	3.2
Union	0.14	0.18	0.21	0.24	0.29

APPENDIX F: Pump curves considered for the sites

Appendix F contains the pump curves of several pump identified to consider in the design.

F.1 Pump curves considered for Ibwa, PHC

This section contains the pump curves considered for PHC, Ibwa.

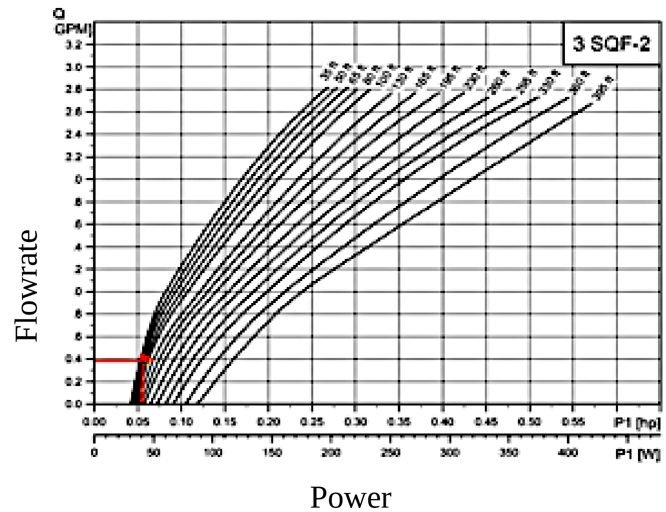

Figure F.1.1: Pump curve of Grundfos 3 SQF-2 Pump (Grundfos, 2018)

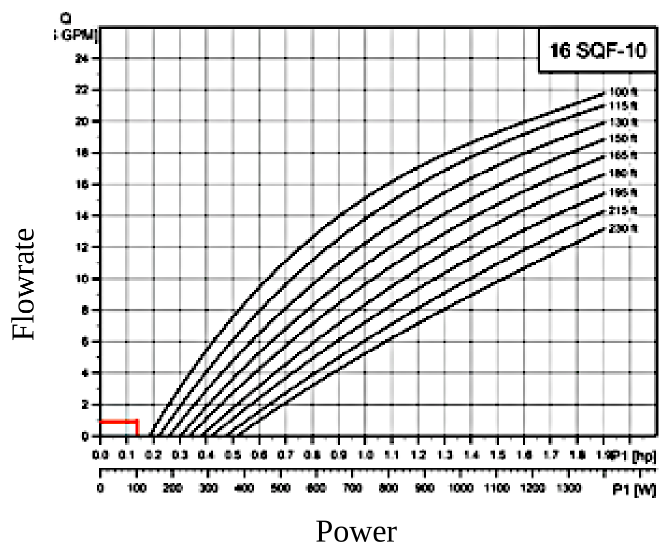

Figure F.1.2: Pump curve of Grundfos 16 SQF-2 Pump (Grundfos, 2018)

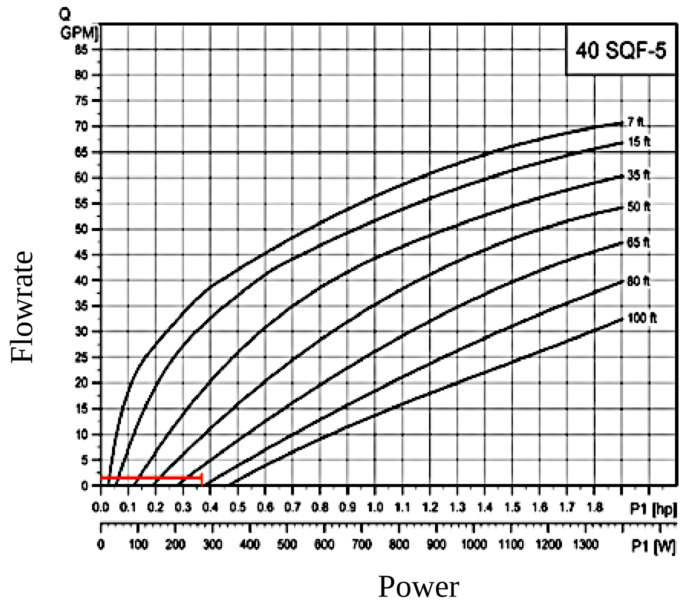

Figure F.1.3: Pump curve of Grundfos 40 SQF-5 pump (Grundfos, 2018)

F.2 Pump curves considered for Kwali, CHC

This section contains the pump curves considered for CHC, Kwali.

