Design, optimization and analysis of a solar water pumping system for Pakistan

Written by

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Abstract

This thesis covers a comprehensive study about the design, optimization and analysis of a solar water pumping system for Pakistani conditions. For the initial part of this thesis, a site was selected in Wasti Jiuan Shah, Tehsil Sadiqabad, Rahim Yar Khan, Pakistan. The site covers 239.6 acres of land on which Rhodes grass crop is grown for commercial purposes. After evaluating the overall motor load to fulfill the required flow rate of $204m^3/hr$, a feasible solution for a solar water pumping system with a battery bank was designed in HOMER software. For the designed solar water pumping system solution, detailed cost analysis and evaluation of ratings of design components for the overall designed system were also obtained using HOMER software. For the next stage of the thesis, a detailed dynamic analysis was performed in MATLAB/Simulink for the designed system with a battery bank for the duration of the first seven days of operation in April, with custom-made blocks for each solar water pumping system component. In the third stage of the thesis, a solar water pumping system with a water tank was designed for the same selected site earlier. Detailed cost comparison for a solar water pumping system with a battery bank and a solar water pumping system with a water tank was also performed. After analysis, it was concluded that a solar water pumping solution with a water tank is a more feasible solution for Pakistani conditions. The fourth stage of this thesis comprises an open-source Emoncms based SCADA (Supervisory control and data acquisition) monitoring system on which environmental, hydro and electrical parameters of a solar water pumping system were reflected. As the last stage of the thesis, data for three hours and forty minutes was logged in the designed SCADA system.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations and Symbols

PV	Photovoltaic
MATLAB	Matrix Laboratory
HOMER	Hybrid Optimization Model for Electric Renewables
VSI	Voltage Source Inverter
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
NPC	Net Present Cost
MPPT	Maximum power point tracking
MPP	Maximum power point
SCADA	Supervisory Control and Data Acquisition

Chapter 1

Introduction and Literature Review

1.1 Introduction

Pakistan is primarily an agricultural economy that contributes about 22.2% of its overall GDP [1] and employs around 42.3% of its overall labor strength [2]. With agriculture being the mainstay of the economy, an essential component of agriculture is water. Pakistan is a country that faces water shortage. With water availability of around 5000m^3 per capita in the 1950s, it has shrunk to around 1000m^3 per capita currently [2] and by 2025, the water shortfall is expected to reach 150.8 Million acre-feet [1]. Bashir et al. [2] stated the reason for shrinking water resources as poor water management due to the availability of fewer small and large dams for water storage, resulting in wastage of water.

To combat the shortage of water supply for irrigation, water pumps are installed. The country's scenario is not ideal as a shortfall of 5,000MW is faced by the country [3]. So, instead of powering the water pumps through electricity, fossil fuels have been used to power water pumps. Since Pakistan is not rich in fossil fuels and is primarily not an oil-producing country; it imports 346,400 barrels of oil on daily basis, which costs a staggering 10.7 billion US dollars to the economy [4], so increased dependence on imported fossil fuel for electricity production has increased the circular debt to 1.2 trillion Pakistani rupees during the period of last five years [5]. With the government policy shift towards renewable and environment-friendly alternative energy sources, reliance on fossil fuels is expected to decrease.

There is a massive potential for renewable energy in Pakistan, which is around 167.7 GW [3]. Among renewable energies, the potential for photovoltaics in particular is immense in the country.

Pakistan is one of the wealthiest countries in terms of its solar potential, which is up to 100,000MW and the average solar insolation for the country is about 5.5kWh/m^2/day [6].

All the above-discussed resources and issues favor using renewable sources instead of fossil fuels in powering water pumping systems in Pakistan. The primary reasons are because the country is not rich in fossil fuel resources. Whereas on the other hand, Pakistan is rich in solar resources, which can be tapped to overcome energy requirements for running water pumps.

There usually are three types of setups for a solar water pumping system. The simplest of three can be seen in figure 1. The arrow in the figure shows the direction of the flow of water. In this type of setup, a variable speed drive is used to control the speed of the pump, which is powered by a photo-voltaic panel or panels.

