Remote Control and Monitoring of a Solar Water Pumping System Using Cellular Network for Sukkur Pakistan

Written by

©Omair Ahmed

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Abstract

In an era marked by increasing global concerns about sustainability and the responsible use of natural resources, the demand for efficient water management systems has taken center stage. This demand is particularly pronounced in regions like Sukkur, Pakistan, where access to surface water is limited, and the need for innovative irrigation solutions is paramount. Addressing this critical challenge head-on, this thesis presents a groundbreaking approach to the design and implementation of a renewable energy-driven water pumping system. At its core, this research seeks to confront environmental issues, drive cost-effectiveness, and promote sustainability by seamlessly integrating solar energy with cutting-edge technological advancements. In the context of Sukkur's unique landscape, this system harnesses the power of photovoltaic energy, augmented by energy storage capabilities in batteries. This symbiotic relationship between solar power and energy storage ensures uninterrupted operation of a submersible AC pump, thus guaranteeing the efficient and sustainable delivery of water—an essential component in meeting Sukkur's irrigation needs. One of the standout features of this research is the development of an integrated microcontroller-based system. This system enables real-time monitoring and the logging of critical operational parameters such as solar irradiance, water levels, and pump status. The inclusion of a GSM module takes system functionality to the next level by providing immediate visibility into the system's status and allowing for remote control. This not only enhances operational efficiency but also ensures convenience for end-users, who can now manage the system from afar. Moreover, this research leverages sophisticated data analysis software and custom-built applications to create user-friendly interfaces for data visualization. These interfaces empower users with comprehensive insights into system performance, making it easier to make informed decisions and optimize

system operation. Highlighting quantitative results and economic benefits underscores the practical implications of the proposed system. By quantifying the impact in terms of energy savings, cost reductions, and environmental benefits, this work reinforces the significance of adopting such innovative approaches. Furthermore, this research contributes not only to the immediate challenge of sustainable water pumping in Sukkur but also sets a precedent for the broader utilization of renewable energy resources in addressing critical irrigation needs worldwide. It serves as a testament to the power of innovative thinking and technology in shaping a more sustainable and resource-conscious future. As the global community grapples with the urgent need to balance economic development with environmental preservation, this thesis stands as a beacon of hope, demonstrating how cutting-edge solutions can lead us toward a more sustainable and prosperous future.

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List of Nomenclature

A. Acronyms and Abbreviations:

AC	Alternating Current
ADC	Analog to Digital Converter
AM	Ante Meridiem
APP	Application
AVR	Advanced Virtual RISC
CSV	Comma Separated File
DC	Direct Current
DWP	Diesel Water Pumping System
GDP	Gross Domestic Product
GPIO	General Purpose Input/Output
GPRS	General Packet Radio Services
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GW	Gigawatt
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
IDE	Integrated Development Environment
LDR	Light Dependant Resistor
MATLAB	Matrix Laboratory
MIT	Massachusetts Institute of Technology
MPPT	Maximum Power Point Tracking

MQTT	Message Queuing Telemetry Transport
MW	Megawatt
NPC	Net Present Cost
OLED	Organic Light-Emitting Diode
PM	Post Meridiem
PV	Photovoltaic
PVWP	Photovoltaic Water Pump
RISC	Reduced Instruction Set Computer
SCADA	Supervisory Control and Data Acquisition
SD	Secure Digital
SIM	Subscriber Identity Module
SMS	Short Messaging Service
SPDT	Single Pole, Double Throw
SPI	Serial Peripheral Interface
SPP	Solar-Powered Pumps
TDH	Total Dynamic Head
TTL	Time To Live
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus

B. Symbols and Variables:

ρ: Density of water

g: Gravitational acceleration (m/s^2)

h: Dynamic head (m)

Q: Water flow (m^3/hour)

η: Motor efficiency

P_h: Hydraulic power of the water pump (Watts)

P_m: Motor Power (Watts)

P: Required Power (kW)

HP: Horsepower

Chapter 1

Introduction and Literature Review

1.1 Introduction

Photovoltaic (PV) systems have reached a level of commercial compatibility and acceptance with regular energy sources. This is because the way they work is simple, which makes it easy for people to set them up and use the power they make. A photovoltaic (PV) system is an electricity generator that takes in sunlight and turns it into electricity that can be used [1]. It has many parts, such as PV modules, a converter/inverter, and batteries for storing energy. The PV cell is the most important part of the PV system. It is made of semiconducting materials, which allow it to turn light into moving electricity. Every solar cell has at least two layers of a semiconducting material (usually silicon) that are arranged in a certain way. When the panel is exposed to sunlight, the moving electrons in these layers create direct current electricity [2-3].

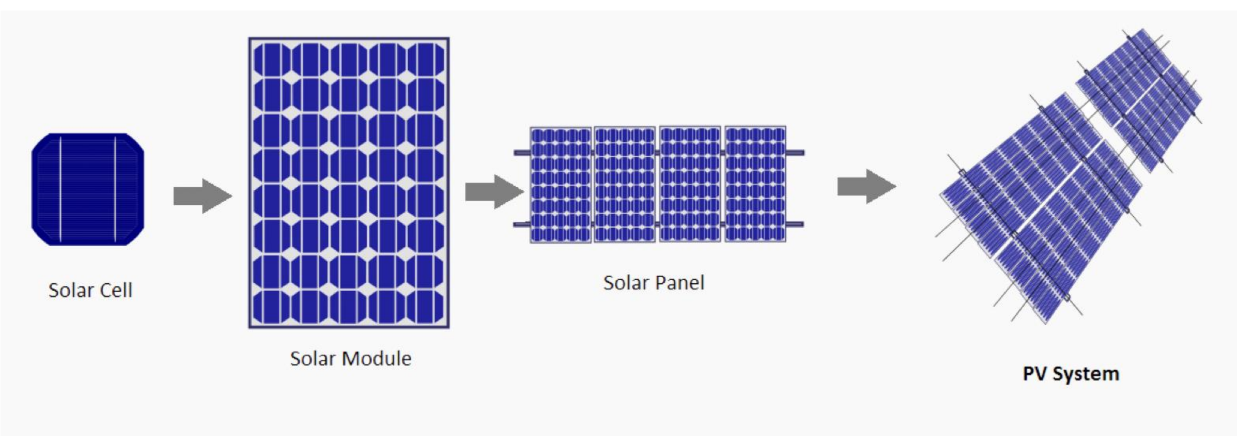

Figure 1.1 PV system constructed from PV module

With the help of an inverter, DC voltage can be changed into AC voltage, or it can be stepped up or down with the help of a boost or buck DC-DC converter. Then, the electricity that was collected is used to run the load. In our case, the load is a water pump with a DC shunt motor, so the load is DC. Then, getting water from a well or borehole as soon as it is again exposed to sunlight. As shown in figure 1.2 one type of off-grid connection is a DC-coupled system structure like the one shown. But if the duty cycle is very high, sometimes a two-stage DC-DC converter can be used. In the sketch below, you can see how a solar water pumping system is put together [2].

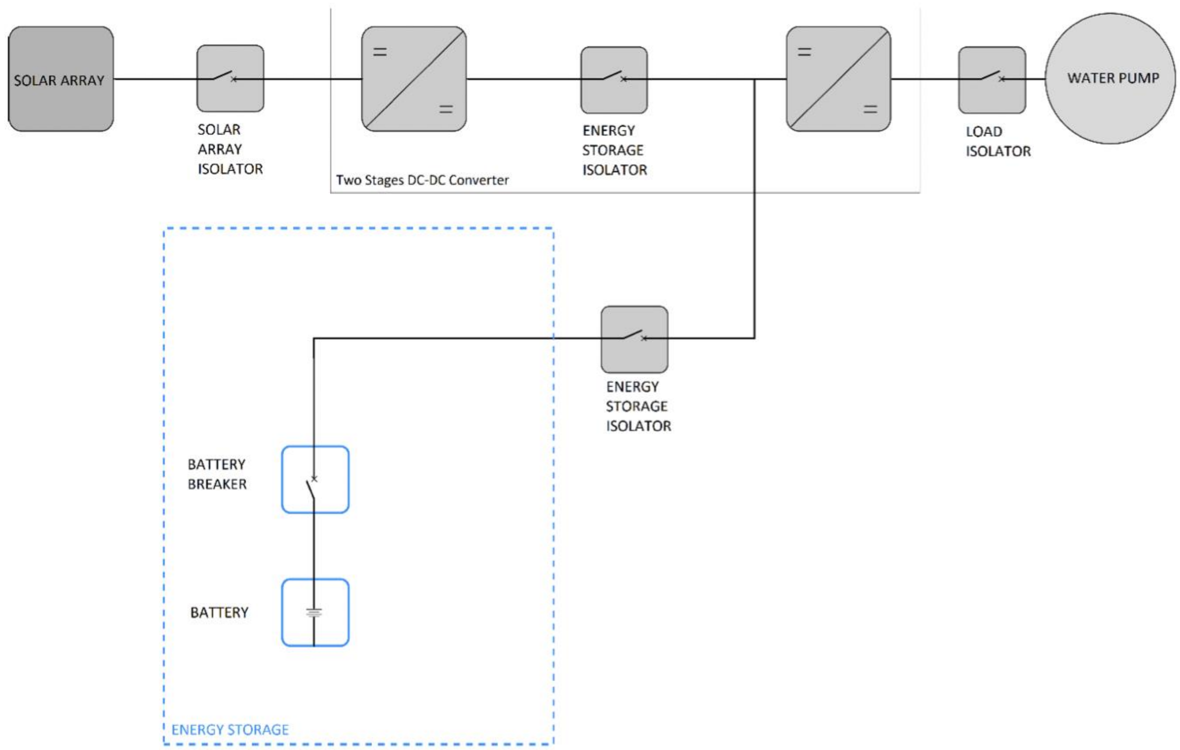

Figure 1.2 Isolated PV solar water pumping system

1.2 Solar Pumps

A solar water pump is driven by the electricity produced by the PV (photovoltaic) panels. This is the opposite of a diesel or grid electricity water pump. The solar-powered pump uses solar energy for operation. It consists of a water storage tank, electrical cables, a breaker/fuse box, a DC water pump, a solar charge controller (MPPT), and a solar panel array. A solar powered water pump is more efficient to operate. These pumps have low maintenance and installation costs. Solar pumps have a lower environmental impact compared to pumps powered by IC engines or utility electricity. The pump with a solar system is a delightful technology with which remote areas can be supplied with water both ecologically and socially. Therefore, it is always the economic technology of choice. Remote areas tend to require mostly diesel engines and human resources for water supply. Solar water pumps are replacing existing pumps and offer many benefits, such as weather and socio-economical stability [4]. These pumps are best suited for reservoirs and irrigation systems. The solar pumps are used in places where grid power is not available and substitutional energy sources (especially wind power) cannot provide enough power. The solar-powered water pump can deliver water where power lines can't reach. These are commonly found in aeration, pond filtration, aquarium filtration, and well pumps. These types of pumps are mainly used in areas that have electricity issues. Otherwise, you will not have a stable power supply. This is an ideal water withdrawal system for green energy that combines the advantages of reliability, economy, and environmental protection [5].

A solar-powered water pumping system has been recognised as an ideal solution for the grid-isolated countryside regions of emerging and advanced countries, including Saudi Arabia, in which substantial amounts of solar radiation are available [6]. Saudi Arabia is one of these countries. Solar powered water pumping systems are able to distribute drinking water without the need for any additional power or the difficult maintenance that is required for other types of water pumping systems, such as diesel pumps. In addition, solar powered water pumping systems, despite the fact that they are not appropriate for large-scale irrigation, are able to operate effectively in regions with small-scale drip irrigation systems [7]. This is the case despite the fact that they are not suitable for large-scale irrigation. Large-scale solar water pumping systems are those that provide service to more than 240 people at once. This criterion determines whether or not the system is considered to be large-scale. However, photovoltaic solar panels are widely used to undertake a variety of agricultural operations. These operations are typically carried out in remote places or in regions where the exploitation of alternative energy sources is preferred [8]. To be more specific, solar powered water pumping devices have been developed over the course of the past decade to reliably generate a sufficient amount of electricity directly from the radiation of the sun in order to provide water for livestock [9].

According to Akihiro et al [10], solar water pumps could be particularly useful in the context of small-scale or community-based irrigation. This is due to the fact that maintaining large-scale irrigation requires a greater quantity of water, which in turn necessitates the use of a larger solar photovoltaic array. According to the research conducted by Ahmad et al. [11], the larger pumping systems have the capability of delivering around 150,000 litres of water per day from an overall head of 10 metres.

When determining the practicability of this pumping system, it is necessary to take into account both the recurring costs over a long period of time as well as the adaptability of the solar-powered water pumping system to different levels of demand at any one time. This development is tied, to some extent, to the capacity of the general populace that utilises the pumping system for irrigation to be able to react to continuously changing demands as well as their own needs. A solar-powered water pumping system is one of the greatest alternative solutions for irrigation, according to Vishwa et al. [12].

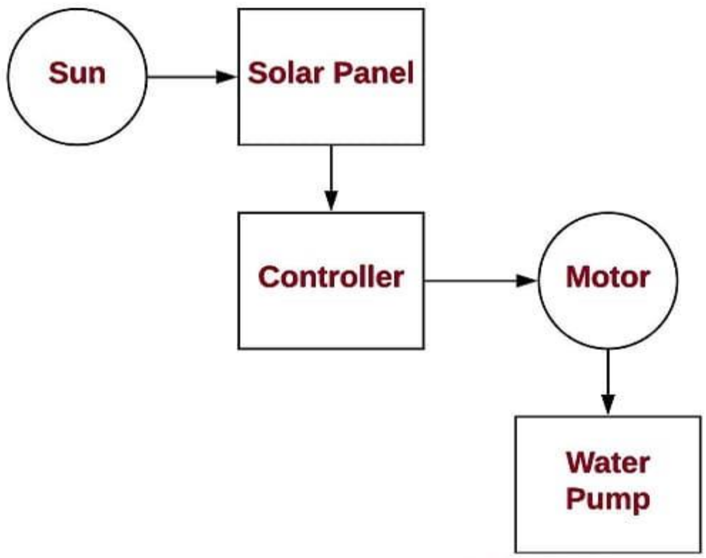

Figure 1.3 Solar Water Pump Block Diagram

The block diagram of the solar powered water pump consists mainly of a controller, an electric motor or battery, a water pump, and solar panels (PV). Basically, a solar panel is an electric pump that works on the electrical energy obtained from solar panels. These panels receive energy from the sunlight. The connected battery or motor controls DC or AC. The controller used in this system is used to adjust the speed and output power.

1.3 Working Principle of Solar Water Pump

A solar pump works on the basis of the photovoltaic principle. During the operation of a solar pump, PV (photovoltaic) systems absorb radiant solar energy and transform it into electricity. This produced enough electricity to supply the entire system. The inverter of the pump converts the direct current output of the PV system into alternating current, which drives the pump. These inverters also adjust the output frequency and voltage in real-time, corresponding to variations in the sunlight intensity to attain the highest power point tracking. As the intensity of the sunlight becomes weaker, the water lifting system realises the function of switching the municipal power that works as auxiliary energy for the water lifting system.

1.4 Pump sizing and system design

The selection of a solar water pumping system is determined by a number of different criteria; nonetheless, these are the most important aspects that should be taken into account [13].

It is possible for the water supply to be either ground water or surface water. In Pakistan, earth surface make up the majority of the country's water sources. The required amount of water, which can be quantified as either the flow rate in metres per second (m^3/s) or the volume of water required over a given period of time, for instance 200 m^3/day. The total dynamic head, often known as TDH, can be measured in either feet or metres. It is important to take into account a number of mechanical friction components.

When it comes to determining the appropriate size for such a system, solar irradiation (measured in W/m^2) is one of the most important considerations. It should be the first issue that is taken into consideration, and as such, the foundation for the construction of such a system. The components of the solar-powered water pumping system, as well as the standard control technique, which is a float switch, are depicted in Figure 1.3. In solar water pumping systems, this control approach is one of the more straightforward options available.

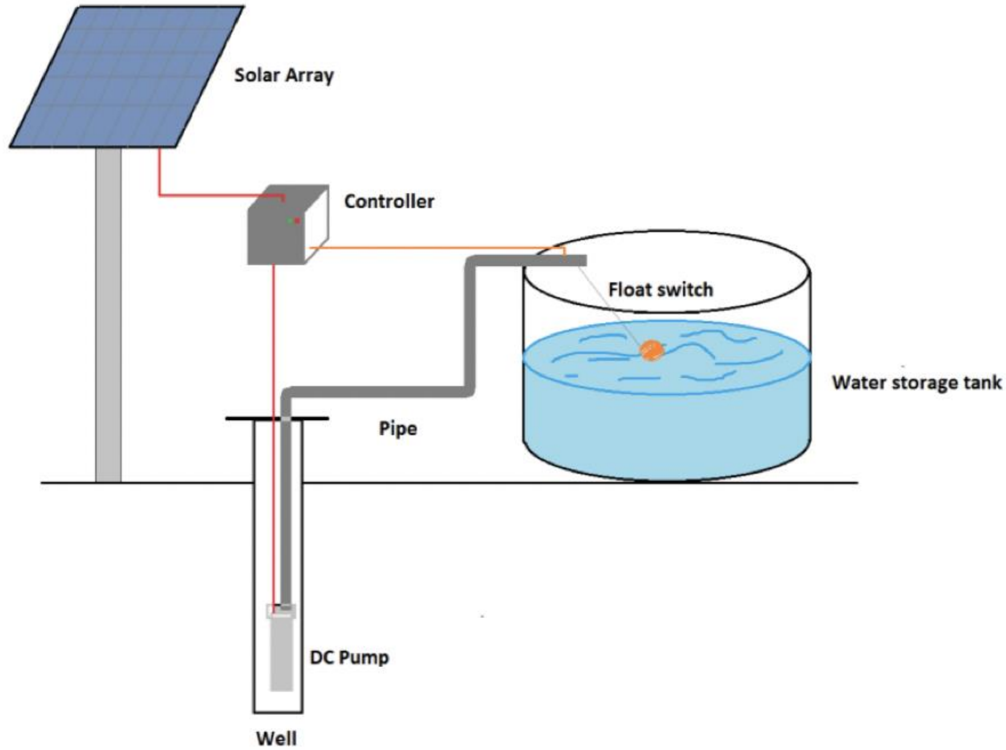

Figure 1.4 Constituents of solar powered water pumping systems.

1.5 Literature Review

Pakistan's economy is largely agricultural, accounting for 22.2 percent of GDP and employing 42.3 percent of the workforce [14]. Water is a critical component of agriculture, which is a sector with enormous economic clout. Water scarcity is a problem in Pakistan. In the 1950s, water availability was over 5000 m3 per capita, but by 2025, that figure is anticipated to shrink to around 1000 m3 per capita [15]. Poor water management was blamed by [15] on a lack of small and big dams for water storage, which resulted in excessive water use.

Water pumps have been installed in order to alleviate the problem of a lack of water for agriculture. The country's situation is not great, since the government is facing a shortfall of 5,000MW [13]. So, instead of using electricity to power the water pumps, fossil fuels have been utilized. Increased dependence on imported fossil fuel for electricity production has resulted in a circular debt of 1.2 trillion Pakistani rupees over a period of the last five years because of Pakistan's lack of fossil fuel resources. The use of fossil fuels is likely to decline as the government shifts its policies toward environmentally friendly and renewable alternative energy sources [14-15].

Pakistan has a huge amount of renewable energy potential, estimated at 167.7 GW [14]. Pakistan's photovoltaic potential is particularly large among renewable energies. Pakistan has one of the highest levels of solar potential in the world, with a capacity of up to 100,000 MW and an average annual solar insolation of 5.5 kWh/m2/day [16]. Using renewable sources instead of fossil fuels in Pakistan's water pumping systems is supported by all of the above-mentioned resources and issues. The country's lack of fossil fuel resources is a major factor. Because of Pakistan's abundance of solar energy resources, water pumps need not rely on fossil fuels anymore.

For a water pumping system to work, it needs a way to get power. When AC power is available from the power grid nearby, AC-powered systems are usually cheaper and require less maintenance. But in many rural areas, water sources are spread out over a large area and there aren't many power lines. It is often too expensive to put in a new transmission line and a transformer at the location. Windmills have been put up in these places for a long time, but many of them don't work anymore because they haven't been taken care of or because they are too old. Internal combustion engines are used in many water pumping systems that work on their own today. These systems are easy to move and set up. But they have some big problems, like the fact that they need to be refueled and fixed on site often and that diesel fuel is often expensive and hard to find in rural areas of many developing countries.

The use of fossil fuels also has an effect on the environment, especially because it releases carbon dioxide (CO2) into the air. CO2 emissions can be cut down by a lot by using renewable energy technologies, which in many cases are already as cheap as fossil fuels. Large wind turbines connected to the grid, solar water heating, and PV systems that don't need to be connected to the grid are all good examples. Because of this, using renewable energy to power water pumping systems is a very good idea.

Windmills have been used to get renewable energy for a long time, but they are quickly being replaced by large-scale wind turbines that are connected to the power grid. PV systems are very reliable, and they are often chosen because they have the lowest life-cycle cost. This is especially true for applications that need less than 10KW, where grid electricity isn't available, and where it's expensive to run an internal combustion engine. PV is a good economic choice if the water source is more than 1/3 mile (about 0.53Km) from the power line [17].