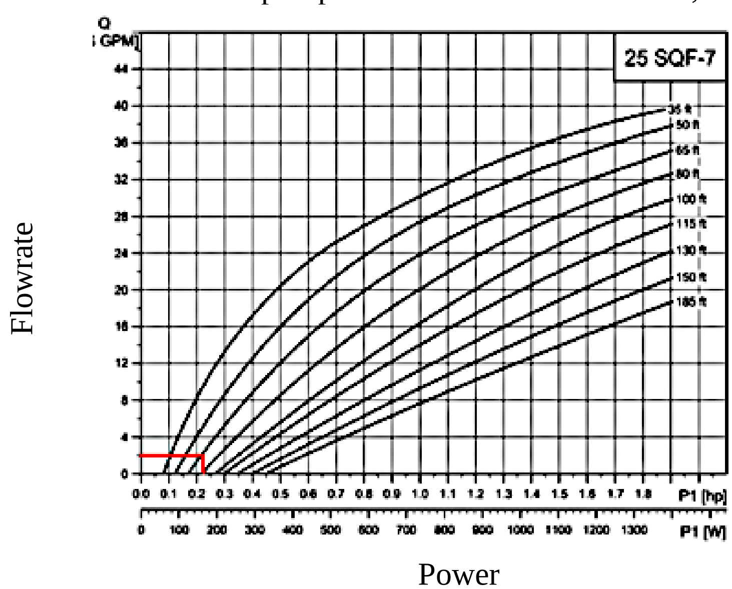

Figure F.2.1: Pump curve of Grundfos 25 SQF-7 Pump (Grundfos, 2018)

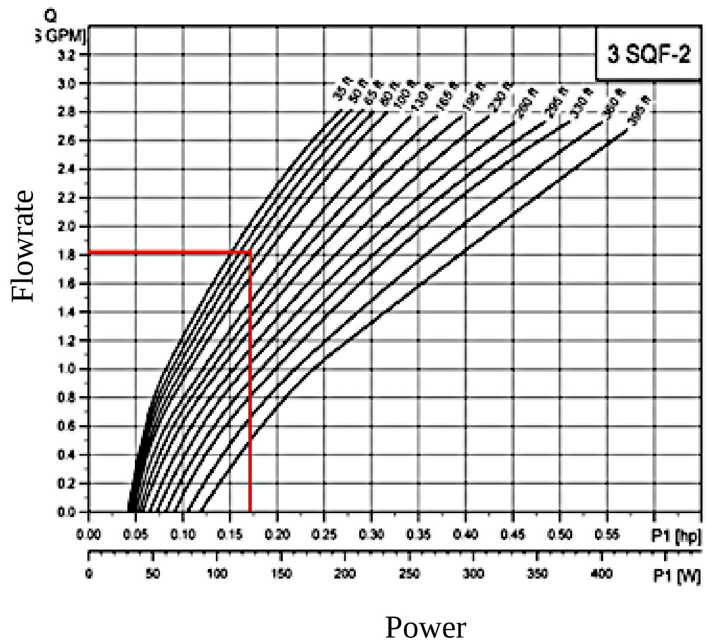

Figure F.2.2: Pump curve Grundfos 3SQF-2 Pump (Grundfos, 2018)

F.3 Pump curves considered for LEA School, Mapa

This section contains the pump curves considered for LEA School Mapa.

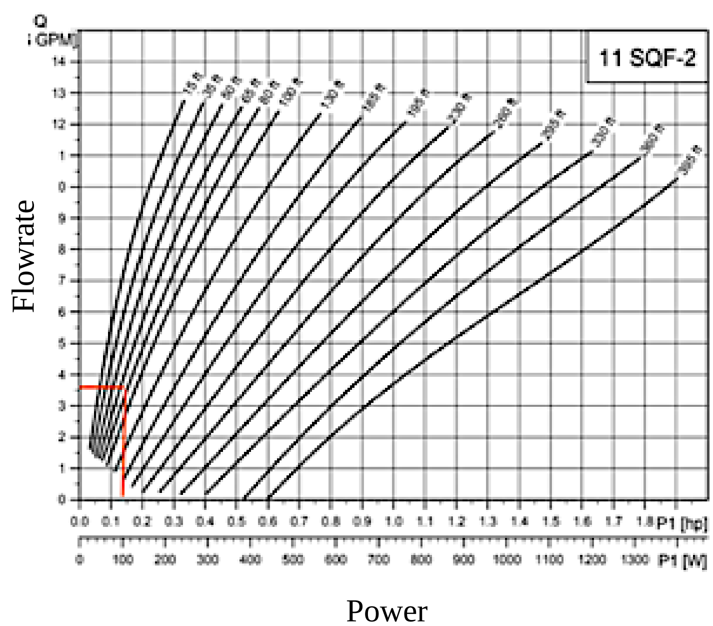

Figure F.3.1: Pump curve Grundfos 11SQF-2 Pump (Grundfos, 2018)

APPENDIX G: UNIRAC Roof mount report for the sites

This appendix contains the cost details of the roof mounts used in the sites. Figure G.1 shows the costing.

UNIRAC

U-BUILDER PROJECT REPORT
VERSION: 1.0

PROJECT TITLE	PROJECT ID	CREATED
SOLARMOUNT Flush	5966E5F2	June 15, 2019, 1:34 a.m.