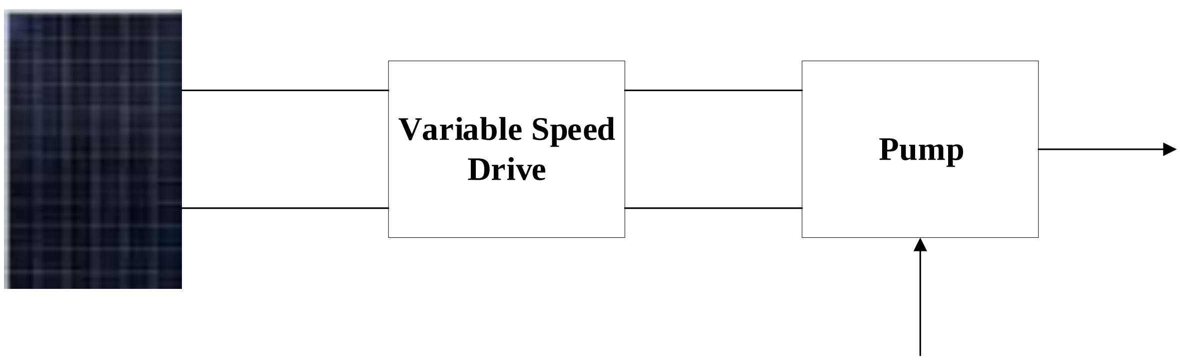


Figure 1: A variable speed drive based solar water pumping system

The second type of setup for a solar water pumping system can be seen in figure 2, which comprises a battery bank, maximum power point tracker and an inverter. These systems are of utility as they can store excess electrical energy, which can power a water pump when required.

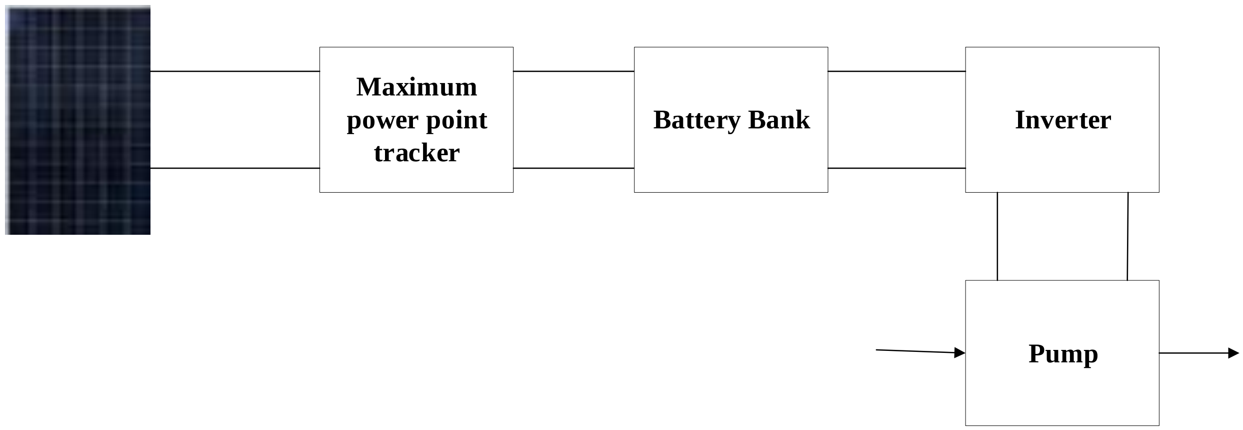


Figure 2: Battery bank based solar water pumping system

Finally, the third type of setup for a solar water pumping system is the one with a water tank, in which a water tank is used to store excess water into the water tank, as shown in figure 3. When the water supply is required, the water tank can fulfill the water requirement for the site.