The author of [18] provides an overview of the significance of water use worldwide, emphasising the need to increase the existing global average irrigation efficiency. Only around 20% of farmed farmland on the planet is irrigated, but this area generates about 40% of the world's food and fibre. Approximately 36 to 47 percent of the food consumed worldwide, according to this source, is grown on irrigated land. Additionally, 66 percent of the freshwater diverted globally and around 80 percent of the freshwater consumed are directly attributable to irrigation. Since the beginning of the 19th century, the amount of irrigated land has dramatically increased throughout the world due to this growth in productivity when irrigation is used. The entire amount of irrigated farmland has grown dramatically, from roughly 8 million hectares in 1800 to forty million hectares in 1900, according to the [19]. At the start of the 21st century, this increase in irrigation levelled off at roughly 270 million hectares. Despite the irrigated land's exponential increase over the past 200 years or so, this growth is anticipated to drastically slowdown in the next years. From 2000 to 2025, global irrigation is anticipated to grow at a pace of roughly 1% annually, down from nearly 3% annually from 1950 to 2000. Due to restrictions on places with potential for irrigation and the cost associated with developing property so that it may be watered, the growth trend for irrigation has slowed down. The author of [20] calculated that the global cost of irrigation development is about $4800 per hectare. Focus must now move to the use of technology developments and additional research discoveries to enhance irrigation techniques to improve irrigation efficiency overall, as limited land resources and economics are now starting to constrain irrigation expansion in terms of area. By doing this, people will be able to generate more food and energy resources for less money, which is crucial for humans to be able to feed an expanding population that is predicted to grow by almost 50% by the year 2050.

1.5.1 Stand-alone water pumping systems

In isolated off-grid locations, water supply systems powered by solar, diesel, and wind have been widely employed to supply water for animals, drinking, and irrigation. The PV array, a power conditioning system, the pump, and the storage module are the four essential parts of a PVWP system, on average [21]. The system layout is straightforward, allowing for a variety of configurations and technical options depending on reliability, performance, and cost considerations [22]. To capture more solar energy, the PV modules can be installed on either a fixed array or a sun tracking system. The water requirements, pumping head, and system layout all affect the type of pump used. The most common type of volumetric pumps are centrifugal ones.

The kind of motor—direct current (DC) or alternating current—determines the power control unit (AC). The DC motor-pump is connected to the PV array via a DC/DC converter in the first instance and via a DC/AC inverter in the second. It is also feasible to connect the DC pumping unit directly to the PV modules in the smallest and most straightforward installations. A charge controller functions as an interface between the PV modules and battery in the event when the storage system is a battery bank as well as between the battery, the power conditioning unit, and the load [10]. According to the needs of the system, reliability, and investment costs, a water storage tank may be used instead of batteries [23].

If the PVWP system is explicitly used for irrigation, watering can be done in one of two ways: either through a water storage tank or a directly connected irrigation system to the PVWP system [24, 25]. The simplest design is connecting the PVWP directly to the irrigation system via a filtering device. There are many irrigation technologies that can be used, including sprinkler, furrow, and micro irrigation. In locations with scarce water supplies, micro irrigation is chosen as a water-saving approach.

Since fossil fuels are not required for PVWP functioning, fuel supply and price fluctuations are not a factor. The great reliability of PVWP systems, which require less maintenance and repair, is another significant benefit. Additionally, PVWP produces little noise and no greenhouse emissions or exhaust flue gases.

At the start of 2000, more than 20,000 PV pumping systems were installed globally [15]. The endeavour to achieve the United Nations' 2010 Millennium Development Goals for the expansion of solar energy applications in the agriculture sector and for improving access to clean drinking water in underdeveloped nations is anticipated to result in an increase in the previous statistic [26]. For instance, by 2014, the Bangladeshi government wants to deploy 10,000 PVWP installations. India deployed more than 50 MWp of standalone PV systems in 2010; a significant portion of these were PVWP systems [27].

Diesel water pumping systems (DWP) can be set up using either mechanical or electrical power transfer. The primary advantage of DWP systems over PVWP is their cheaper initial capital cost. However, because to the high operation and maintenance costs of diesel engines, various studies shown that PVWP systems are more practical than DWP systems from the perspective of life cycle costs [28].

One of the typical uses of wind energy is water pumping. Systems for wind-powered water pumps (WWPs) can be connected to the pump mechanically or electrically. The PVWP and WWP systems both allow for direct connection to the wind generator as well as connection via a power conditioning unit [29]. In general, PVWP systems outperform WWP systems in terms of matching water demand and supply, notably for irrigating crops and caring for animals [30]. Economically speaking, B. Bouzidi [31] demonstrated that PVWP systems cost more per unit of water whereas WWP systems cost less per unit of water. However, the 2011 PV module prices, which were noticeably higher than the current unit pricing in China, were considered in the prior analysis.

The best design for a given application [32, 33], comparisons with other power sources [34, 35], and environmental advantages [35] have been the key areas of research on PVWP systems. However, as no projects have been conducted before, deploying PVWP systems for sustainable growth of agriculture and mitigating grassland degradation in China is a viable application. The Chinese market's contribution to the price reduction of PV modules over the past five years has also boosted the market and development of PVWP systems, particularly for bigger installation capacities and new applications.

1.5.2 PV water pumping systems for farmland preservation and grassland repair

The use of PVWP for grassland irrigation in China has recently gained an increasing amount of interest due to the dual goals of preventing desertification and encouraging the sustainable growth of farmland in China. Both objectives have been a focus in recent years.

The application of PVWP systems for the protection of grazing land was examined in 2011 by the Asian Development Bank (ADB) through the installation of a prototype system with a capacity of 2 kWp in the province of Qinghai [36]. The experiment demonstrated that PVWP systems are technically and economically viable options for minimising the effects of degraded grazing area and lessening the severity of poverty. To choose the location that would be most suitable for the operation of the PVWP system, consideration was given to both the overexploitation of water resources and the practicality of the location. In addition to this, issues concerning the extension of the project's institutional and financial constraints were resolved. In the study, photovoltaic water pumping (PVWP) systems were contrasted with conventional direct water pumping (DWP) systems, however wind water pumping (WWP) technologies were not considered as a possible alternative.

It has been determined how much of Chi-practicable Na's grassland area is suitable for the use of a PVWP irrigation system by considering solar energy resources, precipitation, and terrain slope [37]. It resulted in the creation of 0.42 million km2, which is equivalent to approximately 10.5 percent of the total grassland area in China. It has been investigated in [38] whether it would be feasible to irrigate pasture grass in Inner Mongolia. Particular attention was paid to the evaluation of the water requirement for irrigation over the course of a variety of hydrologic years and the effect this would have on groundwater resources. The fact that there was an adequate supply of water despite the high demand for it was evidence that the pumping did not have any adverse effects on the water supply. However, the dynamic simulation of the system's functioning and the groundwater's response to PV pumping were not taken into consideration. Neither of these factors were considered. In addition, there was a lack of methodical system design and optimization that was based on the water requirements of agriculture and the water supplies that were accessible.

It has been determined in [38] that an analysis of the effects of PVWP systems on the volatility of the groundwater table in Qinghai and the economic sustainability of the system may be found when taking into consideration the revenue generated by the sale of grass. The productivity of irrigated pastureland was found to be increased by a factor of two hundred when compared to the productivity of non-watered pastureland. After considering the total investment costs as well as the price at the local grass market, the PVWP system was distinguished by a payback period of 8 years, demonstrating a good economic return. This was determined by calculating the system's payback period using the price at the local grass market. The studies that were carried out by ADB and X. Gao et al. [36, 18] addressed the profitability of PVWP systems, but the economic applicability related to the sale of grass in a specific region that had a specific grass productivity. In addition, there were no calculations of the productivity of grass depending on the water that was given through irrigation. In addition, a comprehensive examination of the life cycle cost was not performed, which resulted in inaccurate results from the payback time analysis.

1.6 Problem statement

Pakistan's economy is largely agricultural, accounting for 22.2 percent of GDP and employing 42.3 percent of the workforce. Water pumps have been installed in order to alleviate the problem of a lack of water for agriculture. Using renewable sources instead of fossil fuels is supported by all of the above-mentioned resources and issues. Using renewable energy to power water pumping systems is a good idea. Focus must now move to the use of technology developments and additional research discoveries to enhance irrigation techniques in order to improve efficiency overall. The use of photovoltaic water pumping (PVWP) systems are technically and economically viable options for minimising the effects of degraded grazing area and lessening the severity of poverty, authors argue. An in-depth analysis of Pakistan's water pumping infrastructure is going to be carried out as part of this research project's goals. In order to carry out this evaluation, cutting-edge approaches for instant testing and a system that is based on telemetry-based pump monitoring will be utilised. In addition to this, the thesis presents a simulation circuit for a remote-control system that makes use of a cellular network and analyses yearly trends in particular performance parameters via the lens of a pump monitoring technique. A comprehensive analysis of the performance of the pumping plants in the state of Pakistan has not been carried out for a very long time. This study will therefore contribute to the dissemination of knowledge regarding the remote control and monitoring of a water pumping system efficiencies that are present in Pakistan, which system characteristics are typically linked to poor efficiency, and the financial impact related to using pump system maintenance or redesign to improve efficiency.

1.7 Research Objectives

Above literature review establishes familiarity with and understanding of current research in a field of solar water pumping system field before carrying out a new investigation. The conduced literature review enabled us to find out what research has already been done. This study provides remote controlling of water pumping and provide the location of water availability in earth surface in Pakistan. The objectives of study are given below.

1. Design a solar water pumping system for Sukkur Pakistan.
2. Design control of a solar water pumping system using low-cost electronics.
3. Design and demonstration of a low-cost SCADA system for a solar water pumping system.

1.8 Thesis Overview

Chapter 1: Introduction and literature review

This chapter has outlined the literature on remote control and monitoring of a water pumping system located in Pakistan where gaps exist in the literature and how your research contributes to filling one or more of these gaps.

Chapter 2: Design of Solar Power Water Pumping System for Irrigation in Sukkur

This chapter presents the practical implementation of a sustainable solution. The study investigates the designing of a solar-powered water pumping system tailored for irrigation purposes. It thoroughly explores site selection, pinpointing an optimal location for the installation of the system. By aligning technical considerations with the geographic dynamics of the chosen site, this chapter highlights the proposed design with environmental suitability

.

Chapter 3: ***Remote Data Acquisition System for Photovoltaic Water Pumping System***

Transitioning from design to execution, this chapter examines into the practicalities of implementing a remote data acquisition system designed for photovoltaic water pumping using low-cost electronics. The chosen technologies, components, and their interconnections are illustrated upon, highlighting the thorough consideration in achieving robust real-time data acquisition and processing.

Chapter 4: Remote Monitoring, Control and Data Visualization for a Solar Water Pumping System

Building on the foundation laid in previous chapters, this chapter introduces an integrated framework that encompasses remote monitoring, control, and data visualization of the solar water pumping system. Through the convergence of NODE-RED and MIT App Inventor, the chapter elaborates on an all-encompassing system architecture. This architecture empowers users with immediate insights into the system's performance while fostering interaction through user-friendly interfaces.

Chapter 5: Conclusions and recommendations

This concluding chapter summarizes the key findings and contributions of the research. It highlights the significance of the developed solutions for sustainable energy and water resource management in Sukkur. Additionally, the chapter suggests potential avenues for future research and innovation in the field of renewable energy, remote monitoring, and water distribution.

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Chapter 2

Design of a Solar-Powered Water Pumping System for Irrigation in Sukkur, Pakistan

Preface

A version of this chapter has been published in the Jordon Journal of Electrical Engineering (JJEE) Reviews, November 2022. I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript. The Co-authors, Dr. M. Tariq Iqbal supervised the research, provided the research guide, reviewed, and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

Abstract

This chapter presents the design of a solar-powered water pumping system that would be used for irrigation in Sukkur, Pakistan. A dependable model of the pumping system as well as the solar system is designed in PVsyst and HOMER softwares to establish the practical and economic viability of solar-powered water pumping system at the site. The proposed system consists of a submersible centrifugal multistage deep well pump and sixty 480 W solar modules. For the purpose of evaluating the backup system's viability, a battery backup system is also connected to the system. The obtained results show that the proposed solar-powered water pumping system is a potential candidate and a viable option for employment at the selected site and at other sites that have the same conditions for water pumping and irrigation. Moreover, when compared to the cost of using nonrenewable resources, operating and maintenance costs for renewable energy systems are more manageable.

***Keywords*—** Solar-powered pumping system; HOMER; PVsyst; Renewable energy; Pakistan.

2.1 Introduction

One of the main causes of climate change due to carbon emissions and air pollution is the burning of fossil fuels to produce electricity [1] - [3]. In many regions of the world, the development of renewable and sustainable sources of clean energy has gained prominence as a result of factors such as rising prices for fossil fuels and the requirement to attain energy self-sufficiency. [4] - [7]. Due to the high energy requirements of agricultural irrigation, the use of solar powered pumping system (SPPS) has been proposed as a prospective application. For SPPS irrigation to be a practical option, it must be technically and economically feasible, just like any other use of alternative energy. In [8], the authors have investigated the potential for harnessing solar energy in Pakistan's Upper Indus Basin region of Pakistan based on the suitability of the climate and topography. They estimated the suitability of an overall 12.1% slope index of three Hindu Kush-Karakoram Himalaya ranges for the feasibility of a solar-powered irrigation system.

Rana et al. in [9] have investigated the financial and environmental impact of the solar power irrigation system, specifically for Boro rice in Bangladesh. They investigated the possibility of reducing more than one million carbon emissions into the atmosphere from agricultural sources by replacing half of the diesel-powered irrigation systems. Furthermore, they found that the change in the price of irrigation has not shown to have a significant impact on the demand for irrigation, revealing that the irrigation system is highly inelastic.

Grant et al. have proposed a solar-powered drip irrigation system design [10]. They simulated seasonal performance to reduce the life-cycle cost of the system while maintaining operational reliability. They investigated the proposed system in a Moroccan olive orchard to demonstrate the model theory by examining the optimal design's sensitivity to field area, system reliability, and weather conditions. Furthermore, some studies have shown the climatic impact of solar power irrigation systems.

Because of their low environmental impact and low maintenance needs, SPP irrigation systems are increasingly becoming the norm. There is a heavy reliance on nonrenewable energy sources like diesel engines in Pakistani irrigation [11]. Using these nonrenewable sources, on the other hand, is not only expensive but also detrimental to the health of the environment [12] - [18]. Rahman et al. [19] investigated the synergies of solar-powered irrigation as a drought-mitigation strategy in a particularly sun-deprived region of northwest Bangladesh. They argued that many of the benefits of climate adaptation, such as the formation of informal social groups, increased financial security, and new employment opportunities, are indirect, less obvious, and long-term. The feasibility of installing a small-scale solar-powered irrigation system in Uganda was examined in [20] from both a technical and ecological perspective. They calculated that initial irrigation system costs could be cut by 20%.

In [21], the authors have presented the technical viability of using solar power to induce irrigation in Pakistan, offering an alternative to conventional irrigation systems that are based on fossil fuels. They examined five agricultural exports: wheat, maize, rice, sugarcane, and cotton. According to them, for a rice field that covers one hectare, the average amount of solar panels needed to power a 4hp motor pump and keep the flow rate at 68 m3/day is 14 units with a 320 Watt capacity each. Using HOMER Pro [22], Iqbal et al. planned a PV water pumping system that could function independently on a real farm da-ta. An inverter for a pumping system with a capacity of 20.7 kW was part of the system, along with 60 batteries and 78 solar panels. Through the use of MATLAB and Simulink, a dynamic model of the system is simulated. The maximum amount of photovoltaic power that can be extracted is made possible through the use of perturbation and monitoring. In the simulations, it was found that both the voltage and the frequency were consistent.

Here, we look at the feasibility of installing a photovoltaic water pumping system in Sukkur, Pakistan. Compared to the current systems in Pakistan, this one could work. Unlike the rest of the country, the lower part of Pakistan receives an abnormally high level of solar radiation (as seen in Fig. 2.1 [11]). Hence, SPP irrigation is better than both renewable and nonrenewable water supplies. Using PVsysyt [23], we propose a model for an SPP irrigation system that makes use of PVs. The next step is to use HOMER Pro [24] to conduct a comprehensive cost-benefit analysis that factors in all relevant technical, financial, and economic factors.

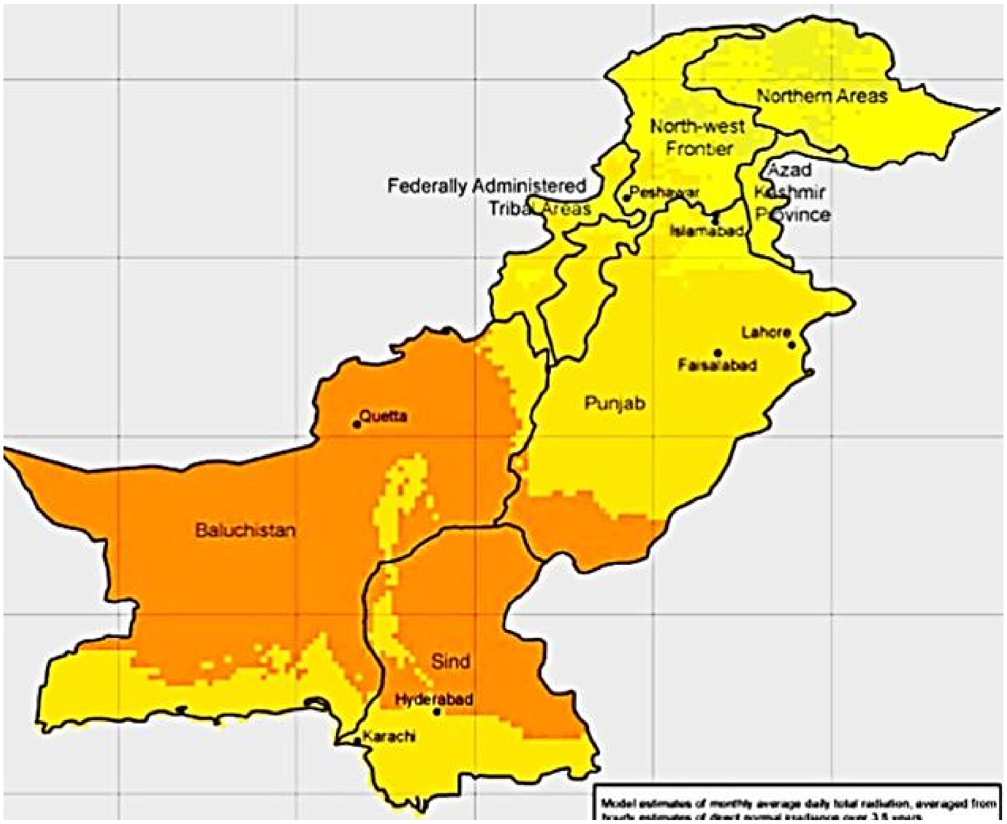

Figure 2.1 Pakistan global horizontal solar radiation [9]

Figure 2.2 Location of the Site on Google Map

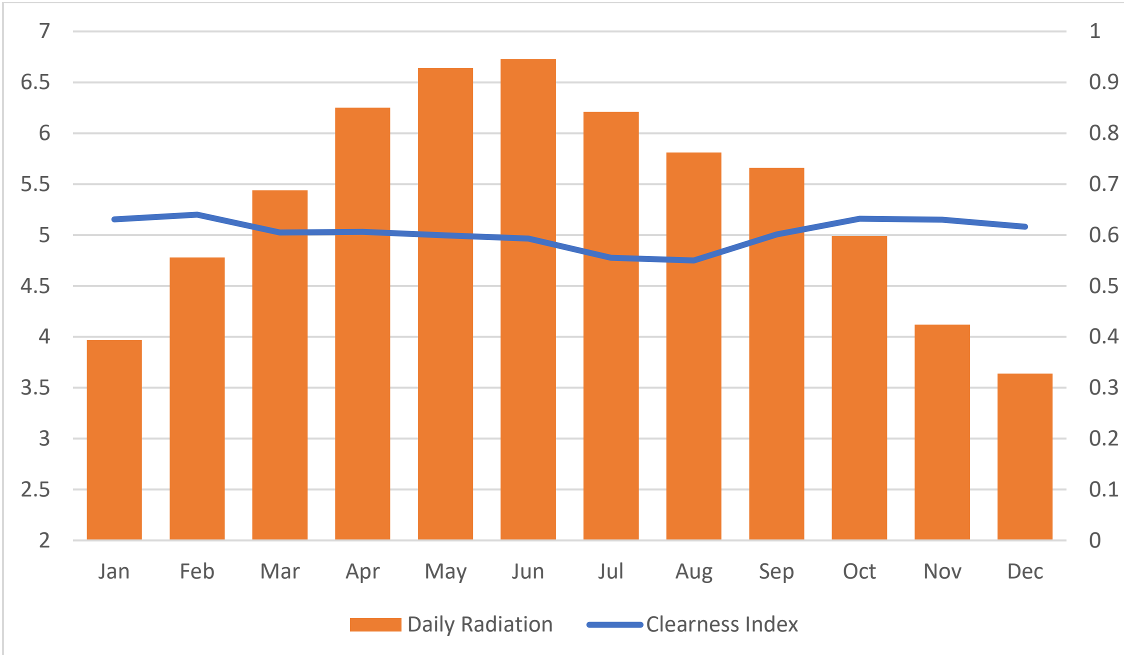

Figure 2.3 Irradiance and Clearance Index of the Site

The organization of the chapter can be seen in the following. The specifics of the location will be discussed in Section II. In Section III, the specifics of the proposed design produced by PVsyst and HOMER PRO are dissected and discussed. Section IV contains the presentation and discussion of the simulated results, and Section V provides a summary and conclusion of the article.

2.2 Site Selection

2.2.1 Site Description

A farm located in the tehsil of Saleh Pat in the district of Sukkur, Pakistan, of 20 acres in size has been chosen as the location for the project. The GPS coordinates of the selected location are 27.481784, 69.051130. The position of the facility is shown on Google Maps in Fig. 2.2. Date palms have been planted across the land, each one spaced out by 20 feet by 20 feet. On the farm, there are around one thousand plants, all of which are in varying phases of development.