NAME	PHC, Ibwa
ADDRESS	Ibwa Nigeria
CITY, STATE	Unknown
MODULE	*Typical 200-270W 60 Cell

Designed by Anamika
SOLARMOUNT FLUSH
*Typical
1 - 200-270W 60 Cell
11 ft^2
0.13 KW

UNVALIDATED MODULE SIZE: The module selected was based on a typical or custom module size. DO NOT USE this information to purchase or install without verifying the exact module dimensions.

BILL OF MATERIALS

LEGEND: Base System Part Accessory

PART NUMBER	PART TYPE	DESCRIPTION	QUANTITY	SUGGESTED QUANTITY	UNIT PRICE (USD)	TOTAL LIST PRICE (USD)
320168M	Rail	SM RAIL 168" MILL	1	1	39.62	39.62
302035M	End Clamp	SM PRO SERIES UNIV END	4	4	2.52	10.08
008009P	Grounding Lug	ILSCO LAY IN LUG (GBL4DBT)	1	1	5.75	5.75
004055M	Flashing	FLASHKIT PRO, MILL 10PK	4	4	7.25	29.00

BASE SYSTEM PRICE	ACCESSORIES PRICE	TOTAL PRICE
$49.70 $0.382 PER WATT	$34.75 $0.267 PER WATT	$84.45 $0.650 PER WATT

This design is to be evaluated to the product appropriate Unirac Code Compliant Installation Manual which references International Building Code 2009, 2012, 2015 and ASCE 7-05, ASCE 7-10 and California Building Code 2010, 2016. The installation of products related to this design is subject to requirements in the above mentioned installation manual.

Figure G.1: Cost estimates of roof mount from UNIRAC (UNIRAC, 2019).

APPENDIX H: Quotation from Lorentz for the PS-250S Submersible unit

LORENTZ

Invoice Recipient	COD-House TX 79364 USA Phone: Fax:
Document No.	US 1002966
Customer No.	103-000020
Your contact	Estevan Villarreal, estevan.villarreal@lorentz.de
Ref.	Meg Harper
Your Reference	Accounts Payable, travis.walters@lorentz.de;eric.marcias@lorentz.de
Date	19. November 2018
Shipping Method	FOB ,Incoterms 2010
Payment Terms	Due on Receipt
valid until	19. December 2018 subject to prior sale
Date of delivery	19. December 2018
Delivery Address	Texas TX 79364 USA

LORENTZ US CORP.
710 S. Hwy 84, P.O. Box 249
Slaton TX 79364, USA
Phone: +1 (806) 728-0110
Fax: +1 (806) 728-0112
www.lorentz.de

Managing Director: Eric Macias
TAX No.: 32055656055

Bank Details:
For wired information please call:
+1 (806) 728-0110

Sales Quotation

Pos.	Description	Quantity	UoM	Price/UoM $	Net Amount $
1	**PS2-150 Controller-0.3kVA** Item Code: 07-000500 Pump Controller, Datamodule, Solar(PV)/Battery operation	1	pc.	837.00	837.00
2	**PU150 HR-04S-3, NPT 1", UL** Item Code: 10-000200 Submersible Pump Unit, Helical Rotor Pump, ECDRIVE 150-HR-S	1	set	1,643.00	1,643.00
3	**HELiOS ST72M190W Solar Panel** Item Code: 23-900020	1	pc	370.00	370.00
4	**Pole Mount PM-1-1 incl. bracket** Item Code: 19-900040 PV-Module Mounting System Top of Pole, kit mounting structure without pole or beam	1	set	248.00	248.00
5	**Well probe sensor** Item Code: 19-000000 Water level sensor for dry run protection. POM protection enclosure, max. 5 bar	1	set	122.00	122.00
6	**Well Probe Sensor Wire** Item Code: 19-900005 14-2 FLT NO GROUND	80		0.70	56.00
7	**Float Switch** Item Code: 19-000030 Float Switch for tank, 2m cable, change-over switch function	1	pc.	38.00	38.00
8	**Surge Protector** Item Code: 19-000280 Surge protector, outdoor, max. 14V	1	pc.	41.00	41.00
9	**Liquid Level Sensor, 20m/66ft** Item Code: 19-004480 Gauge Pressure Type, AISI304, 4..20mA, 12-28VDC, 0.5%FS	1	set	463.00	463.00
10	**Liquid Pressure Sensor, LPS-500** Item Code: 19-004450 0-500kPa, AISI304, G1/2", 4..20mA, 11-28VDC, 0.5%FS	1	set	300.00	300.00
11	**PV Disconnect 440-40-1** Item Code: 19-000137 PV disconnect switch 440VDC/40A, 1 string, plastic box, IP54	1	pc.	286.00	286.00
12	**Manual speed controller**	1	pc	52.00	52.00

Page 1 / 2 Carry-over 4,456.00

Figure H.1: Cost estimates of Lorentz Pumps (Lorentz, 2019).