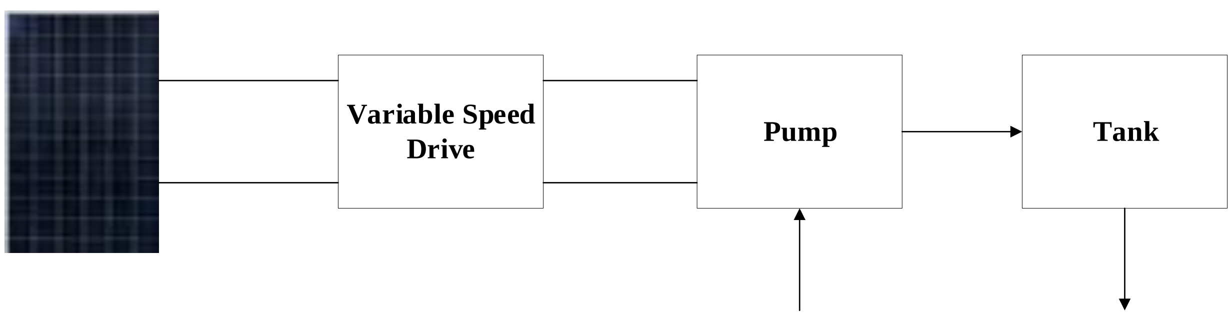


Figure 3: Solar water pumping system with water tank storage

Different components of a solar water pumping system are discussed in the following section.

1.1.1 Types of PV Cells

The type of PV cells used to power solar water pumping systems, which are widely available in the market are.

- Monocrystalline cell
- Polycrystalline cell
- Thin Film cell.

Monocrystalline Cell: This photovoltaic cell consists of pure silicon, a continuous single lattice structure drawn into thin wafers and doped to form a P-N junction. A typical monocrystalline silicon cell can be seen in figure 4.

Figure 4: A typical monocrystalline cell [7]

Polycrystalline cell: This type of photovoltaic cell consists of grains of crystals produced from cast square ingots, which involves cutting silicon into thin plates [8]. A typical polycrystalline cell can be seen in figure 5.

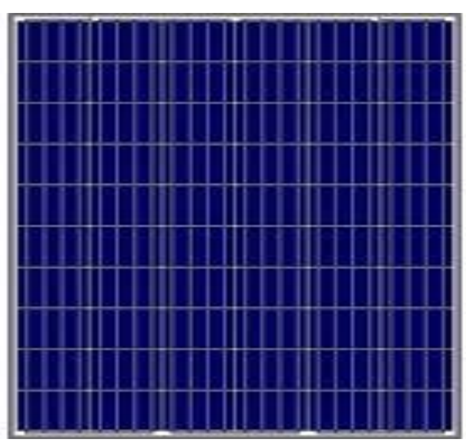


Figure 5: A typical polycrystalline cell [9]

Thin-Film Cell: This photovoltaic is made by depositing a thin layer of photovoltaic material over plastic, metal or glass [10]. It is commercially available in four types of technologies Cadmium Telluride (CdTe), Amorphous Silicon (a-Si), Copper Indium Gallium Selenide (CIGS) and Gallium Arsenide (GaAs) [11]. An example of a thin-film cell can be seen in figure 6.

Figure 6: An example of a thin-film cell [12]

1.1.2 Maximum Power Point Tracking technique

One of the most well-known maximum power point techniques used in solar water pumping systems is perturb and observe method.

Perturb and Observe (P&O) Method: This MPPT algorithm is mainly used due to its low price and straightforward implementation [13]. Firstly, initial voltage and current measurements are taken at a default duty cycle. These values are then used to measure the instantaneous power. A perturbation value of ΔD (change in default duty cycle) is then selected, which represents the change in duty cycle. Now, the choice is to select the type of perturbation. If the positive perturbation is selected, then a positive change in the duty cycle is observed. Similarly, if the negative perturbation is selected, a decrease in the duty cycle is implemented. Afterwards, instantaneous voltage and current values are measured; these values are then used to calculate the instantaneous power. The current power value is then compared with the previous power value. If the current power level is more significant, then a positive perturbation is perused, and if negative, then a negative perturbation is perused. This process continues until a point is achieved, which is generally regarded as MPP (Maximum Power Point) [14].

MPP varies for different temperatures and irradiances. Typically, there is a specific MPP for a specific irradiance and temperature. Hence, throughout the day, MPP keeps on varying and so does the search for the right MPP by the MPPT. In figure 7, a flowchart for the algorithm of the P&O MPPT method can be seen.