2.2.2 Solar Radiation at the Selected Site

One of the most crucial aspects of a site's viability is the quantity of solar irradiance it receives. Measured solar irradiance is the amount of energy from the Sun that is received at a given location and distance from the Sun. From 3.64 to 6.73 kWh/m2/day, as depicted in Fig. 2.3, radiation from the sun is readily available throughout the year. The clearance index is a measurement of how well one can see through the air. Similarly, Fig. 2.3 depicts this for the location. Its annualized rate of change is between 0.550 and 0.640, and it has never been higher than 1. The sun's horizon line at the chosen location is shown in Fig. 2.4.

2.2.3 Calculation of the load for the water pump

For the solar water pump load, the site data collected is as follows:

Water required by date palm tree = $287\ L/day$ [22] (1)

Water required by 1000 date palm trees = $287\ m^3/day$ (2)

Flow Rate for 24 hours = $11.958\ m^3/h$ (3)

The amount of time spent in direct sunlight that is ideal each day is between six and eight hours. As a result, a higher flow rate is necessary in order to keep the pump operating for 6–8 hours in order to collect the necessary amount of water. The increase in flow rate will be calculated as 24 hours divided by 6 hours, which is equal to four times. So,

$$\text{Flow Rate} = 11.958 \times 4 = 47.8\ m^3/h \quad (4)$$

$$\text{Water depth} = 100\ feet = 30.48\ m \quad (5)$$

$$\text{Total Dynamic Head} = 35\ m \quad (6)$$

Hydraulic power of the water pump (P_h) is calculated as:

$$P_h = \rho \times g \times h \times \frac{Q}{3600} = 4557.5\ W \quad (7)$$

where = density of water, g = gravitational acceleration (m/s^2), h = dynamic head, Q = water flow ($m^3/hour$).

Motor efficiency (η) is estimated to be 80%. Therefore, Motor Power (P_m) will be:

$$P_m = \frac{p_h}{\eta} = \frac{4557.5}{0.8} = 5696.82\ W \quad (8)$$

The pump efficiency is estimated to be 50%, so:

Required Power (P) is calculated as:

$$P = \frac{5696.82}{0.5} = 11.394\ kW \quad (9)$$

Since a motor is required in horsepower, therefore, the required pump is estimated to be $15.27\ hp$.

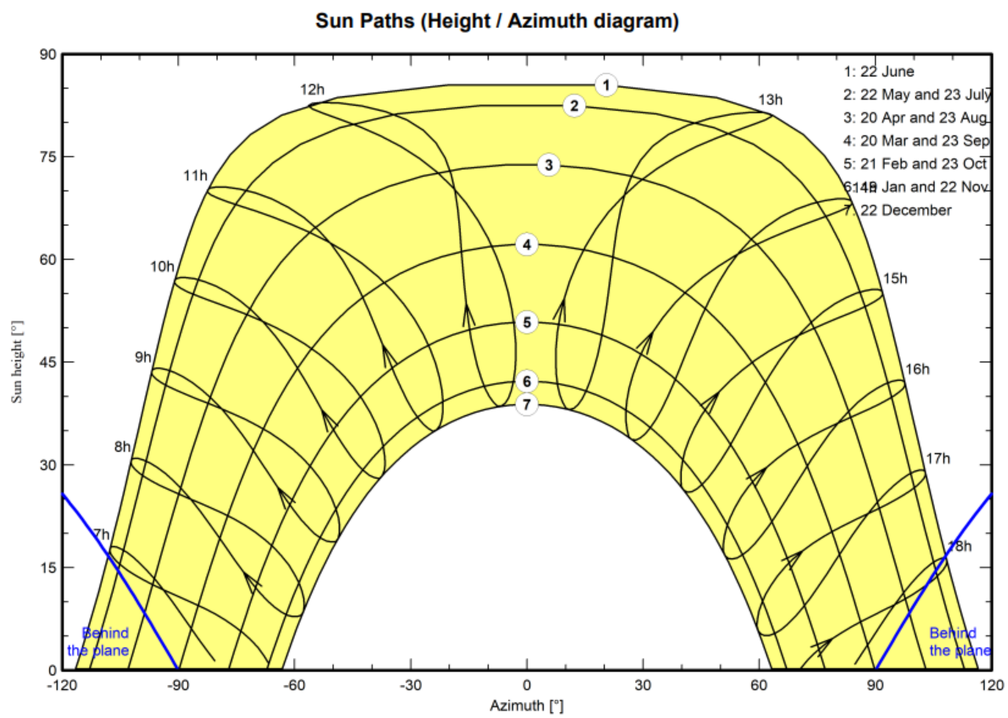

Figure 2.4 Sun Horizon line at the project location.

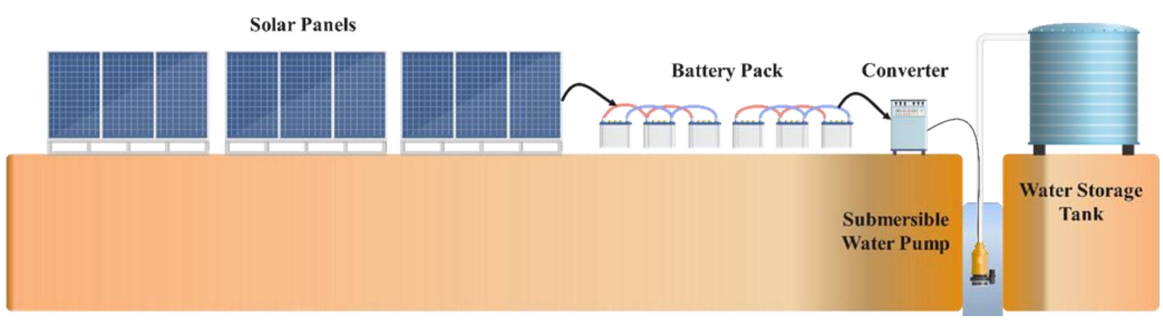

Figure 2.5 Schematic of deep well system

2.3 Design of PV Based Water Pumping System

The PV based water pumping system that would be used for irrigation was designed with the help of PVsyst software [23]. Pvsyst's primary focus is analyzing and improving PV systems as well as sizing them. The estimated design cost is then calculated using the Hybrid Optimization Model for Electric Renewables (HOMER) software [24]. To get the best possible results from using HOMER, we must optimize its economic costs.

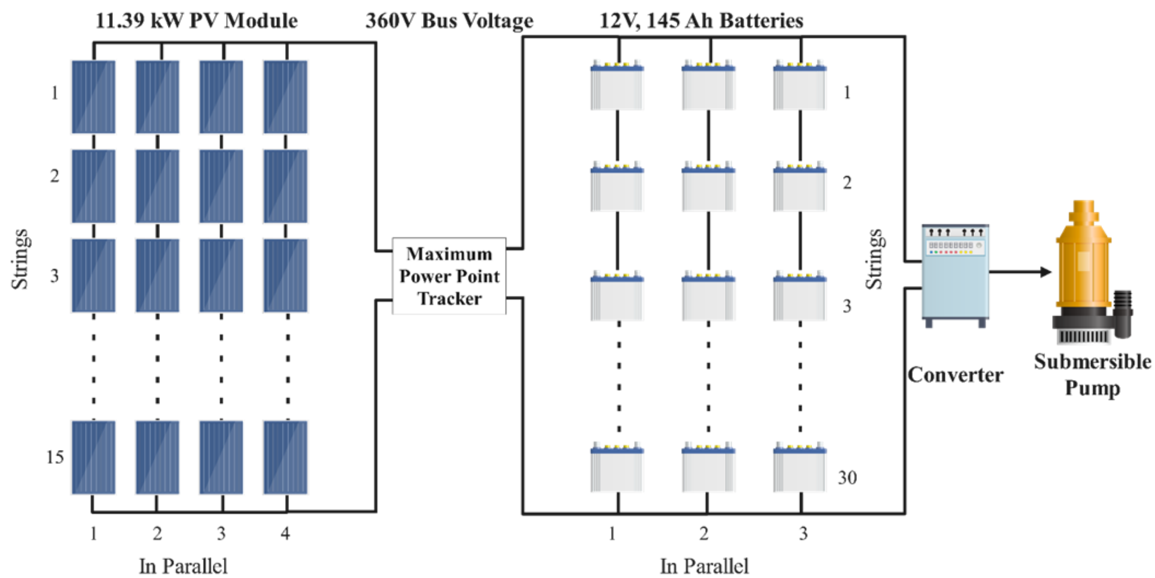

Figure 2.6 Configuration of proposed system

2.3.1 Design of the Based pumping system in PVSyst

For PVsyst to determine the system's output, it needs to be given the system's location (including GPS coordinates) and solar irradiance data (obtained from the Meteonorm database). The specified location is covered by these statistics for the years 1996 through 2015. After that, we detail how much water will be needed, as well as the features of the PV modules and the pump that will allow them to work together. The following discussion will elaborate on the specifics of these demands.

1. Water and Pumping Requirements

The water level in the well is stable at a depth of about 100 feet (30.5 meters), and the rate of drawdown is 1 meter per cubic meter per hour. A pump that can be submerged to a depth of 90 meters. Considering that 287 m3/day is the yearly average, a water storage tank with a capacity of 574 m3/day is required to store enough water for two days. The schematic of the proposed system is shown in Fig. 2.5 and Fig. 2.6.

2. The photovoltaic system

Although the calculated electrical power is 11.39 kW, PVsyst suggested using an AC pump with a capacity of 13 kW. This means that a photovoltaic system with a capacity of 15.36 kW is

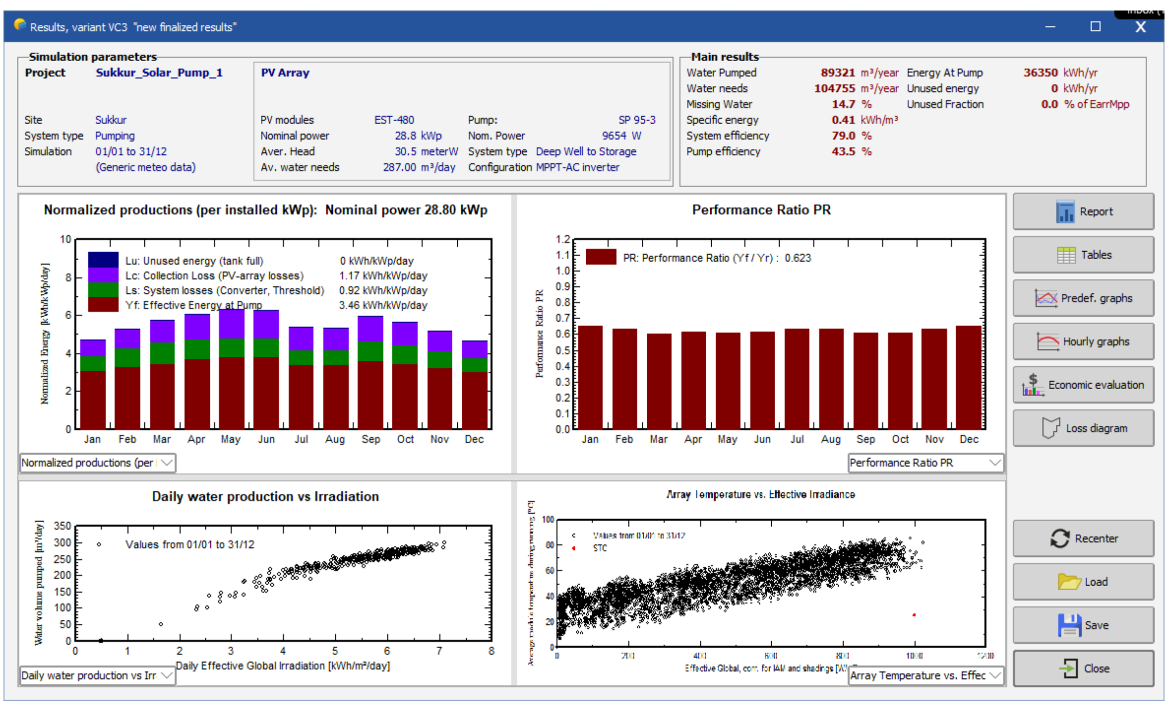

Figure 2.7 Simulation result of proposed system in PVsyst

recommended for installation to account for any potential electrical losses. However, because of this, 54% of the water was wasted. This means that a photovoltaic system with a capacity of 28.8 kW should be installed. Therefore, the water shortage issue was resolved to the extent that it dropped from 54% to 14.7%.

The proposed photovoltaic (PV) system will feature sixty individual modules of solar panels, each of which will have 480 watts of power. The ENN Solar EST-480 photovoltaic model will serve as the basis for the proposed system. A total of four 15-strings would are connected to the module in a series configuration.

The recommended tilt angle for the summer season is 140 degrees, while the recommended tilt angle for the winter season is 440 degrees. It has been determined that the azimuth angle is 0 degrees. In addition to that, you will need an AC-MPPT converter, which stands for maximum power point tracking, and it must have an efficiency of 97% or higher. Fig. 2.7 shows the configuration of the Utilized PV system.

2.3.2 System Configuration in HOMER

A comma-separated values (CSV) file containing information about the building's electrical consumption is read by HOMER (CSV). HOMER will use this information to calculate the optimal dimensions for the PV module and the battery storage. After everything is said and done, HOMER will give the selected setup a score. The evaluation will take into account the levelized cost analysis in addition to the net present cost (NPC). For a year, HOMER will have access to the site data we provided. Modelling the same photovoltaic (PV) system with an 11.39 kW nominal load yields the same results. Because of the abundant solar insolation, the pump is expected to run for a total of 6 hours every day. An average daily load of 68.36 kWh will be incurred due to the 6-hour period of operation. Additionally, a backup battery system has been built in. As a result, there is a better chance of having power on days with precipitation or cloud cover. Moreover, it might come in handy late at night if absolutely necessary.

2.3.3 System Configuration in HOMER

NPC

The NPC of a Component, also known as its life-cycle cost, is calculated by taking the present value of all the costs associated with installing and operating the Component over the course of the project's life-time, subtracting the present value of all the revenues that the Component generates over the course of the project's lifetime, and then multiplying the result by one hundred. The net present cost of each component in the system, as well as the total cost of the system, is determined by the HOMER.

Levelized cost of Energy

The levelized cost of energy, or COE, is what HOMER refers to as the average cost incurred per kilowatt-hour of usable electrical energy generated by the system.

Annualized Operating Cost

The annualized operating cost is the value of all costs and revenues, excluding those associated with initial capital expenditures.

Table 2.1 Results of the Proposed System in PVsyst

Month	**Global Efficiency** (kWh/m^2)	**Array Energy at MPP** (kWh)	**Pump Operating Energy** (kWh)	**Average Total Pump at Head** (meterW)	**Water volume pumped** (m^3/day)	**Water Used** (m^3/day)	**Missing Water** (m^3/day)
January	144.1	3471	2767	61.46	220.6	228.2	58.83
February	144.7	3458	2688	62.64	239.1	239.1	47.89
March	174.2	4096	3109	62.56	249.8	249.5	37.53
April	177.1	4098	3201	61.17	261.8	261.2	25.82
May	190.5	4313	3410	60.97	269.8	270.3	16.72
June	184	4182	3330	60.58	271.3	271.4	15.6
July	163.2	3729	3047	58.88	237.2	236.7	50.27
August	161.6	3731	3040	59.18	237.8	238.6	48.36
September	174.8	4022	3127	61.19	255.9	255.3	31.67

October	172.5	3980	3084	61.04	243.8	244.2	42.77
November	153.2	3583	2834	62.34	234.4	234.5	52.51
December	141.6	3371	2712	61.08	215.9	217.7	69.34
Year	**1981.6**	**46033**	**36350**	**61.03**	**244.7**	**245.5**	**41.5**

2.4 Results

2.4.1 PVsyst Design Result

PVsyst delivers the simulation results for the photovoltaic system that is coupled to the water pump. The proposed system will produce a total of 89,321 m3 worth of water over the course of a single year. Fig. 2.8 depicts, over the course of one year, the normalized water output that is generated for every kW of installed capacity. It has been determined that the overall efficiency of the system is 79%, whereas the efficiency of the pump has been calculated to be 43.5%. Table 2.1 provides a monthly basis, of the production of renewable energy and the consumption of water over the course of a year. This breakdown is presented in conjunction with the consumption of water.

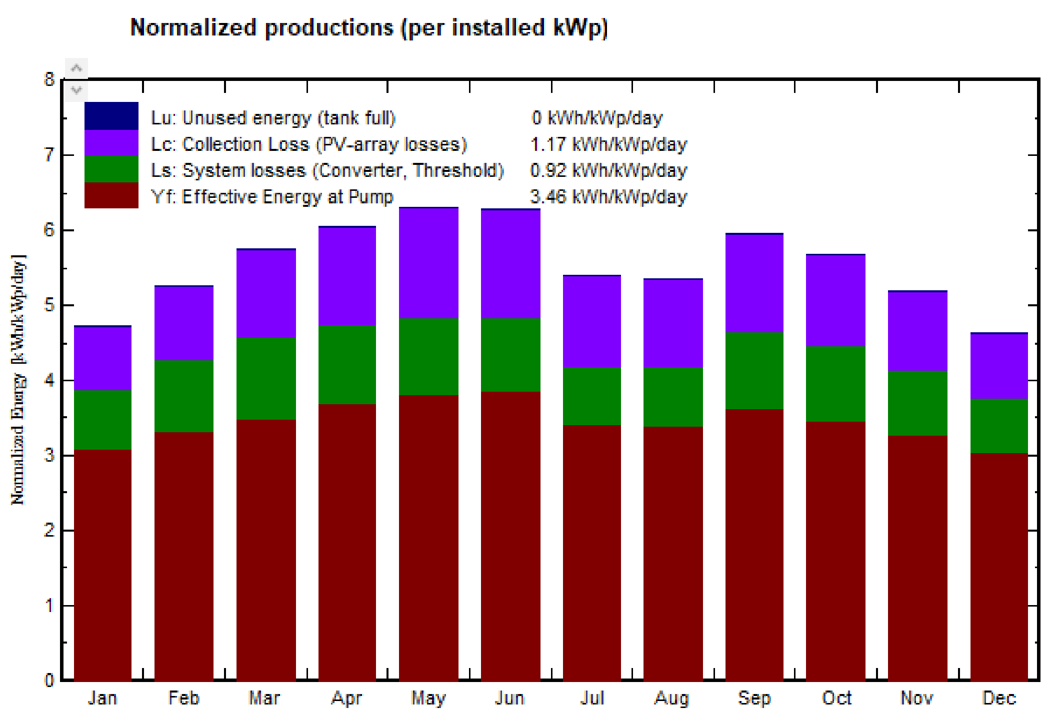

Figure 2.8 Monthly normalized water productions per installed kW over the period of one year (kWh/kWp)

It is estimated that the proposed system will have an efficiency of 1981.6 kWh per square meter for amount of power it produces per area. The total energy produced by the array when it operates at its maximum power point is estimated to be 46 MWh per year, while the energy produced by the pump when it is in operation is 36 MWh per year. Furthermore, it is estimated that the total head of the pump is 61mW on average. While the proposed system pumps an average of 244.7 m3, the user will draw an average of 245.5 m3 of water from the system on a daily basis. This results in an average loss of water quantity of 41.5 m3, which is referred to as missing water.

2.4.2 HOMER Design Result

Block diagram of the utilized PV system that was simulated in HOMER is depicted in Fig. 2.9. One AC bus and one bus carrying direct current (DC) are necessary to realize the design in its full potential. The DC bus is connected to the PV system and a battery backup. There is a connection between the pump and the DC-AC converter via the AC bus.

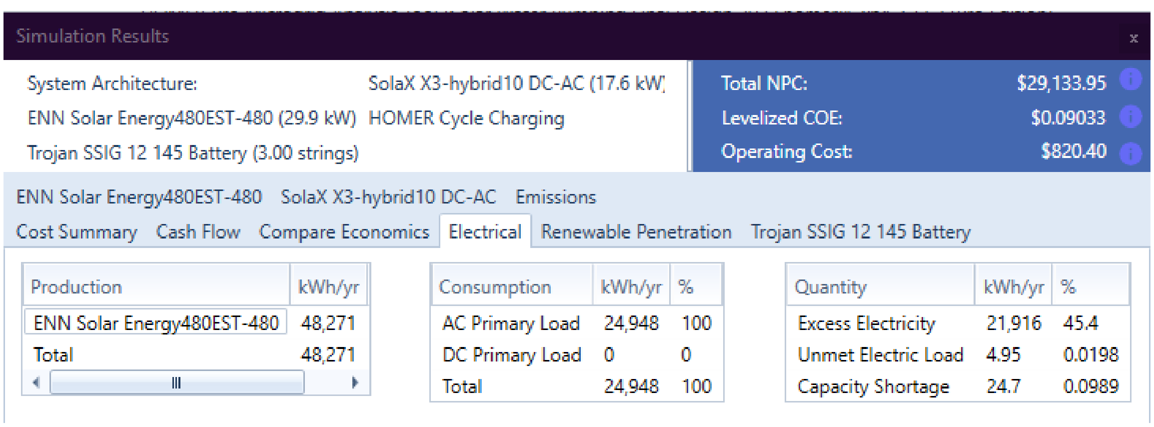

Figure 2.9 Simulation result of proposed system in HOMER

The foundation for the PV system is the same as that used by PVsyst; it is the ENN Solar Energy480EST-480 system. The feasibility of using a backup system is also evaluated by connecting a battery to the system. To power the system, readily available Trojan SSIG 12 145 batteries were incorporated into the blueprints. Homer's PV setup and battery pack specifications are listed in Tables 2 and 3, respectively.

Table 2.2 Details of ENN Solar Energy 480 EST-480

	Value	Unit
Rated Capacity	29.9	kW
Mean Output	5.51	kW
Mean Output (per day)	132	kWh/day
Capacity Factor	18.4	%
Total Production (per year)	48,271	kWh/year

Table 2.3 Details of Trojan SSIG 12 145

	Value	**Unit**
Batteries	90	Qty.
String Size	30	Batteries
String in Parallel	3	Strings
Bus Voltage	360	Volts
Autonomy	44.3	Hours
Nominal Capacity	158	kWh
Annual Throughput	3,059	kWh/year
Lifetime Throughput	43,650	kWh

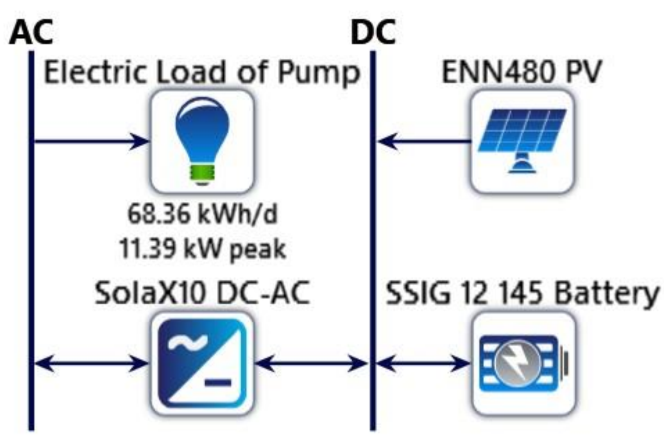

Figure 2.10 System block diagram in HOMER

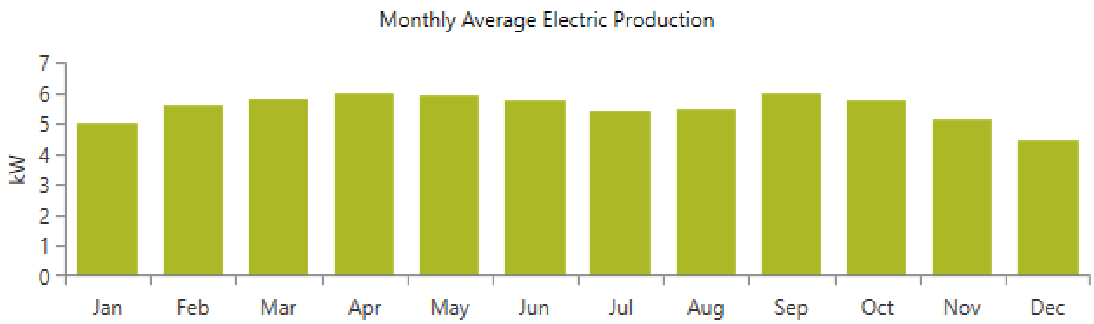

Figure 2.11 Monthly average electric production of proposed system in HOMER

Table 2.4 Annualized Cost Summary of the Proposed System in HOMER

Component	**Capital ($)**	**Replacement ($)**	**O&M ($)**	**Salvage ($)**	**Total ($)**
ENN Solar Energy480EST-480	$717.77	$0.00	$508.85	$0.00	$0.00
SolaX X3-hybrid10 DC-AC	$34.66	$0.00	$36.66	$0.00	$0.00
Trojan SSIG 12 145 Battery	$681.22	$298.17	$17.10	$0.00	-$40.09
System	**$1,433.65**	**$298.17**	**$562.61**	**$0.00**	**-$40.09**

Table 2.5 Comparison With Non-Renwable Resources

	Solar Powered	**Natural Gas Powered**	**Diesel Powered**	**Grid Connected**
Initial Investment	High	Low	Low	Low
O&M Cost	Low	Medium	High	Medium
Maintenance	Medium	High	High	Medium
Environmental Impact	Eco-Friendly	Emits Medium Pollution	Emits High Pollution	Emits Medium Pollution

The itemized cost of the proposed system is provided in Table 2.4. The annualized initial cost of PV panels is $717.77 while operating and maintenance (O&M) cost is estimated to be $508.85 per year. There is no replacement cost of the PV panels. The DC-AC converter initial cost is $34.66 while annual O&M cost is $36.66. The battery pack initial cost is approximated to be

$681.22 while O&M cost is $17.10 per year. There is also a replacement cost of $8,714.36 in the 15th year and estimated to be $298.17 per year.

The NPC has a market value of $29,142.90, and annual operating expenses will be $820.68. The initial investment cost was $18,534, and the market value of the NPC is $29,142.90. The estimated value of the levelized cost of energy (COE) per kilowatt hour is $0.09036. The cost breakdown of the proposed system is presented in Fig. 2.12. Fig. 2.13 presents the cash flow of the proposed system. The initial cost is determined to be $18,533 according to cash flow analysis, with the cost of replacing the battery estimating $8,714.36 every 15 years. After 25 years, the project will have a salvage value of $2,163.64.

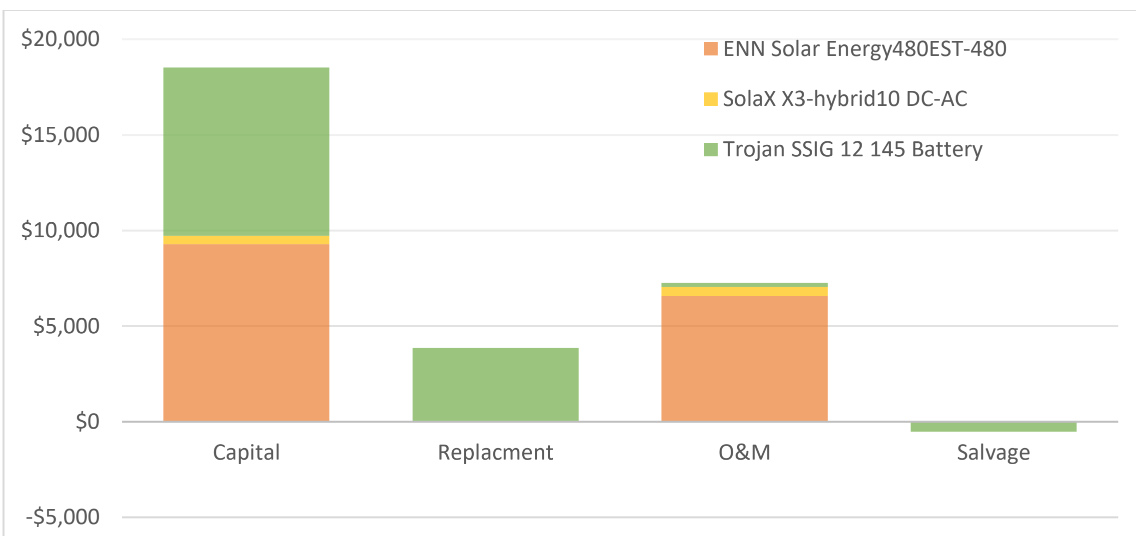

Figure 2.12 Cost summary of the proposed system

2.5 Comparison of the Proposed System with Non-renewable Resources

We have compared our model with two other generators that use non-renewable resources, such as diesel and natural gas generators, as well as grid-connected systems

[25, 26]. The analysis of non-renewable resources can be found in Table 5. In comparison to diesel-powered, natural gas-powered, and grid-connected systems, the initial investment costof our proposed model is significantly higher; however, overall, it results in significantly reduced costs for both operation and maintenance. In addition, the proposed system requires only a moderate O&M cost in contrast to other non-renewable resources.

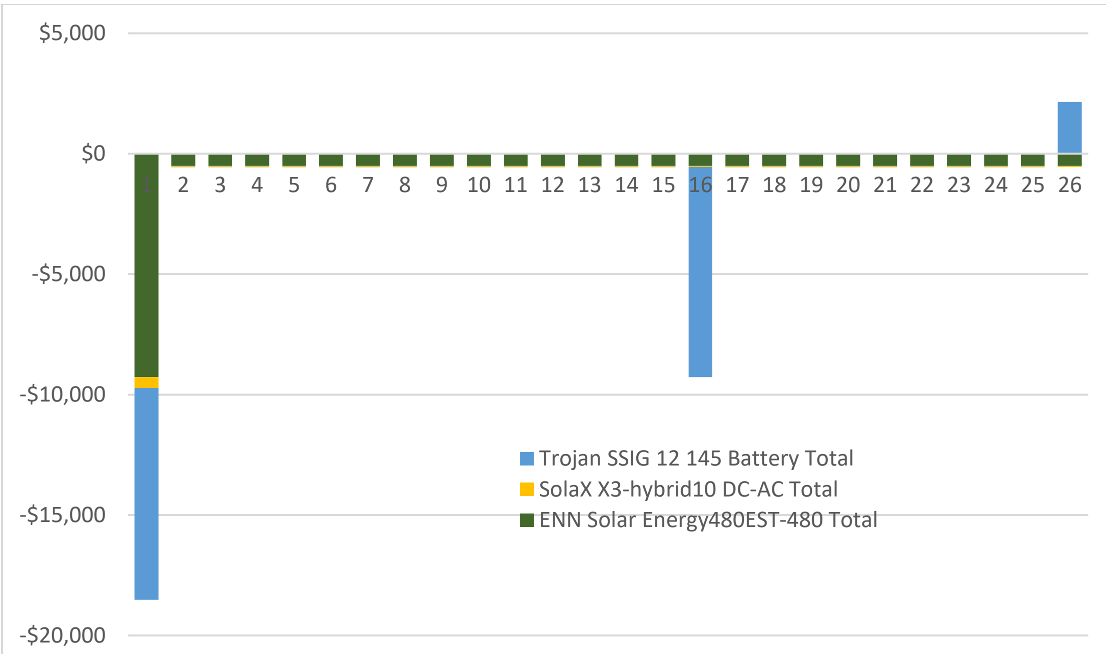

Figure 2.13 Cash flow of the proposed system for over the period of 25 years

Table 2.6 Comparison of Prposed Model With Diesel And Natural Gas Gensets

	Only PV with backup	**PV with backup and Natural Gas Genset**	**PV with backup and Diesel Genset**	**PV without backup and Natural Gas Genset**	**PV without backup and Diesel Genset**
Capital Investment	$18,533.53	$15,900.68	$18,836.64	$45,807.24	$41,423.11
Replacement	$3,854.60	$4,440.46	$5,476.92	$709.22	$858.65
O&M Cost	$7,273.09	$6,541.86	$6,618.87	$29,765.33	$26,642.43
Fuel Cost	$0.00	$3,143.79	$1,224.12	$21,272.36	$36,857.03
Salvage	-$518.32	-$391.52	-$833.15	-$297.85	-$148.53
Total (NPC)	**$29,142.90**	$29,635.27	$31,323.40	$97,256.29	$105,632.71

Table 2.7 Comparison With Grid Tied System

	Only PV	Grid-Tied PV
Capital Investment	$18,533.53	$25,696.27
Replacement	$3,854.60	$0.00
O&M Cost	$7,273.09	-$36,196.79
Fuel Cost	$0.00	$0.00
Salvage	-$518.32	-$678.49
Total (NPC)	$29,142.90	-$11,179.01

We have run simulations of our model alongside natural and diesel generator sets and compared all of these to rechargeable energy sources. We have simulated PV systems with backup, as well as PV systems with natural gas or diesel generators with backup, and PV systems with generators but without battery backup. Table 6 presents an illustration of the comparison of the simulated models. It shows that the proposed system has lowest NPC when only PV system and battery backup system are used. The NPC is determined to be

$29,142.90 while PV along with battery backup and with non-renewable sources is between

$29,635.27 and $31,323.40. If the same PV system is used without battery backup, the systemis quite inefficient. However, if we add a non-renewable system with PV only and no battery backup is used, the NPC ranges from $97,256.29 to 105,632.71 which is quite high. Therefore,the PV system with battery backup is the recommended system when compared to other options.

Furthermore, we have simulated a model that includes a grid-tied system with net metering, despite the fact that there is currently no chance that the grid will be extended tothe location of the project. The comparison is detailed in Table 7. It is clear that the project will actually become profitable with a negative NPC once the proposed system is connected to the grid. On the other hand, connecting to the grid in the near future is unlikely to happen.

2.6 Conclusion

An irrigation water pump powered by renewable energy sources is modelled after this study's findings. After showing how to design a submersible AC pump according to a site's water requirements in Sukkur, we used HOMER Pro to estimate the system's up-front andrecurring costs. Specifically, 60 PV panels (4 strings of 15 panels) will be connected in series to provide the necessary 29.9 kW of PV capacity for the system. In addition, 90 12V 145Ah batteries connected in 3 strings of 30 in series are needed for the system to function properly. We have analysed how the proposed system stacks up against conventional energy sourceslike natural gas and diesel generators. From our testing, we have learned that the net present cost of a solar-powered pumping system is significantly lower than that of a system that relies on non-renewable energy sources. The proposed system becomes financially viable with a negative net present cost if the same system can be connected to a net metered grid. After conducting extensive research and optimizing the system with HOMER, it was determined that the O&M costs are fair when weighed against those of non-renewable energy sources.

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Chapter 3

Remote Data Acquisition System for Photovoltaic Water Pumping System in Sukkur

Preface

A version of this chapter has been accepted in the European Journal of Electrical Engineering and Computer Science (EJECE), June 2023. I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript. The Co-author Dr. M. Tariq Iqbal supervised the research, provided the research guide, reviewed, and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

Abstract

Access to high-speed intsernet connectivity is limited in Sukkur, Pakistan, making alternative communication technologies essential for real-time monitoring and control of photovoltaic (PV) water pumping systems. This chapter presents the design, implementation, and evaluation of a GSM-based remote data acquisition and logging system for a PV water pumping system in Sukkur. Leveraging abundant sunlight in the region, the proposed system utilizes 2G GSM technology for communication between the PV system and the remote monitoring station. A network of sensors captures key parameters, and the acquired data is processed, stored, and transmitted using 2G GSM, enabling remote access and real-time monitoring from any location with GSM coverage. The implemented system incorporates an Arduino microcontroller for core operation and employs an SD card for data logging. Real-time data logging allows for detailed tracking and analysis of system performance, facilitating troubleshooting and optimization. Data stored on the SD card can be transferred to a computer for further analysis using data analysis software or custom applications, providing meaningful representation of trends and insights into system operation. The system also features an OLED display for real-time feedback on essential parameters, including solar irradiance, water level, and pump status. Furthermore, the integration of user prompts and GSM communication enables remote monitoring and control, empowering users to inquire about system status and remotely activate or deactivate the pump through SMS commands. The system offers a robust and adaptable solution for efficient management and maintenance of the solar-powered water pumping system in Sukkur, Pakistan.

Key words — GSM; PV water pumping system; remote data acquisition system; Pakistan.

3.1 Introduction

In recent years, the utilization of renewable energy technologies has revolutionized various sectors, including agriculture and water resource management [1]–[3]. To meet the increasing demand for irrigation in regions with limited access to reliable electricity grids, photovoltaic (PV) water pumping systems have emerged as a sustainable solution [4], [5]. By harnessing solar power, these systems offer an environmentally friendly and cost-effective alternative to traditional diesel or grid-connected pumps [6]–[8].

Efficient monitoring and control mechanisms are crucial for optimizing the performance and effectiveness of PV water pumping systems [9], [10]. Accurate and real-time data acquisition plays a vital role in enabling informed decision-making, effective maintenance, and performance evaluation [11]–[13]. However, traditional manual data collection methods are labor-intensive, time-consuming, and prone to human errors. Consequently, the integration of remote data acquisition and logging systems has become imperative for ensuring the reliable operation of PV water pumping systems.

There has been a growing interest in the use of wireless technologies for monitoring and control of water pumping systems in recent years. This is due to the many advantages that wireless technologies offer, such as their flexibility, low cost, and ease of installation. In [14], a GSM-based distribution transformer monitoring system was developed. The system used a GSM modem to collect data from sensors installed on the transformer, and then sent the data to a central database for analysis. In [15], a GSM-based monitoring and control system was developed for photovoltaic power generation systems. The system used a GSM modem to collect data from sensors installed on the photovoltaic panels, and then sent the data to a central server for analysis. In [16], a wireless monitoring management system for water supply pipe network based on GPRS was developed.

The system used GPRS to collect data from sensors installed on the water supply pipe network, and then sent the data to a central server for analysis. In [17], the study describes the design and implementation of a real-time monitoring system for fresh water quality. The system uses a wireless sensor network to collect data from sensors installed in a freshwater resource, and then sends the data to a central server for analysis. Thomson et. al in [18] presented a novel application using simple microprocessor, accelerometer, and GSM components to record graduated time-step information flows of lever pumps. Shariff et. al in [19] have explored the hardware and software design for a photovoltaic remote monitoring system. The system uses a voltage sensor, current sensor, temperature sensor, and irradiation sensor to collect data from a photovoltaic system. The data is then transmitted to a central monitoring station using a GSM modem. Mo et. al [20] presented a system for automatically measuring and reporting water quality. The system uses a GSM network to send data from sensors to a central monitoring station. In [21] N. Barsoum and A. Peter have presented a system for monitoring and controlling the temperature and soil moisture in a greenhouse. The system uses a GSM modem to transmit data from sensors in the greenhouse to a central monitoring station.

Some other studies explored the data logging system along with data acquisition systems. For instance, the study presents the design and development of a fast and low-cost data logger for PV water pumping systems [22]. The data logger uses a microcontroller to collect data from sensors installed on the PV system, and then stores the data in a memory card. Hunar et. al [23] explored the use of a GSM wireless datalogger to monitor a small hydro power generation system. The datalogger collects data from sensors and transmits it to a central monitoring station using a GSM modem. B. Getu [24] proposed a system for remotely controlling water pumps in a garden plantation using Arduino and GSM technology. The system uses a microcontroller, a GSM modem, and sensors to collect data on the water level in the tank and the soil moisture level. Another study [25] explored a system for remotely monitoring the operation of a power transformer using GSM technology. The system uses a microcontroller, a GSM modem, and sensors to collect data on the load currents and temperature of the transformer. Similarly, in [26] suggested a system for remotely monitoring the water level in a tank using GSM technology. The system uses a microcontroller, a GSM modem, and a water level sensor. The data is stored and then transmitted to a mobile phone, where the user can view it and act if necessary.

Several other studies have explored the utilization of wireless technologies such as Wi-Fi and IoT for monitoring and controlling of water pumping systems. For instance, [27] describes how to design and assemble a low cost online monitoring and Wi-Fi data acquisition system using free software applied to microgeneration based on renewable energy sources. The system uses an embedded Wi-Fi modem coupled to a microcontroller board based on the free tool SanUSB. Another study [28] have explored a system for monitoring the performance of a photovoltaic water pumping system using the Internet of Things (IoT). The system uses a microcontroller, a GSM modem, and sensors to collect data on the performance of the system. The data is then transmitted to a cloud-based server, where it can be viewed by the system operator. Similarly, [29] describes a system for monitoring the performance of a water pumping system using a lithium-ion battery, free open-source software, and IoT technologies. [30] explores a system for monitoring using IoT technologies.

3.2 Simulation of the Proposed Setup

The simulation is done in Proteus VSM. The software does not have the libraries to simulate the Arduino Microcontroller. However, the library is available online and are imported in the simulation environment. Fig. 3.1 shows the simulation of the proposed system. The logic state point is used to imitate the light dependent resistor module that provides a digital input to the microcontroller. When the logic state is set to zero, it suggests that there is high solar irradiance while when it is set to one, it presents a lower solar irradiance. A simple DC motor is also used to imitate the water pump and is controlled by a relay. A library of GSM module with model GSM900 is imported into the environment to simulate the GSM connectivity. However, the library is not fully functional resulted in partial responses.

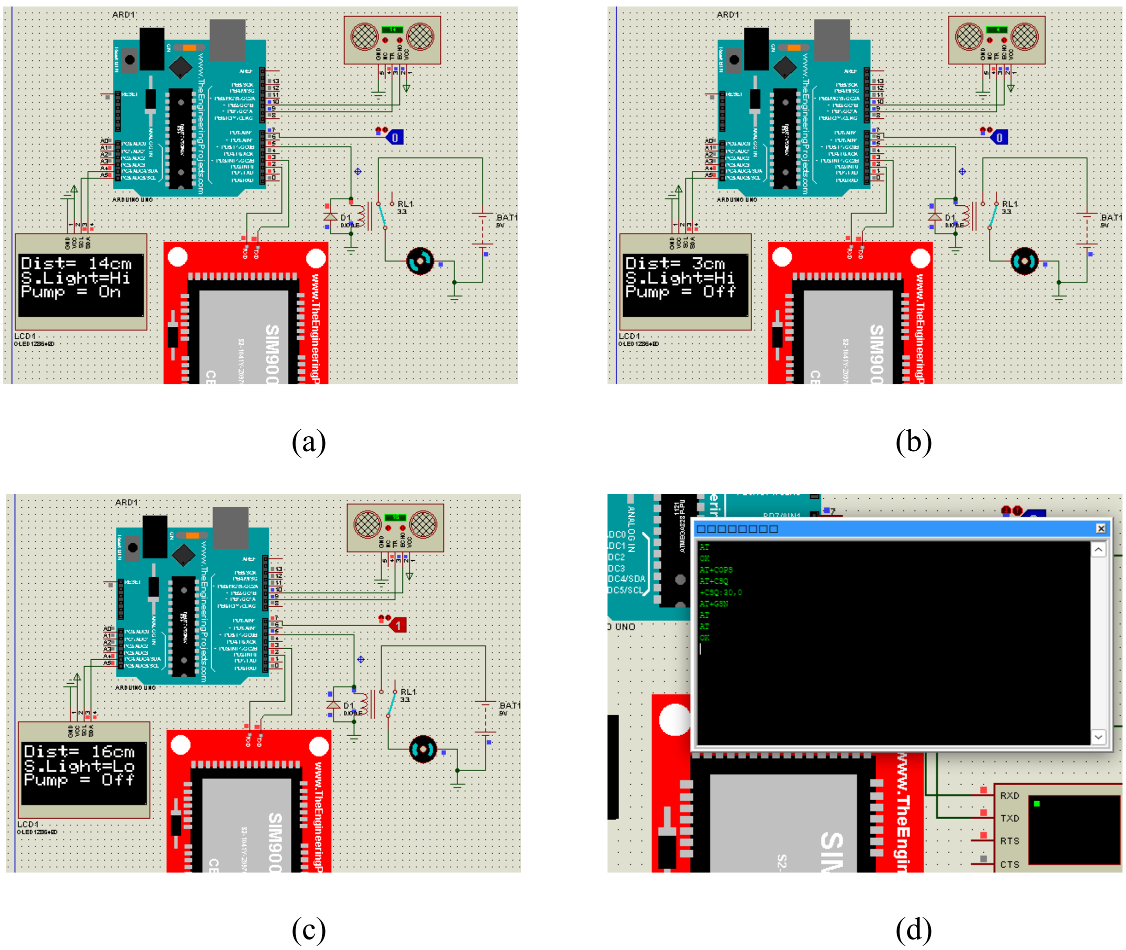


Figure 3.1 Simulation Setup of the proposed system

The setup was designed and tested for the logic when there is sufficient sun light / solar irradiance and level of water is low in the tank. The ultrasonic sensor measures the distance to the water level and sends the value to Arduino using I2C. The Arduino converts the value to cm and displays it on the LCD. As the water level increases, the distance gets lower and at full level, the ultrasonic measures 5cm. This is the threshold where the system assumes the water level is high. Below that level it is considered low. Fig. 3.1(a) shows the state of pump when the conditions are met, Fig. 3.1(b) and Fig. 3.1(c) illustrates the state of pump when either one of the conditions are not met resulting in pump not running. Fig. 3.1(d) illustrates the communication between Arduino and the GSM900 module, however, the library is not fully functional resulting in missed responses and partial communication. The setup was validated in the simulation setup and moved to the hardware experimental setup.

3.3 Components of the Proposed System

The system consists of following components:

- Arduino UNO R3
- 128 x 64 OLED for local display
- 220 Ω and 4.7 kΩ Resistors
- Ultrasonic Distance Sensor for water level measurement
- Photoresistor to measure solar irradiance.
- Motor for the pump
- Single Pole Double Throw (SPDT) Relay for motor control
- 18650 Li-ion Battery Cells for backup
- Sim800l GSM Module for 2G network connectivity

Let us go over each of them one at a time, starting with the first one:

3.3.1 Arduino Uno R3

The Arduino UNO R3 is a robust microcontroller board that is widely favored for a broad spectrum of applications, from robotics to home automation projects. It accommodates a plethora of sensors and modules, empowering inventors to devise various projects like weather stations, digital thermometers, and even simple robots. Its built-in USB interface facilitates uncomplicated communication with computers, thereby enabling project control and data collection.

Arduino UNO R3 supports C and C++ programming languages, using the Arduino Software (IDE), which is intuitive and friendly even to those new to coding. It makes the board a first choice for beginners. However, seasoned developers can also capitalize on the IDE's potential to craft more intricate code structures. Furthermore, the board can be programmed using other development environments compatible with AVR microcontrollers for additional flexibility. The Arduino UNO R3 boasts 14 digital I/O pins and 6 analog input pins. The digital pins are multifunctional, supporting inputs from various sensors, such as light sensors, pressure sensors, and infrared receivers. The analog input pins, on the other hand, cater to measuring analog signals, such as those from variable resistors or analog temperature sensors.

Beyond the I/O pins, the UNO R3 possesses an onboard USB to serial converter, which eases the programming and debugging process. It also supports bootloader, making it possible to upload new code without the use of an external hardware programmer. The Arduino UNO R3 operates on a 5V power supply and has a maximum current per I/O pin of 20mA. It also possesses a clock speed of 16MHz, ensuring speedy and dependable processing. Considering its versatility, flexibility, and ease of use, the Arduino UNO R3 is a popular choice amongst hobbyists, students, and professionals. The following tables elaborate on its features, available peripherals, pinouts, and other specifications:

Table 3.1 Pin Configuration of Arduino UNO R3

Pin Label	**Function**
0 (RX)	Digital pin used for serial communication (reception)

1 (TX)	Digital pin used for serial communication (transmission)
2 – 13	Digital I/O pins
A0 - A5	Analog Input pins
GND	Ground pins
Vin	Input voltage to Arduino when using an external power source
5V	Provides 5 volts
3.3V	Provides 3.3 volts
IOREF	Carries the voltage reference for the board
Reset	Resets the microcontroller

- Digital pins 0 (RX) and 1 (TX) are also used to receive (RX) and transmit (TX) TTL serial data.
- Digital pins from 2 to 13 can be used as input or output, using pinMode(), digitalWrite(), and digitalRead() functions.
- Pins A0 to A5 can be used as analog inputs using analogRead() function and as digital I/O pins using digitalRead(), digitalWrite() and pinMode() functions.
- GND, 5V, and 3.3V pins are power pins.
- Vin pin can be used when running the board with an external power source (6-12V).
- IOREF pin allows shields to adapt to the voltage provided by the board.
- Reset pin takes the board to a reset state.

3.3.2 Organic Light-Emitting Diode (OLED) 128 x 64 Display

As depicted in the prior diagram, an OLED, an acronym for "organic light-emitting diode," displays are electronic display units that can be utilized in a wide array of applications. A 128x64

OLED display is a versatile module commonly employed in a myriad of devices and circuits. OLEDs denoted as "128x64" signify that the display has a resolution of 128 pixels horizontally and 64 pixels vertically. Each pixel on this OLED is individually lit, which leads to a brighter and more visible display than many other types. Approximately 8192 unique pixels can be controlled on the 128 x 64 smart dot matrix display.

Figure 3.2 Liquid Crystal Display (128 x 64)

This OLED incorporates two main elements: the command operations and the data operations. The command operations encompass various instructions sent to the display for configuration and control. The data operations include the data stored for visualization on the screen. To manage the display, the first step involves loading data into the appropriate registers, forming the blueprint of the desired image or text to be displayed on the screen. Following this, command instructions are entered into the registers that dictate the actions of the screen.

An additional benefit of OLED screens is their inherent contrast, negating the necessity for a contrast control potentiometer. The brightness can be controlled via software commands, providing a broader range of brightness control compared to traditional displays. The following table will illustrate the dimensions and details of the 128x64 OLED used in this setup.

Table 3.2 Pin Configuration of OLED

Feature	**Specification**
Module	128x64 OLED
Display Color	White / Blue / Yellowish Blue
Driver IC	SSD1306
Diagonal Size	0.96"
Interface	I2C / SPI
Operating Voltage	3.3V / 5V
Pixel Size	0.154 x 0.154 mm
Module Size	27.0 x 27.0 mm

3.3.3 Ultrasonic Distance Sensor

Ultrasonic sensors, as its name suggests, use ultrasonic waves to do distance measurements. The sensor head is responsible for both the transmission of an ultrasonic wave and the reception of the wave after it has been reflected from the target. The distance to the target may be determined using ultrasonic sensors by measuring the amount of time that elapses between the signal's emission and receipt. A single ultrasonic element is used for both emission and reception in an optical sensor, but an ultrasonic sensor only has a single ultrasonic element. An optical sensor has a transmitter and a receiver. One oscillator in a reflecting type of ultrasonic sensor is responsible for both the transmission and reception of ultrasonic waves in alternating fashion. This makes it possible to reduce the size of the sensor head.

Figure 3.3 An Ultrasonic Sensor for displacement measurement

The formula below may be used to determine the distance that must be traveled:

$$\text{Distance L} = 1/2 \times T \times C$$

where L is the distance, T is the amount of time that passes between the emission and the reception, and C is the speed at which sound travels at ultrasonic frequencies. (The value is increased by half because T represents the amount of time spent traveling the go-and-return distance.)

3.3.4 Photoresistor

The terms "photon" (which refers to light particles) and "resistor" were combined to create the name "photoresistor." One kind of resistor is known as a photoresistor, and it is distinguished from other resistors by the fact that its resistance drops as the amount of light reaching it rises. In other words, when there is a rise in the amount of light that is hitting the photoresistor, there is an increase in the amount of electric current that is flowing through it.

Photoresistors are sometimes referred to as LDRs, which stands for light-dependent resistors. Other names for photoresistors include photoconductors, photocells, and semiconductor photoresistors. When exposed to light, a photoresistor will only experience a change in its resistance. Silicon and germanium are two examples of the types of high-resistance semiconductors that are used to make photoresistors. In addition to that, they are constructed out of a variety of additional components, such as cadmium sulphide and cadmium selenide. When there is no light present, the photoresistors behave as if they are made of materials with a high resistance. On the other hand, when there is light present, the photoresistors behave as though they are made of materials with a low resistance.

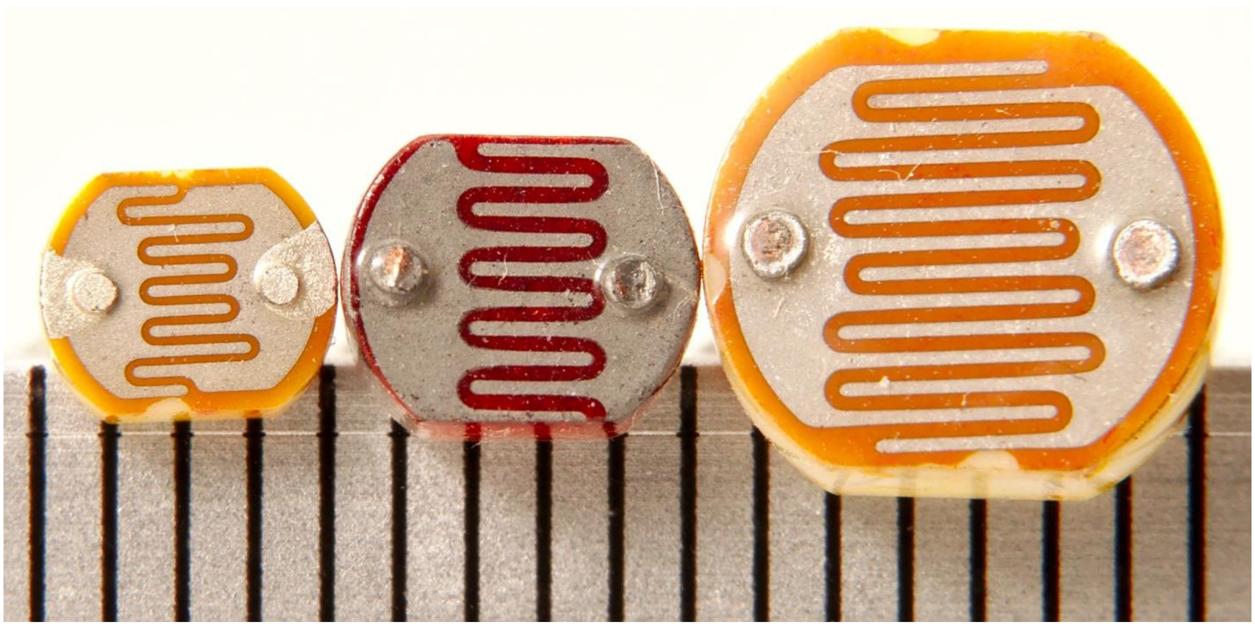


Figure 3.4 A set of photoresistors

3.3.5 GSM SIM800L

The GSM SIM800L module is a device that enables wireless communication by converting digital data into radio waves, contrary to a radio receiver. Its operation hinges on the principles of mobile communication, illustrating that whenever digital signals are transformed into radio waves, data transmission over a cellular network is possible. Because of this transformation, the module can connect to a GSM network and execute significant tasks like sending SMS, making or receiving phone calls, and providing GPRS for internet access. The SIM800L module finds applications in a wide variety of fields, including but not limited to home automation, tracking systems, remote sensing, and IoT projects.

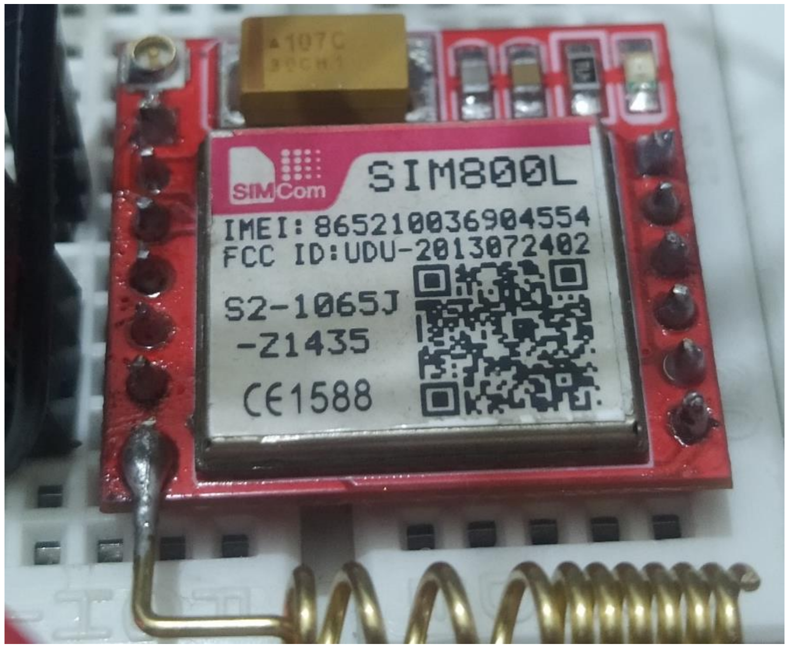


Figure 3.5 GSM Moudle SIM 800L

To maintain a continuous connection and deliver data when required, the module incorporates several essential elements. The module works on Quad-Band (850/900/1800/1900 MHz) which covers GSM networks in all countries. The following are the main components of a GSM SIM800L module:

• Antenna Interface: The Antenna Interface is a vital stationary part of the module. It's the connector where an external antenna is attached to provide better network reception.

• SIM Card Slot: The SIM Card slot holds the SIM card which connects the module to the cellular network. The SIM card provides the necessary credentials and identification to connect to the service provider's GSM network.

• Power Supply: This is the input for the power source required for the operation of the module. The module requires a DC power supply usually in the range of 3.4V to 4.4V.

• UART Interface: The UART Interface enables communication between the module and microcontrollers or computers. It allows sending commands to the module and receiving responses or data from the module.

• Status Pins: These pins provide necessary status information like network status, ringing indication, etc.

• ADC, GPIO Pins: Some models of the SIM800L module also provide ADC and GPIO pins for more flexible usage.

3.3.6 18650 Li-ion Battery Cells

In the rapidly evolving world of electronics and energy storage, the 18650 Lithium-ion (Li-ion) cell has emerged as an efficient and versatile energy storage device that enables portability by converting stored chemical energy into electrical energy. The functional principle of these cells is rooted in electrochemical reactions, demonstrating that when specific chemicals in the cell undergo reactions, electrical energy is generated. This essential conversion process underscores the ability of the 18650 cell to energize a wide array of devices, fulfilling significant roles such as powering motors, illuminating LEDs, and providing energy to intricate electronic circuitry.

The adaptability of the 18650 Li-ion cell extends to a multitude of applications across various domains. As a common power source for portable power banks, it guarantees continuous operation of mobile devices. Modern laptop batteries rely on these cells to deliver efficient and long-lasting power for heavy-duty tasks. Furthermore, in the arena of electric vehicles, the 18650 cells are commonly employed to build high-capacity battery packs, offering the potential to drive the vehicle for hundreds of miles on a single charge. The compact form factor and rechargeability make them a superb choice for numerous portable electronic gadgets, including flashlights, handheld GPS units, and high-performance drones.

Despite their small size - 18mm in diameter and 65mm in length - these cells are remarkably powerful. Operating typically at a nominal voltage of 3.7V, they can supply a considerable amount of power to a diverse range of electronic devices. The specific chemistry and design of the cell dictate its capacity, which can range from approximately 1800mAh to 3600mAh. This vast capacity range ensures prolonged operation of the device it powers.

A crucial point to note about the 18650 cell is its classification as a lithium-ion battery. This classification signifies that it utilizes the movement of lithium ions from the negative electrode to the positive electrode during discharge, and vice versa during charging. This migration of lithium ions is the primary mechanism behind the cell's capacity to store and release energy. Due to their high energy density, impressive cycle life, and absence of memory effect, lithium-ion cells, such as the 18650, have become the preferred choice of battery for a multitude of modern electronic devices.

3.3.7 Water Pump

The water pump is an electric motor and is a device that converts electrical energy into mechanical energy. Their operation is based on the theories of electromagnetism, which demonstrate that there is a force exerted whenever an electric current is present in a magnetic field. Because of this force, torque is produced on a loop of wire that is present in the magnetic field. This torque forces the motor to spin, which results in the motor carrying out meaningful work. Motors are used in a broad variety of applications, including but not limited to fans, power tools, home appliances, electric vehicles, and hybrid automobiles.

For motors to continue to spin and provide power when required, they have many distinct moving components. Direct current (DC) and alternating current (AC) are the two types of electricity that may be used to power motors; each has several advantages and disadvantages. The following are the primary components that make up a DC motor:

- **Stator:** The stator is the stationary part of the motor, and more precisely the magnet. To achieve greater levels of power, electromagnets are often used.
- **Rotor:** The rotor is the coil positioned on an axle and spins at high speeds; it is responsible for supplying the system with rotational mechanical energy.
- **Commutator:** This component, known as a commutator, is essential in DC motors. If it were not for it, the fluctuating current would produce opposing forces that would prevent the rotor from being able to spin in a continuous motion. By switching the direction of the current every time, the coil completes a half turn, the commutator makes it possible for the rotor to spin.
- **Brushes:** These are known as brushes, linked to the power source's terminals to enable the passage of electric current into the commutator.

3.3.8 Single Pole Double Throw (SPDT) Relay

Due to the structure of its internal components, the Single Pole Double Throw (SPDT) relay is an excellent choice for usage in many different applications. It consists of one common terminal and two contacts, each of which may be configured in one of two distinct ways: either one of the contacts can be Normally Closed while the other can be Normally Open, or it can be Normally Open while the other can be closed. When there is no voltage applied to the coil, one circuit "receives" current while the other circuit does not; however, when the coil is energized, the situation is reversed, and the other circuit is the one that "receives" current. Therefore, the SPDT relay can be thought of as a method of switching between two different circuits.

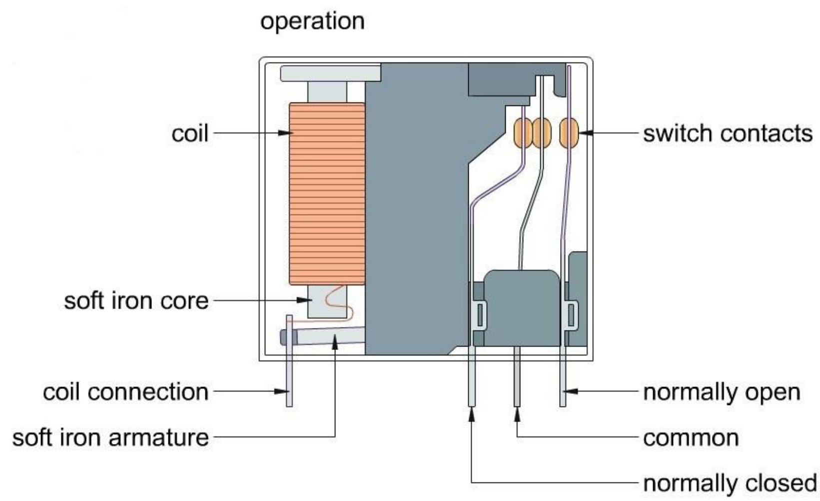


Figure 3.6 A general structure of SPDT Relay

3.4 Control Strategy for the PV Water Pumping System

The system depicted in Figure 3.7 illustrates a comprehensive flow chart that outlines the essential steps required for the optimal functioning of the solar-powered water pumping system. The flow chart encompasses various scenarios that the system may encounter and highlights the corresponding actions the system must undertake in response.

To begin, the system initiates by checking the availability of sufficient solar irradiance to activate the photovoltaic (PV) pump. If the measured irradiance falls below the threshold value required to start the pump, the system enters a waiting period of one minute before rechecking the irradiance level. This iterative loop continues indefinitely until the irradiance surpasses the threshold, as it is crucial for the system to rely on adequate solar energy to operate effectively.

Upon confirming the presence of sufficient irradiance, the system proceeds to monitor the water level within the tank. If the water level is already high, indicating the tank is adequately filled, the

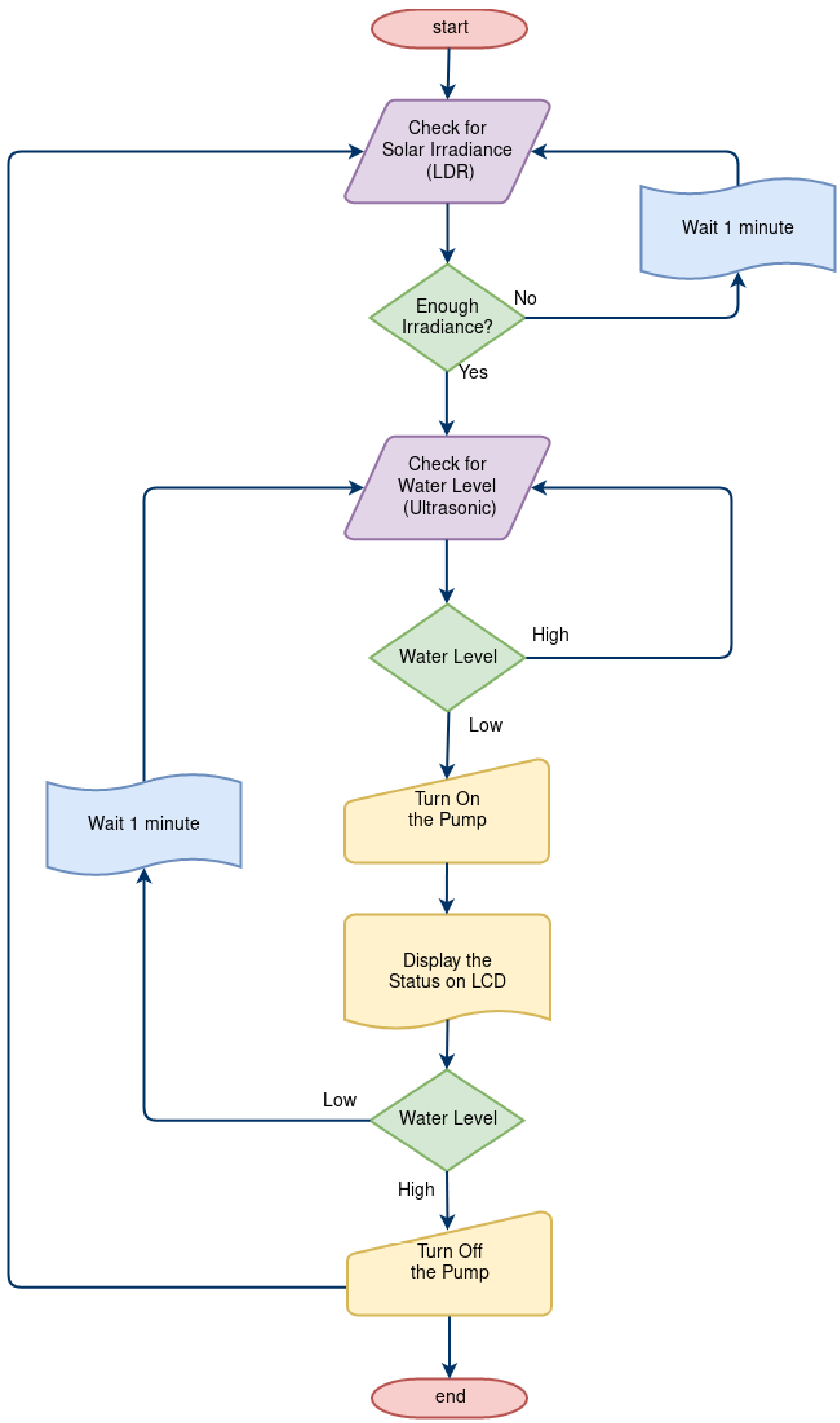


Figure 3.7 Flowchart of the control strategy of PV water pumping system

pump remains deactivated. However, if the water level is low, signaling the need for water replenishment, the system sends a signal to the relay, activating the pump motor. Concurrently, the OLED screen connected to the local system displays the current state of the pump, providing immediate feedback on its operation.

After a set time, the system reevaluates the water level to ensure it has not exceeded the predetermined limit. If the water level has reached or exceeded this limit, the system automatically shuts off the pump to prevent overflow or any potential damage. Conversely, if the water level remains below the limit, the system continues to operate the pump until the limit is reached, ensuring a controlled and efficient water flow.

Once this loop is completed, the system again checks the water level. If the water level drops below the low level once more, indicating the need for further water supply, the pump resumes its operation. This iterative process ensures the continuous maintenance of a safe and adequate water level within the tank, promoting both system reliability and user convenience.

The flow chart presented in Figure 3.7 serves as a comprehensive guide, outlining the necessary steps for the system to operate optimally. By relying on sufficient solar irradiance and activating the pump only when the water level falls below the low level, the system maximizes its efficiency and effectiveness. Moreover, the incorporation of an automatic shut-off mechanism when the water level exceeds the predetermined limit serves as a crucial safety feature, preventing potential overflow or damage. Overall, this flow chart provides a clear understanding of the system's operation and highlights the key considerations necessary for its optimal performance.

Arduino is used as the main control unit. A 128 x 64 OLED display is connected to Arduino for local display. A photoresistor module is used to measure solar irradiance and will be used to determine the sun's availability. Ultrasonic sensor is used to metarule the water level in the water tank. A SPDT relay is used to control the switching of the pump motor. The table below shows the control logic used for the system. Three levels are defined for both water level and solar irradiance. These are (a) Low, (b) Mid, and (c) High. The pump turns on when there is at least Mid solar irradiance. The pump does not turn on when there is Low irradiance even though water level is required. This is because Low irradiance will not be enough to power up the pump.

In addition to its autonomous operation and user prompts, the solar-powered water pumping system incorporates a battery backup feature. This allows the system to run on battery power if prompted by the user to forcefully turn on the pump, even in situations where the solar irradiance may be insufficient. This battery backup capability ensures continuous water pumping operation, providing a backup solution when the system relies on stored energy rather than solar power. However, it's important to note that the system imposes a time limit for forcefully turning on the pump. This time limit is set to prevent excessive battery usage and optimize energy efficiency. Once the set time for forceful pump activation is reached, the system will automatically revert to its default mode of operation, where the pump relies on solar power and the available irradiance level. This time limit acts as a safeguard, preventing unnecessary battery drainage and promoting sustainable energy use.

Table 3.3 Logic of starting pump based on water level in tank and sun availability

		Water level		
Solar Irradiance		**Low (0)**	**Mid (1)**	**High (2)**
	Low (0)	Off	Off	Off
	Mid (1)	On	On	Off
	High (2)	On	On	Off

3.5 Hardware Realization

To implement the system described in the flow chart, the following hardware components are required:

- Photovoltaic (PV) panel - to provide the energy needed to operate the system.
- Water level sensor - to determine the water level in the tank.
- Relay - to control the pump motor.
- Pump motor - to pump water from the tank.
- OLED screen - to display the current state of the system.
- Arduino - to control the system operations and communicate with the hardware components.
- 18650 Li-ion Battery - to power the sensors and Arduino.

The overall structure of the system is given in Figure 3.8. The PV panel is connected to the system to power the main controller. The water level sensor is connected to the microcontroller board and is used to determine the water level in the tank. The relay is connected to the microcontroller board and controls the pump motor. The pump motor pumps water from the tank when it is activated.

The microcontroller board (Arduino) is the brain of the system and is responsible for controlling the system operations. It receives input from the water level sensor and determines whether the water level is low enough to activate the pump. It also communicates with the relay to turn on the pump motor when it is needed.

The microcontroller board also communicates with the OLED screen to display the current state of the system as shown in Figure 3.9. The system can be powered by the battery, which is charged by the PV panel. When there is sufficient irradiance, the PV panel generates energy, which is used to charge the battery and power the system. When the sun is not shining, the system will use the energy stored in the battery to continue operating.

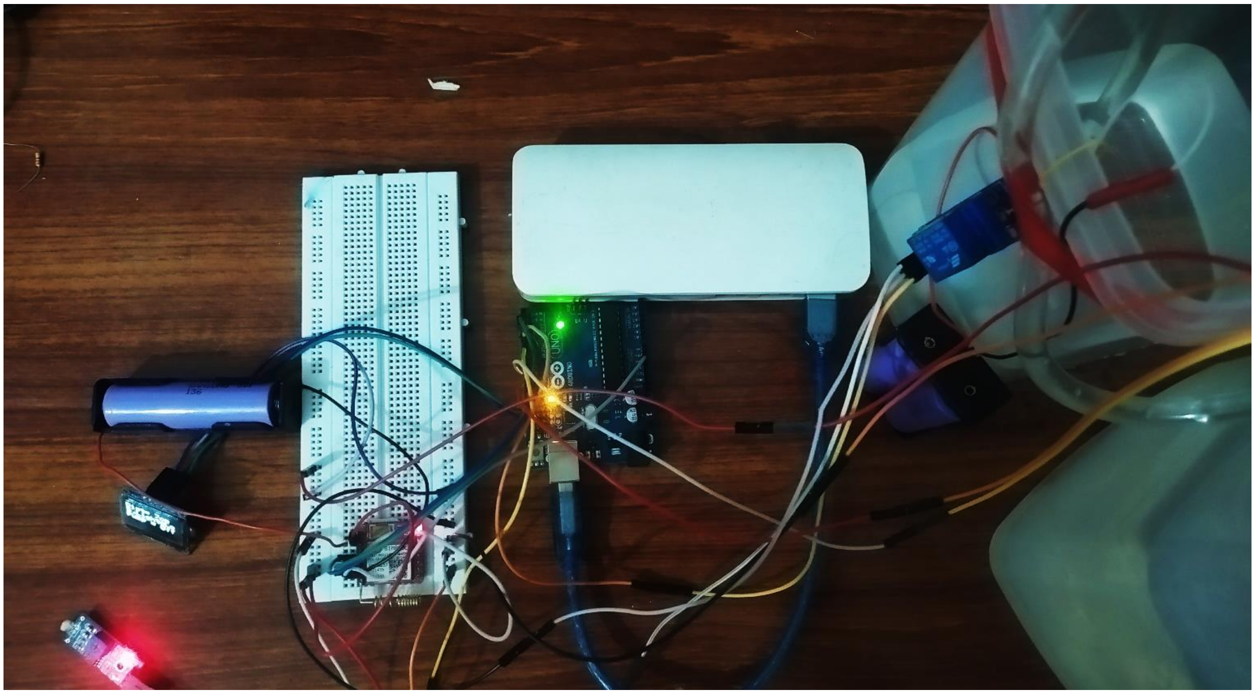


Figure 3.8 Overall hardware implementation of PV water pumping system

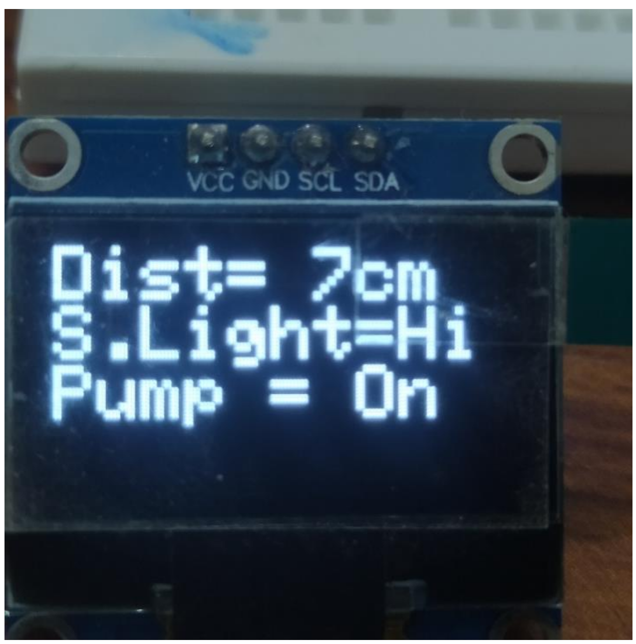


Figure 3.9 Status displayed on OLED of PV water pumping system.

In the proposed setup, a pair of 18650 Lithium-ion (Li-ion) battery cells is utilized to provide the necessary power to operate a DC water pump. These cells, each typically operating at a nominal voltage of 3.7V, can be connected in series or parallel, depending on the voltage and current requirements of the pump. In this setup, the cells are connected in serios to provide voltage of 7.4V while keeping the capacity (mAh) constant. Figure 3.10 illustrates the cells used in this setup.

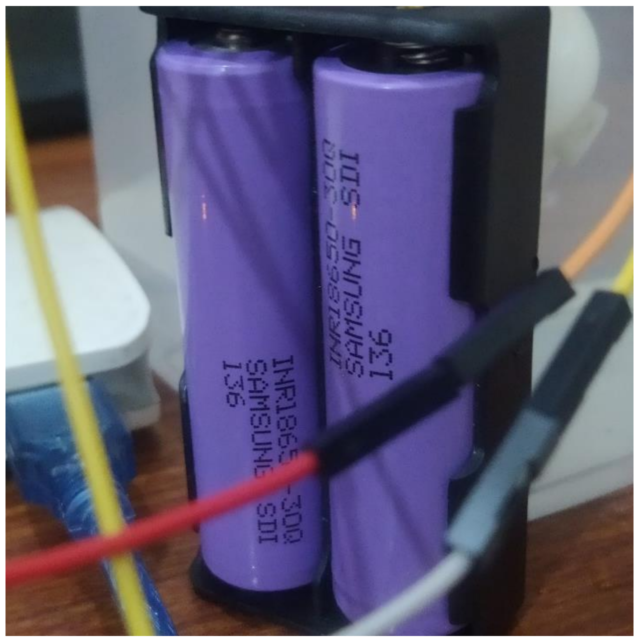


Figure 3.10 Two 18650 Li-ion Battery Cells to power up the DC pump

For this demonstration, the system utilizes two water tanks - a reserve tank, equipped with a DC pump and a SPDT relay, and a main tank, equipped with an ultrasonic sensor for water level measurement as shown in Figure 3.11. The reserve tank functions as a backup, with its DC pump transferring water to the main tank as needed. The pump operation is regulated by an SPDT relay, controlled by the Arduino. When the water level in the main tank, monitored by the ultrasonic sensor, falls below a set threshold, the microcontroller triggers the relay to start the pump. Conversely, once the water level is restored, the microcontroller deactivates the relay, halting the pump and water transfer.

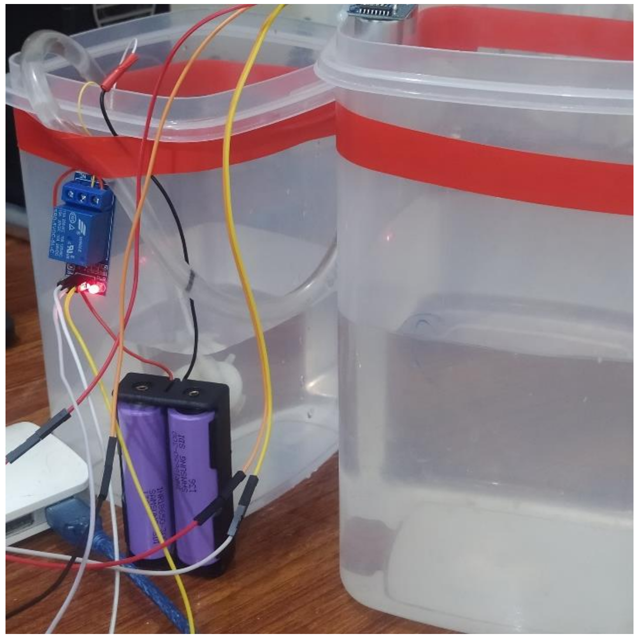


Figure 3.11 The two water tanks for demonstration: Reserve water tank with dc pump (Left); Main water tank with ultrasonic sensor

As shown in Figure 3.12, a Light Dependent Resistor (LDR) module is used to gauge solar irradiance to ensure the pump operates primarily under ample sunlight, maximizing the utilization of solar energy. The LDR module, sensitive to light intensity, varies its resistance inversely with light levels - less resistance with more light and vice versa, making it adept at measuring sunlight strength. A potentiometer linked to the module allows for customization of the LDR's sensitivity, adjusting the threshold of light intensity needed for pump activation. Consequently, the sensor's response to sunlight can be finely calibrated according to the system's requirements. The LDR module produces a digital signal - high or low - depending on the sufficiency of sunlight. If the light intensity surpasses the preset threshold, the output is high; if not, the output is low. This signal is used by the microcontroller to control the DC pump's operation. The pump is activated to move water from the reserve to the main tank when the LDR output is high, indicating sufficient sunlight. Conversely, with a low signal suggesting inadequate sunlight, the pump remains off, conserving energy. This mechanism ensures efficient use of solar energy and responsive water transfer management based on real-time environmental conditions.

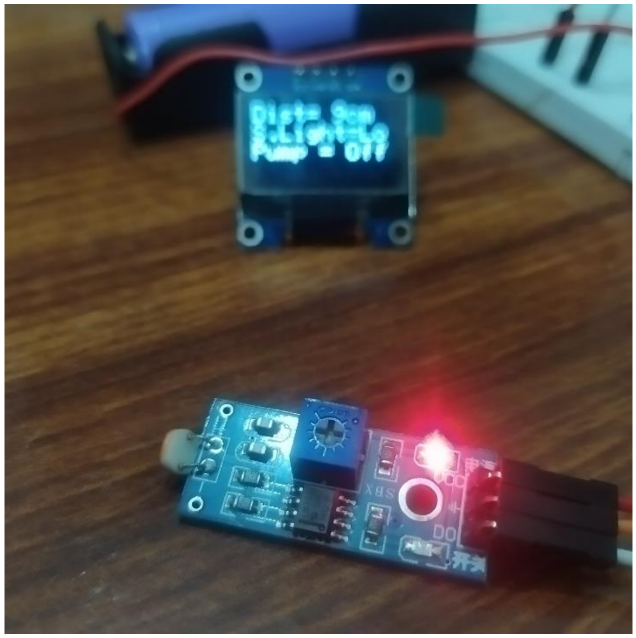


Figure 3.12 LDR module with OLED in background

An SD card is incorporated in this system to serve as a data logging platform, storing various forms of measured data pertinent to the operation and monitoring of the system. This data includes parameters such as the water level in the main tank, the amount of solar irradiance detected by the LDR module, and the timestamps marking when the pump is switched on and off. The water level data, ascertained by the ultrasonic sensor in the main tank, provides valuable information on the tank's status and the system's water usage over time. The irradiance data, derived from the LDR module, gives insights into the daily and seasonal patterns of sunlight availability, which can be crucial in optimizing the system's reliance on solar energy.

The pump operation timestamps are particularly important as they allow for the analysis of the system's operational efficiency and energy consumption. By tracking when the pump is turned on and off, the system can determine how long the pump runs each day and how its operation corresponds to the solar irradiance and water level data. By logging these types of data, the system becomes capable of monitoring its operation over extended periods, facilitating the identification of trends, the diagnosis of potential issues, and the implementation of improvements. The use of an SD card for data storage ensures a large amount of data can be stored in a compact and easily retrievable format. Furthermore, the data stored on the SD card can be easily transferred to a computer for further analysis and visualization.

3.6 Data Logging

The provided table represents a 25-row dataset that has been logged by an Arduino microcontroller onto an SD card. The data showcases various parameters that are crucial for the operation of a solar-powered water pumping system. As depicted in the data, the initial water level of 21cm decreases progressively to values such as 18cm, 15cm, 12cm, and so on meaning the tank was filled linearly. Additionally, the water level is randomly decreased at certain points to simulate emptying the tank.

The parameters included in the logged data are the Pump Status, indicating whether the pump is turned on or off; the Water Level (cm), which ranges from 21cm to 5cm; and the LDR Status, which can be either High or Low. The pump operates based on the solar irradiance (LDR Status), only turning on when the status is High, indicating sufficient solar energy, and when the water level is more than 5cm away from the bottom of the tank. This data logging is essential for monitoring and analyzing the system's performance, enabling insights into the pump's operation, water level variations, and solar energy availability over time.

Table 3.4 Data Logged by the System

Sr. No	Pump Status	Water Level (cm)	Solar Irradiance
1	OFF	21	LOW
2	ON	18	HIGH
3	ON	15	HIGH
4	ON	12	HIGH
5	ON	9	HIGH
6	ON	7	HIGH
7	OFF	7	LOW
8	ON	5	HIGH
9	OFF	5	LOW
10	OFF	5	LOW
11	ON	21	HIGH
12	ON	18	HIGH
13	ON	15	HIGH
14	ON	12	HIGH
15	ON	9	HIGH
16	ON	7	HIGH
17	OFF	7	LOW
18	OFF	7	LOW
19	ON	5	HIGH
20	OFF	5	LOW
21	OFF	5	LOW

22	ON	21	HIGH
23	ON	18	HIGH
24	ON	15	HIGH
25	ON	12	HIGH

3.7 User Controlled Setup

In addition to its autonomous operation, the solar-powered water pumping system can also be controlled and monitored by user prompts. This is facilitated by incorporating a GSM (Global System for Mobile Communications) module into the system, enabling communication between the system and the user via GSM network. The GSM module serves as a bridge between the user and the system, allowing for real-time communication and exchange of information. The user can initiate prompts at any time to inquire about the system's status, such as the current solar irradiance level, water level in the tank, and pump status. Upon receiving such prompts, the system, utilizing the GSM module, generates an SMS (Short Message Service) containing the requested status information. This SMS is then transmitted to the user's mobile device, providing them with the requested system status update.

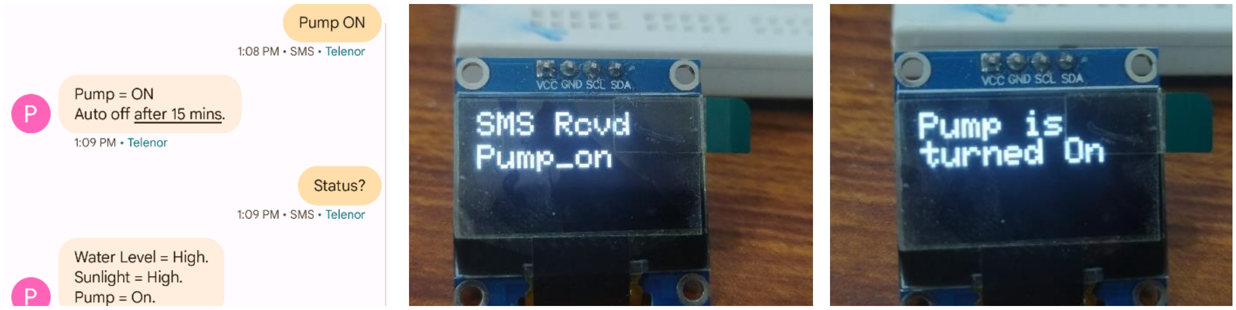
Furthermore, the user is empowered to control the system's operation based on their discretion and specific requirements. By sending an SMS with the message to turn on the pump, the user can remotely activate the pump, instructing the system to start pumping water. Similarly, if the user desires to manually turn off the pump, they can send an SMS command to the system, instructing it to cease pump operation.

In Figure 3.13, a user initiates a system status prompt by sending an SMS with the message "Status?" to the system as shown in Figure 3.13 (a). Upon receiving the SMS, the system acknowledges the message and proceeds to read its contents. The system then displays a brief acknowledgement on the second line of the display, indicating that the SMS has been received as illustrated in Figure 3.13 (b). After a short delay, typically a few seconds, the system formulates a response and sends it back to the user as shown in Figure 3.13 (c). This response contains the current system status, providing the user with the necessary information they requested.

(a) (b) (c)

Figure 3.13 User prompt about system status

In Figure 3.14, the user prompts the system to turn on the pump by sending an SMS command with the message "Pump ON" as shown in Figure 3.14 (a). Upon receiving the SMS, the system recognizes the command and acknowledges the message as illustrated in Figure 3.14 (b). The system then processes the command and initiates the pump activation procedure. After a brief delay to ensure proper pump startup, the system sends a response back to the user, confirming the pump activation as shown in Figure 3.14 (c). This response serves as an acknowledgment and provides reassurance to the user that their command has been successfully executed. The pump will continue operating until it receives a command to turn off or reaches a predetermined condition for automatic shut-off.

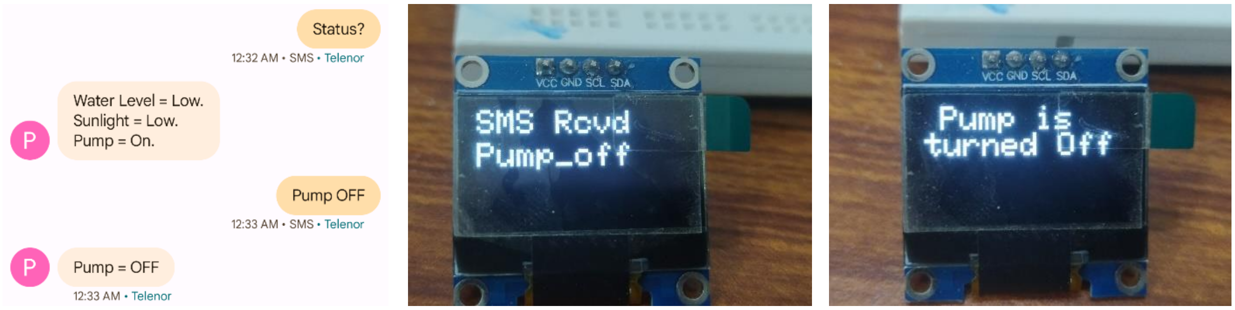


(a) (b) (c)

Figure 3.14 User prompt regarding turning the pump on

In a similar manner, the user can prompt the system to turn off the running pump by sending an SMS command with the message "Pump OFF" as illustrated in Figure 3.15 (a). Upon receiving this specific command, the system recognizes the user's intent and acknowledges the received SMS as depicted in Figure 3.15 (b). Once the system processes the command, it initiates the procedure to deactivate the pump. This involves safely shutting down the pump and halting the water pumping operation. After ensuring the pump has been successfully turned off, the system sends a response back to the user, confirming the pump deactivation as depicted in Figure 3.15 (c). This response serves as an acknowledgment and provides reassurance to the user that their command has been executed, and the pump is no longer in operation.

By leveraging SMS communication, the system empowers users with the ability to remotely control the pump's status and operation. The prompt to turn off the running pump via SMS command enhances user convenience and ensures that they have direct control over the water pumping process. This seamless interaction between the user and the system facilitates efficient management of the system, ultimately enhancing user satisfaction and overall system performance.



(a) (b) (c)

Figure 3.15 User prompt regarding tunning the pump off.

The integration of user prompts and GSM communication into the solar-powered water pumping system enhances its usability and convenience. Users have the flexibility to monitor system parameters and receive updates remotely, allowing them to stay informed about the system's performance and take necessary actions if required. The ability to remotely control the pump operation via SMS commands empowers users to actively manage the system's water supply based on their specific needs, ensuring efficient water management and convenience.

By leveraging the GSM module's capabilities, the system enables seamless communication between the user and the system, facilitating prompt information exchange and remote-control functionality. This integration enhances user experience, providing them with a direct means to interact with and manage the system, thereby maximizing the system's adaptability and usability.

3.8 Conclusions

A solar-powered water pumping system, as built in this setup, hinges on an Arduino microcontroller for its core operation. As part of this intelligent system, the necessity of monitoring and logging key parameters - including solar irradiance, water level, and pump status - is emphasized. The data collated from these parameters serves multiple purposes, providing insights to optimize system performance and the potential to identify, troubleshoot, and pre-emptively address any issues that might emerge. Critical to this data logging is the use of an SD card coupled with the Arduino. This setup presents a practical and efficient platform for local data storage and management. The Arduino SD library, a highly compatible and versatile tool, facilitates the real-time reading and writing of data to the SD card. As such, pertinent information concerning system operation - from solar irradiance detected by the LDR module, water level ascertained by the ultrasonic sensor, to the operational status of the DC pump - can be logged instantly and directly onto the SD card. This real-time data logging feature allows for detailed tracking and analysis of the system's performance, thereby enhancing the efficiency of troubleshooting procedures and optimization of the overall system.

Further enhancing the utility of this setup is the ability to transfer data stored on the SD card to a computer. Once transferred, data analysis software or custom-built applications can be utilized to visually represent and analyze this data. Such software tools can provide a user-friendly interface, simplifying data access, and meaningful data representation. This can take the form of graphs and charts, illustrating trends in solar irradiance, water level fluctuations, and pump operation times over various periods - providing valuable insights into the system's operation and performance.

In addition to data logging and analysis, real-time feedback of essential system parameters is provided through an integrated OLED display. This display delivers immediate and concise readouts of current measurements, including solar irradiance and water level, and crucially the status of the DC pump. Such real-time updates offer immediate visibility into the system's functioning and potential issues. Powering the system is a pair of 18650 Li-ion cells. These cells provide reliable and efficient operation to the DC water pump and other system components. In sum, this Arduino-based system offers a robust solution for monitoring and optimizing a solar-powered water pumping system. With the benefit of real-time data logging, easy access to historical data, and the utility of an immediate feedback display, the system lends itself to convenient management and maintenance. These combined factors work in synergy to ensure the best possible performance and efficiency of the solar-powered water pumping system.

The incorporation of user prompts and GSM communication in the solar-powered water pumping system allows for remote monitoring and control. Users can inquire about system status and receive real-time updates by sending SMS prompts. The system acknowledges and responds to these prompts, providing information on solar irradiance, water level, and pump status. Additionally, users can remotely activate or deactivate the pump by sending specific SMS commands. This integration enhances user convenience and empowers them to actively manage the water pumping process based on their needs. The seamless communication facilitated by the GSM module ensures efficient information exchange and remote-control functionality, enhancing the overall usability and adaptability of the system.

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Chapter 4

Remote Monitoring, Control and Data Visualization for a Solar Water Pumping System

Preface

A version of this chapter has been accepted in European Journal of Electrical Engineering and Computer Science (EJECE), August 2023. I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript. The Co-author Dr. M. Tariq Iqbal supervised the research, provided the research guide, reviewed, and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

Abstract

Access to clean water is a significant challenge in many regions, including Sukkur, Pakistan. The effective management of water resources is a critical challenge, particularly in areas with limited access to surface water sources. This chapter presents a remote monitoring of water pumping system designed to address water distribution challenges in Sukkur, Pakistan. The system utilizes a combination of hardware components, including Arduino Uno, Raspberry Pi 2, ultrasonic sensor, and GSM modules, to enable remote monitoring, control, and data visualization. The system architecture incorporates Node-RED, a powerful flow-based programming tool, to facilitate data communication, storage, and visualization. To enable remote monitoring and control, users can send SMS commands to the Arduino Uno, connected to the GSM module, to query the system's status and control the pump's operation. Additionally, a mobile application developed using the MIT App Inventor platform allows users to interact with the system, visualize real-time and historical data, and receive updates on water levels and pump status. The Raspberry Pi 2 serves as a server and cloud storage for the system.

Key words — remote monitoring; Node-RED; GSM module; Arduino; Raspberry Pi 2; MIT app inventor; MQTT protocol; water management

4.1 Introduction

Access to clean and reliable water is a fundamental necessity for the well-being and sustainable development of communities, however, many regions across the globe, including Sukkur in Pakistan, struggle with significant challenges in managing their water resources effectively [1]–[3]. These challenges are further intensified in areas with limited connectivity options, where the implementation of modern monitoring and control systems becomes a difficult task [4], [5]. The city of Sukkur, located in the Sindh province of Pakistan, experiences water scarcity due to various factors such as rapid population growth, increasing agricultural demands, and unreliable infrastructure [6], [7]. The existing water supply systems often struggle to meet the demands of the population, resulting in irregular distribution and inadequate access to clean water [8], [9].

In such a scenario, it becomes imperative to develop innovative solutions that leverage renewable energy sources and advanced communication technologies to optimize water resource utilization [10], [13]. The solar-based water pumping system presented in [14] allows for the extraction and distribution of water from underground sources, mimicking the conditions prevalent in Sukkur. In areas where Wi-Fi and 3G/4G connectivity options are limited, traditional methods of remote monitoring and control become impractical. Several works have explored the usability of various technologies to monitor and control solar-based water pumping systems. For instance, author in [15] focuses on the design and analysis of a solar water pumping system for a fish farm in Pakistan. The study examines the performance and efficiency of the system, considering factors such as solar radiation, water demand, and the specific requirements of a fish farm. The findings provide insights into the optimization of solar water pumping systems in agricultural applications. Authors in [16] explore the implementation of an IoT-based fishpond monitoring system to enhance productivity. While not directly focused on solar-based water pumping systems, it provides valuable insights into the integration of IoT technologies for monitoring and controlling water-related systems in agricultural settings. Authors in [17] discusses the application of IoT monitoring for solar-powered pumps in a hydroponic house. It explores the use of sensors and data communication technologies to monitor and control water pumping systems. The findings contribute to the understanding of effective monitoring strategies for solar-based water pumping

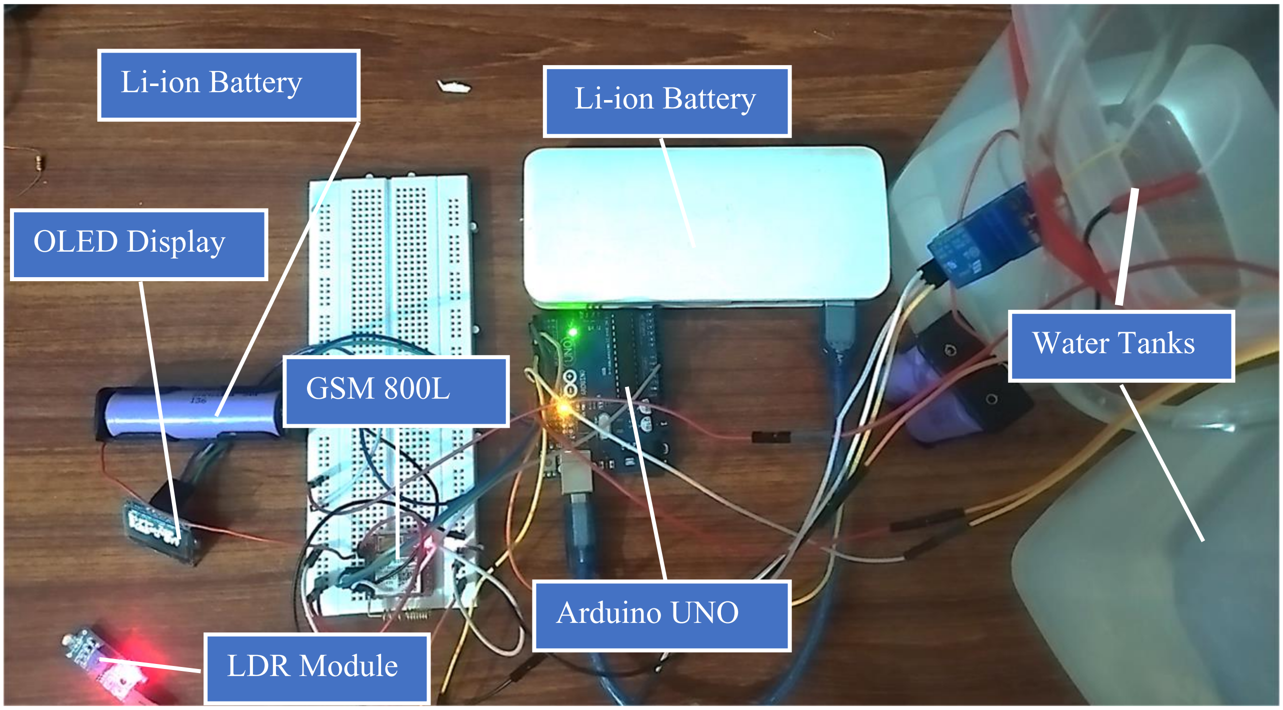


Figure 4.1 Test Hardware Setup of the proposed system

systems. In [18], the authors focused on the modelling and simulation of a solar water pump using Arduino Uno in Proteus. The study presents a simulation-based approach to analyze the performance and efficiency of the system. [19] presents the automation and control of a solar-powered water pumping system using a microcontroller for aquaculture. The study explores the application of automation and control techniques in solar-based water pumping systems. The findings contribute to the understanding of system optimization for specific applications, such as aquaculture. [20] discusses the development of an economical SCADA system for solar water pumping in Iran. It addresses the challenges and considerations in implementing a cost-effective SCADA system for monitoring and controlling solar-based water pumping systems. The findings contribute to the understanding of SCADA system design and implementation in resource-constrained settings. [21] focuses on the development of an IoT-based open-source SCADA system for PV system monitoring. While not specific to water pumping systems, it explores the integration of IoT technologies and the MQTT protocol for monitoring and control. The study provides insights into the use of SCADA systems for monitoring solar-based systems. [22] discusses an open-source IoT-based SCADA system for remote oil facilities using Node-RED and Arduino microcontrollers. Although focused on oil facilities, it presents insights into the development and implementation of SCADA systems for remote monitoring and control. discusses an open-source IoT-based SCADA system for remote oil facilities using Node-RED and Arduino microcontrollers. Although focused on oil facilities, it presents insights into the development and implementation of SCADA systems for remote monitoring and control. discusses an open-source IoT-based SCADA system for remote oil facilities using Node-RED and Arduino microcontrollers. Although focused on oil facilities, it presents insights into the development and implementation of SCADA systems for remote monitoring and control. discusses an open-source IoT-based SCADA system for remote oil facilities using Node-RED and Arduino microcontrollers. Although focused on oil facilities, it presents insights into the development and implementation of SCADA systems for remote monitoring and control.

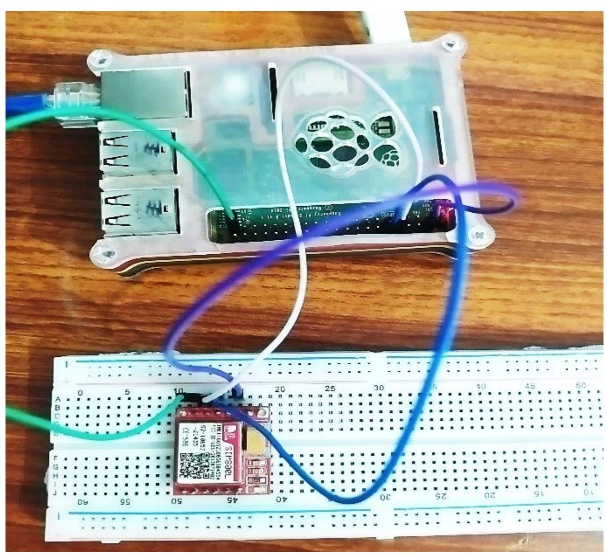


Figure 4.2 GSM module connected with Raspberry Pi 2.

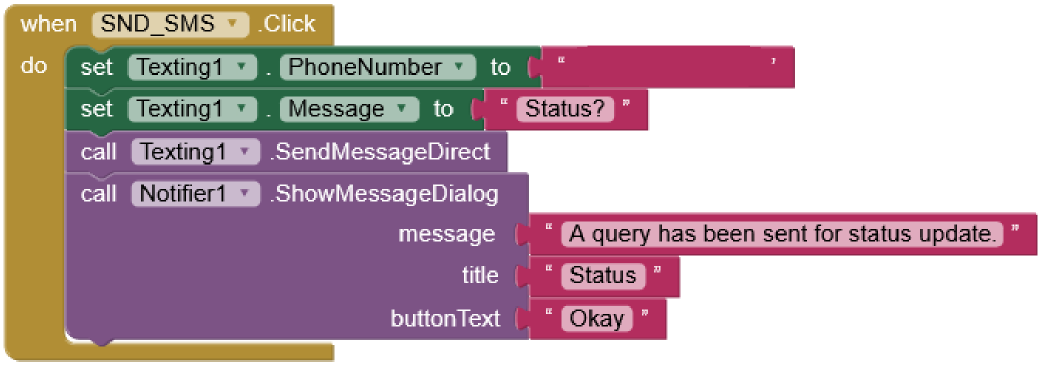


Figure 4.3 A design block in MIT App Inventor when a query is generated from user app.

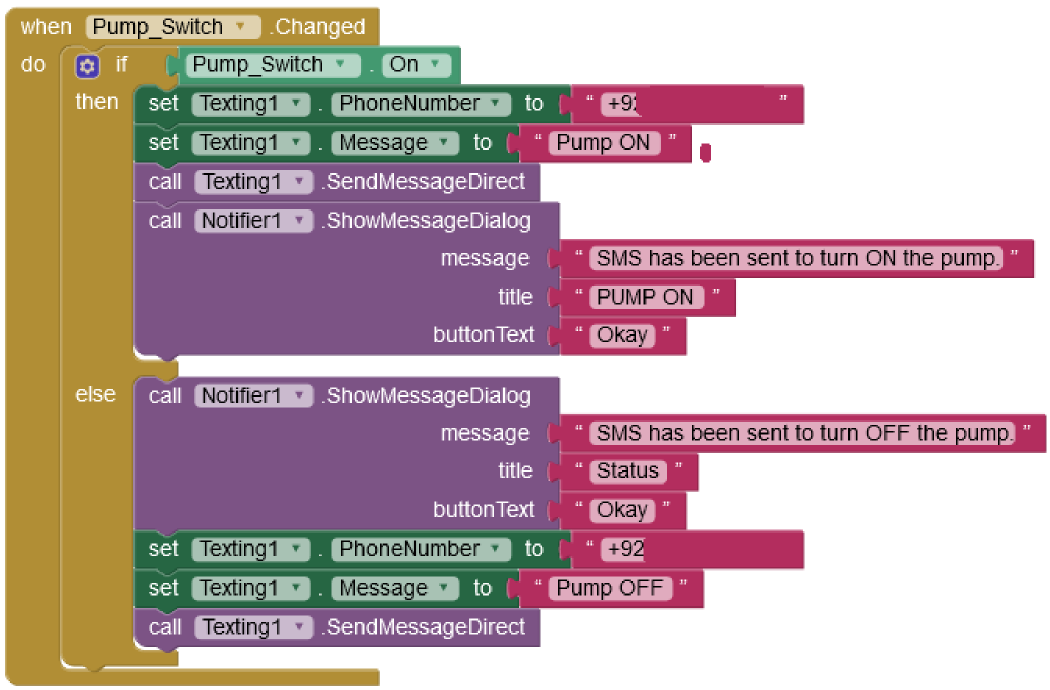


Figure 4.4 MIT App Inventor design block to turn on and turn off the pump on user discretion.

This chapter presents a control and monitoring of the solar-based water pumping system employing GSM technology for SMS communication between the system components. An Arduino Uno microcontroller, a Raspberry Pi 2, and an app developed using the MIT App Inventor platform. The app, equipped with GSM and MQTT functionalities, enables users to send commands, query system information, and receive updates on the water pumping system's status.

Figure 4.5 A section of MIT App Inventor design block when text is received from Arduino and processed to display on app dashboard.

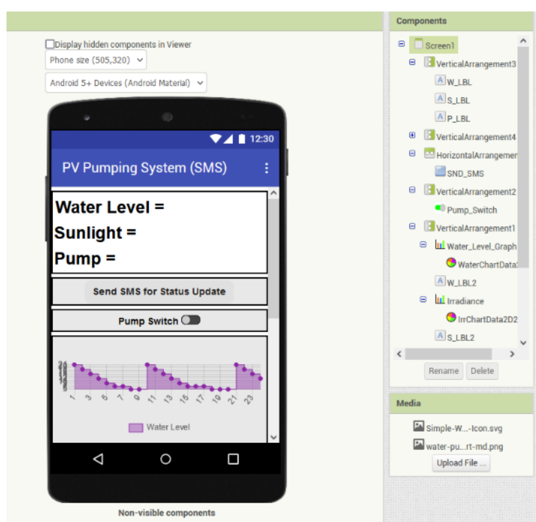


Figure 4.6 An android mobile app is designed using MIT App Inventor.

4.2 System Architecture and Hardware Setup

The system architecture and hardware setup of the solar-based water pumping system comprise a pumping system controlled by an Arduino Uno microcontroller with a GSM module, a Raspberry Pi 2 acting as a server and cloud storage unit, and a user app developed using the MIT App Inventor platform. The following subsections explored each aspect of the hardware setup.

4.2.1 Arduino Uno and Control Setup

The overall Arduino based hardware setup is illustrated in Fig. 4.1. The hardware consists of and Arduino UNO R3 microcontroller. The controller is connected with a light dependent resistor (LDR) module that measure the available sunlight. The Arduino is also connected to an ultrasonic sensor that measure the water level in one of the two tanks, mimicking the underground water tank and outer water tank. The Arduino is power by a power bank that consist of Li-ion battery cells and provides 5V DC power to Arduino using a step-up DC-DC converter of 3.7V to 5V. The Arduino has a GSM connectivity using a SIM800L module. The Arduino Uno processes incoming SMS commands and sends responses containing relevant information, such as current water levels and pump status.

4.2.2 Raspberry Pi 2 and Node-RED Integration

The Raspberry Pi 2 is used to work as a server and cloud storage unit and illustrated in Fig. 4.2. Since this setup presents a solar-based water pumping system in remote areas where limited connectivity is available, the Raspberry Pi 2 has been connected to another GSM module to communicate with the Arduino. It is connected to the Arduino Uno via another GSM module, establishing communication between the two units. The Raspberry Pi 2 is also connected to the internet through Ethernet, enabling connectivity for remote access and data exchange. This provides the connectivity to the end-user android mobile app.

To facilitate data storage and visualization, the Raspberry Pi 2 incorporates Node-RED, a flow-based programming platform. Node-RED provides a user-friendly interface for configuring data flows and creating a dashboard to visualize the collected data. The Raspberry Pi 2 receives SMS updates from the Arduino Uno at regular intervals, processes the data, and stores it in a CSV file. Node-RED's capabilities allow for the creation of a visually appealing and informative dashboard that displays real-time water levels, historical trends, and system performance metrics.

4.2.3 User App Developed with MIT App Inventor

To enable user interaction and provide an interface, an app is developed using the MIT App Inventor platform. The designed app is illustrated in Fig. 4.3. The app is equipped with both GSM and MQTT functionalities, allowing users to send commands and receive updates through SMS or MQTT protocol. The user app provides users with the ability to query system information, request status updates, and send specific commands for actions such as starting or stopping the pump. It also includes data visualization features, displaying the last 25 values of water levels and pump status communicated over GSM or MQTT. The app enhances the system's usability by providing users with remote access to monitor and control the water pumping system through their smartphones.

4.3 Software Implementation

The software implementation of the solar-based water pumping system encompasses the programming and integration of various components, including the Arduino Uno, Raspberry Pi 2, and the user app developed using the MIT App Inventor platform. This section provides an in-depth overview of the software implementation, outlining the control logic, data management, and visualization aspects of the system.

4.3.1 Arduino IDE

The Arduino Uno serves as the central controller of the system, responsible for monitoring water levels, receiving SMS commands, and sending responses. The code written for the Arduino utilizes the Arduino programming language, which is based on C/C++. The control logic implemented in the code ensures that the pump operates efficiently based on the water level readings from the ultrasonic sensor and sunlight readings from LDR module. When the water level in the outer tank falls below a certain threshold, the Arduino triggers the pump to extract water from the underground tank and fill the outer tank provide there is sufficient sunlight to power the system. Additionally, the Arduino is programmed to respond to SMS commands from the Raspberry Pi or user queries, providing relevant information such as current water levels and pump status.

4.3.2 Node-RED

On the Raspberry Pi 2, the Node-RED platform is utilized to handle data storage and visualization. Node-RED provides a visual programming interface that allows for easy integration and flow-based programming. Fig. 4.7 shows the steps and flows used to provide storage capability and communication between Raspberry Pi 2 and Arduino, as well as between User App and Raspberry Pi 2. Fig. 4.7 (a) presents a SIM800 GSM module that is included in the flow of Node-RED to communicate with the GSM hardware module. Fig. 4.7 (b) shows the module is used to get the SMS from the Arduino, and then splits the text in meaningful data by using a function of text splitter. The data is then stored in CSV file on the raspberry pi storage. Fig. 4.7 (c) illustrates the stored data is then used to display on the dashboard of the Node-RED. Fig. 4.7 (d) shows the data is also communicated with the user app via MQTT protocol. Using Node-RED, the Raspberry Pi 2 receives SMS updates from the Arduino at regular intervals. The received data, including water levels and pump status, is processed and stored in a CSV file for future reference and analysis.

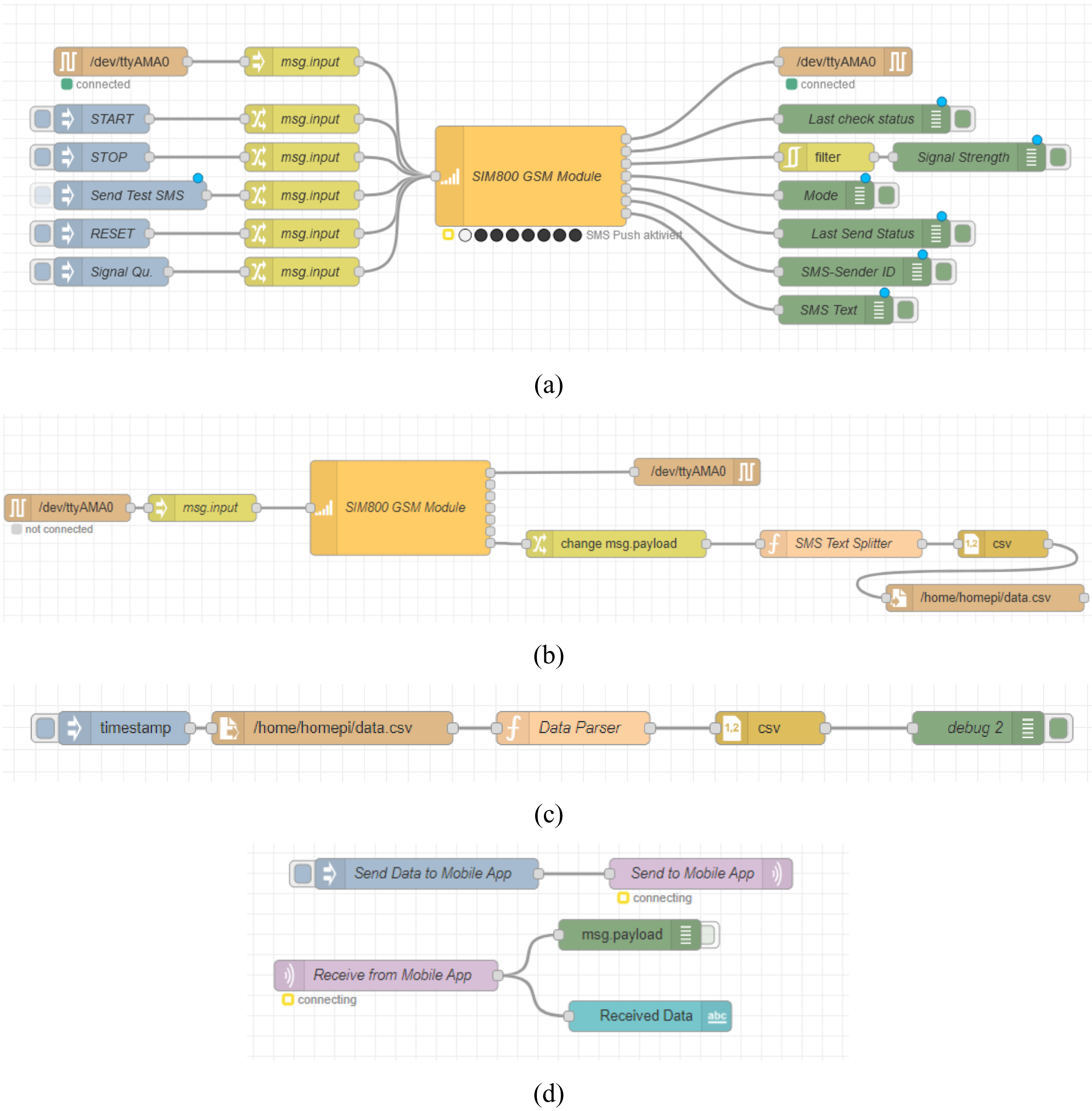


Figure 4.7 A Node-RED setup followed in this setup. (a) A SIM800 GSM module is included in the flow of Node-RED to communicate with the GSM hardware module. (b) The module is used to get the SMS from the Arduino, and then splits the text in meaningful data by using a function of text splitter. The data is then stored in CSV file on the raspberry pi storage. (c) The stored data is then used to display on the dashboard of the Node-RED. (d) The data is also communicated with the user app via MQTT protocol.

Furthermore, Node-RED enables the creation of a user-friendly dashboard to visualize the collected data. The dashboard can display real-time water levels, historical trends, and system performance metrics, providing users with a comprehensive overview of the water pumping system's operation.

4.3.3 MIT App Inventor

The user app, developed using the MIT App Inventor platform, plays a crucial role in enabling users to interact with the solar-based water pumping system. Fig. 4.4, Fig. 4.5, and Fig. 4.6 present the design blocks used in designing the core functionalities of the user app. The app features both GSM and MQTT functionalities, allowing users to send commands and receive updates through SMS or MQTT protocol. The app's interface is designed to be intuitive and user-friendly, providing options to query system information, request status updates, and send commands for specific actions. Additionally, the app incorporates data visualization capabilities, displaying the last 25 values of water levels and pump status communicated over GSM or MQTT. This feature allows users to monitor the system's performance and make informed decisions based on the displayed information.

4.4 Data Communication And Management

Effective data communication and management are crucial aspects of the solar-based water pumping system. This section delves into the details of how data is exchanged between the components, specifically focusing on the communication between the Arduino Uno, Raspberry Pi 2, and the user app. Furthermore, it explores the data management processes, including storage, retrieval, and visualization of the collected data. Fig. 4.7 provides the overall communication between the three nodes.

4.4.1 Communication between Arduino Uno & Raspberry Pi

The Arduino Uno and Raspberry Pi 2 establish communication using GSM modules. The Arduino Uno, equipped with a GSM module, sends SMS updates to the Raspberry Pi 2 at regular intervals. These updates contain vital information such as water levels in the outer tank and the status of the pump. The Arduino Uno processes the incoming SMS commands from the Raspberry Pi 2 and responds accordingly, providing real-time data to the Raspberry Pi 2 for further processing.

The Raspberry Pi 2, upon receiving SMS updates from the Arduino Uno, utilizes the Node-RED platform for data processing. The Node-RED flow is configured to process the incoming SMS messages, extract relevant data, and store it in a CSV file for future analysis. This data includes timestamps, water level readings, and pump status information. The use of Node-RED's visual programming interface simplifies the data processing tasks and ensures seamless integration with the storage and visualization components of the system.

4.4.2 Data Storage and Retrieval with Node-RED and Raspberry Pi 2

Node-RED, running on the Raspberry Pi 2, facilitates data storage and retrieval. As the system receives updates from the Arduino Uno, the data is logged and stored in a CSV file. This file serves as a repository for the collected data, enabling historical analysis and monitoring of the system's performance. The CSV file can be accessed and queried for specific data points, such as water levels at different timestamps or pump status during specific intervals. Node-RED provides the flexibility to retrieve data from the CSV file using various data manipulation and filtering techniques. Users can retrieve the stored data based on their requirements and gain insights into the system's behavior over time.

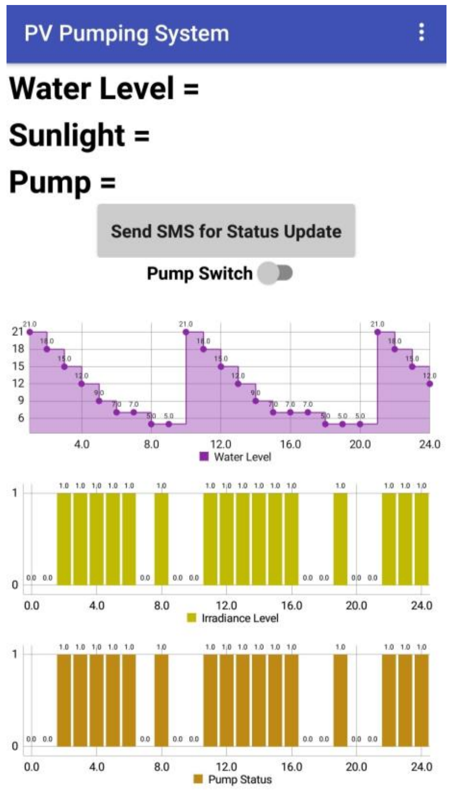
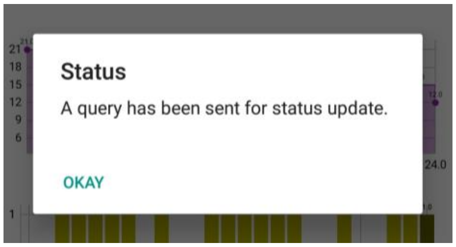


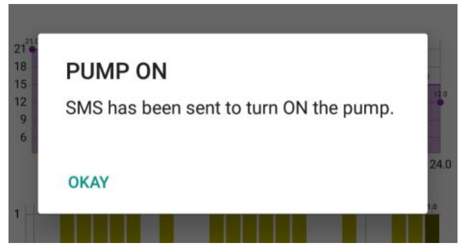
Figure 4.8 User Application designed in MIT App Inventor

4.4.3 Data Visualization through Node-RED Dashboard and User App

The Node-RED platform, in conjunction with the Raspberry Pi 2, offers powerful visualization capabilities. It enables the creation of a user-friendly and interactive dashboard that displays real-time and historical data about the water pumping system. The dashboard provides visual representations of water levels, pump status, and other relevant metrics. The Node-RED dashboard presents the collected data in the form of charts, graphs, and gauges. Users can monitor the system's performance, track water level trends, and analyze pump behavior through intuitive visualizations. This empowers users to make informed decisions and take necessary actions based on the displayed information. In addition to the Node-RED dashboard, the user app developed using the



(a)



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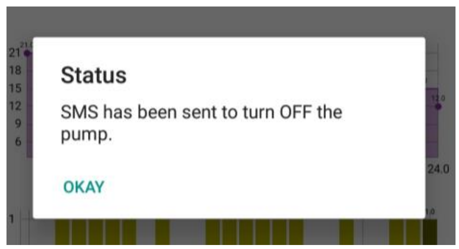

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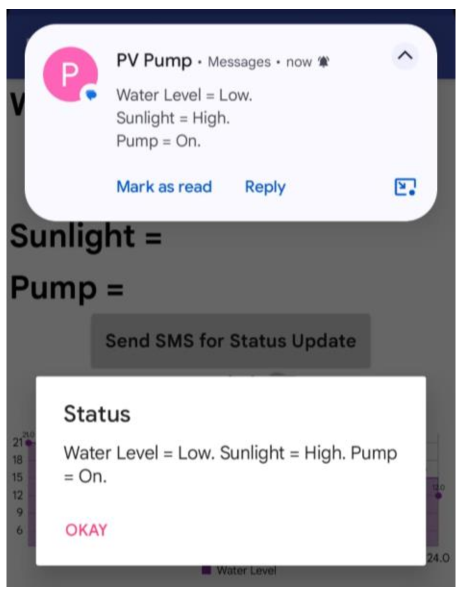

(d)

Figure 4.9 Working of User Application. (a) A prompt SMS is sent to Arduino to query the status of the pumping system. (b) and (c) A prompt SMS is sent to either turn on or turn off the pump. (d) A response received on the Application from the Arduino.

MIT App Inventor platform also includes data visualization features. The app can display the last 25 values of water levels and pump status communicated over GSM or MQTT. This feature provides users with a quick overview of the system's recent performance and allows them to monitor the water pumping system's status remotely through their smartphones.

4.5 Results and Discussion

Fig. 4.8 shows the Android mobile application developed using the MIT App Inventor platform. To ensure its functionality and validate its performance, the application was installed on two mobile phones, undergoing comprehensive testing and evaluation. The application's primary function is to facilitate communication between the user and the Arduino Uno microcontroller as well as user and raspberry pi. By simply sending a text SMS with the keyword "Status?" to the Arduino, users can obtain real-time information about the system's status. The Arduino promptly responds with a detailed message containing essential data regarding the water level, sunlight availability, and pump status. Some possible responses received from the Arduino are as follows:

- "Water Level = Low, Sunlight = Low, Pump = Off" indicates that the water level in the tank is low, sunlight availability is low, and the pump is currently turned off.
- "Water Level = High, Sunlight = High, Pump = Off" signifies that the water level in the tank is high, there is sufficient sunlight available, and the pump remains switched off.

Fig. 4.9 shows the prompt and responses received from Arduino and User Application. To query the status of the pumping system, a prompt SMS was sent to the Arduino Uno, as depicted in Fig. 4.9 (a). This SMS command requested information about the current status of the pump and the water levels in the outer tank. Fig. 4.9 (b) and 10 (c) illustrate scenarios where prompt SMS commands were sent to the Arduino Uno to either turn on or turn off the pump. These commands allowed users to manually manage the operation of the pump, ensuring efficient water distribution.

As shown in Fig. 4.9 (d). The response was transmitted back to the user through the GSM module connected to the Arduino. It contained relevant information, such as the current water levels and the pump's operational status. This real-time feedback enabled users to stay informed about the system's performance and make informed decisions regarding water management. Users can also query the Raspberry Pi 2 via the MQTT protocol over a Wi-Fi connection. Upon receiving the query, the Raspberry Pi 2 promptly processes the request and generates an appropriate response. The response includes vital information such as current water levels, historical data trends, and system performance metrics. This seamless communication between the mobile application, Arduino Uno, and Raspberry Pi 2 ensures that users have access to comprehensive and up-to-date information The integration of the mobile application, Arduino Uno, and Raspberry Pi 2 through these communication channels represents a significant achievement in remote monitoring and control. The combination of SMS commands and MQTT queries provides users with multiple avenues to access relevant system information, enabling effective decision-making and ensuring optimal water distribution.

4.6 Conclusion

This study presented a solar-based water pumping system designed to address water distribution challenges in Sukkur, Pakistan. The system demonstrated its effectiveness in remote monitoring, control, and data visualization, offering a practical solution for areas with limited access to surface water sources. The integration of hardware components, including Arduino, Raspberry Pi 2, and GSM modules, enabled efficient water management and remote operation. The software implementation, such as the MIT App Inventor-based user app, Node-RED, and data communication protocols, provided user-friendly interfaces and reliable data visualization.

While the system presented in this chapter has demonstrated promising results, there are several areas for future work and improvement. Implementing predictive analytics and machine learning algorithms can enable the system to anticipate water usage trends and make intelligent decisions in real-time. Additionally, expanding the scalability of the system to accommodate larger water pumping requirements and multiple pump configurations would be beneficial. This could involve integrating multiple pumps and tanks, along with developing sophisticated control strategies to ensure optimal water distribution and pressure management.

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Chapter 5

Conclusions & Future Work

This thesis represents a substantial endeavor, encompassing the exploration, development, and practical implementation of a solar-powered water pumping system aimed at alleviating irrigation challenges, with a primary focus on the distinctive context of Sukkur, Pakistan. Throughout this research journey, we have witnessed the transformative potential of combining renewable energy and cutting-edge technologies to tackle pressing environmental issues. This conclusion critically assesses the contributions of the research and outlines avenues for further work that directly address the issues unearthed during this comprehensive study.

Foremost among the accomplishments of this research is the successful realization of a sustainable and economically viable water pump system. The core innovation lies in the seamless integration of solar energy, harnessed through a network of photovoltaic panels, which powers a submersible AC pump and stores excess energy in batteries. This holistic approach not only fulfills the crucial irrigation needs of Sukkur but also significantly reduces dependence on finite, non-renewable energy sources. A pivotal aspect of our implemented system is the incorporation of an intelligent monitoring and control system, centered around the Arduino microcontroller platform. This system facilitates real-time data logging and monitoring of critical operational parameters, such as solar irradiance, water levels, and pump status. The combination of the Arduino platform, SD card data storage, and sophisticated algorithms contributes not only to the system's efficiency but also to its robustness and ease of troubleshooting.

Complementing the technical features, the inclusion of an OLED display and a GSM module enhances the practicality of the system. The OLED display offers immediate insights into system performance, while the GSM module enables remote communication and control, augmenting user convenience and system manageability. Moreover, the integration of user-friendly interfaces and data visualization tools through software applications, including the MIT App Inventor-based user app and Node-RED, underscores the system's user-centric design. This accessibility, coupled with the system's overall reliability, positions it as a promising solution for regions like Sukkur. While this research has achieved significant milestones, it also opens doors to future explorations and improvements, which are imperative to realize the full potential of such systems. The critical appraisal of this research highlights the following areas for further work:

- **Advanced Analytics and Machine Learning:** Incorporating predictive analytics and machine learning algorithms can enable the system to proactively respond to changing conditions. By leveraging historical data and real-time inputs, the system can optimize energy usage, water delivery, and resource allocation, thereby maximizing efficiency.
- **Scalability and Multi-Pump Configurations:** Expanding the system to cater to larger water pumping requirements and accommodating multiple pumps and tanks in an integrated network is a logical progression. Research into adaptive control strategies and advanced management techniques for larger-scale implementations is warranted.
- **IoT Integration and Cloud-Based Solutions:** Embracing Internet of Things (IoT) technologies can elevate system monitoring and control to new levels. The incorporation of cloud-based solutions for data storage and analysis can enhance scalability, real-time tracking, and remote management capabilities.

- **Energy Storage Innovation:** Investigating emerging energy storage technologies, such as advanced battery chemistries or novel energy storage methods, holds potential for further enhancing energy efficiency, cost-effectiveness, and system longevity.
- **Enhanced Robustness and Reliability:** To ensure consistent performance under varying environmental conditions, ongoing research should explore advanced control algorithms, predictive maintenance strategies, and robust fault detection mechanisms.
- **Environmental Impact Assessment and Sustainability:** As the system extends its reach, comprehensive environmental impact assessments are vital. Ensuring that the system's deployment aligns with sustainability goals and minimizes ecological impact is crucial for long-term success.

Articles in Refereed Publications

- Omair Ahmed and M. Tariq Iqbal. " Design of Solar Power Water Pumping System for Irrigation in City of Sukkur." *Jordan Journal of Electrical Engineering. (2022)*

- Omair Ahmed and M. Tariq Iqbal. " Remote Data Acquisition System for Photovoltaic Water Pumping System in Sukkur, Pakistan." *European Journal of Electrical Engineering* (2023)

- Omair Ahmed and M. Tariq Iqbal. " Remote Monitoring, Control and Data Visualization for a Solar Water Pumping System." *European Journal of Electrical Engineering* (2023)

Regional Conference Publications

- Omair Ahmed and M. Tariq Iqbal. " Design of a Solar Water Pumping System for Sukkur, Pakistan." 31st *IEEE Newfoundland Electrical and Computer Engineering Conference (NECEC*) 2022.