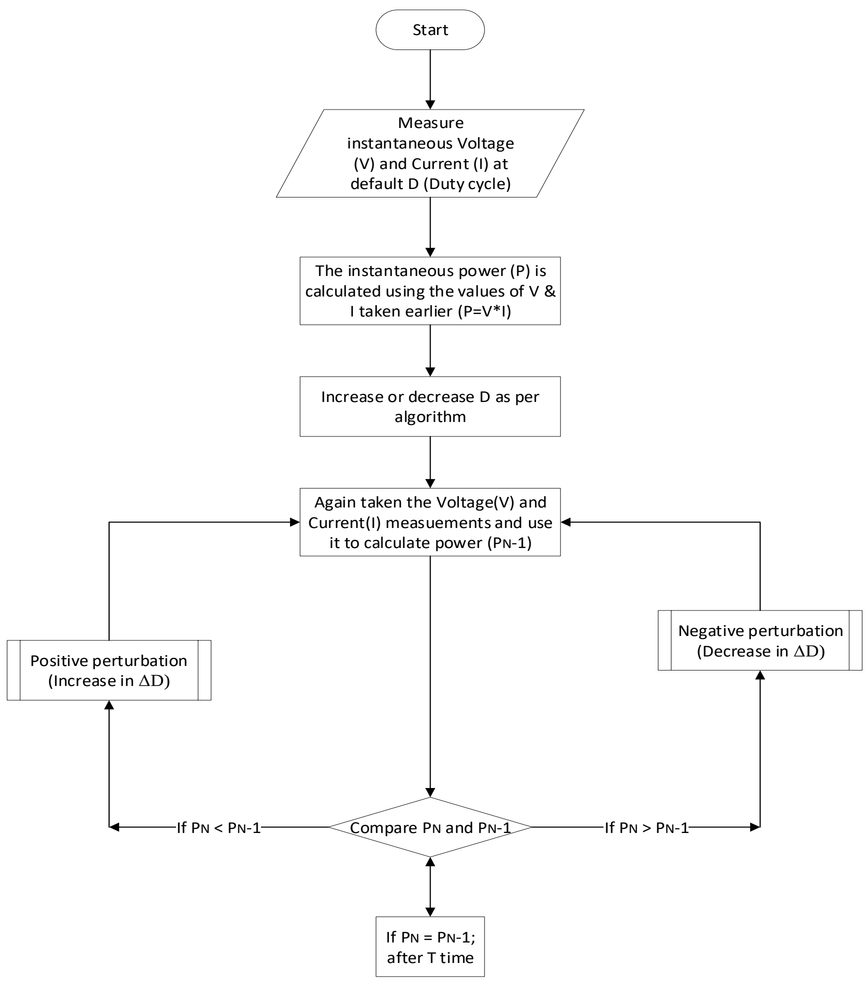


Figure 7: Flowchart of the algorithm for P&O MPPT Method

1.1.3 DC-DC Power Converter

Buck-Boost Converter: It is typically a power converter used to step up and step down the output DC voltage compared to DC input voltage. It has the capability of both boosting or bucking the output voltage as compared to the input voltage. A typical buck-boost converter can be seen in figure 8 below. In the figure, Vs is the source or input voltage, Vo is the output voltage and S is the switch which is usually an IGBT, D is a diode, L is an inductor and C is a capacitor.

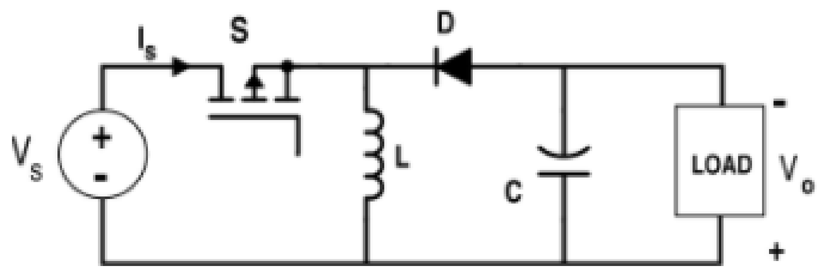


Figure 8: A Buck-Boost Converter [15]

1.1.4 Inverter

Three Phase Full bridge inverter Configuration: It does DC to AC conversion by operating the switches in a set sequence based either upon 120^o Conduction or 180^o Conduction mode of operation. A typical three-phase full-bridge inverter configuration can be seen in figure 9.

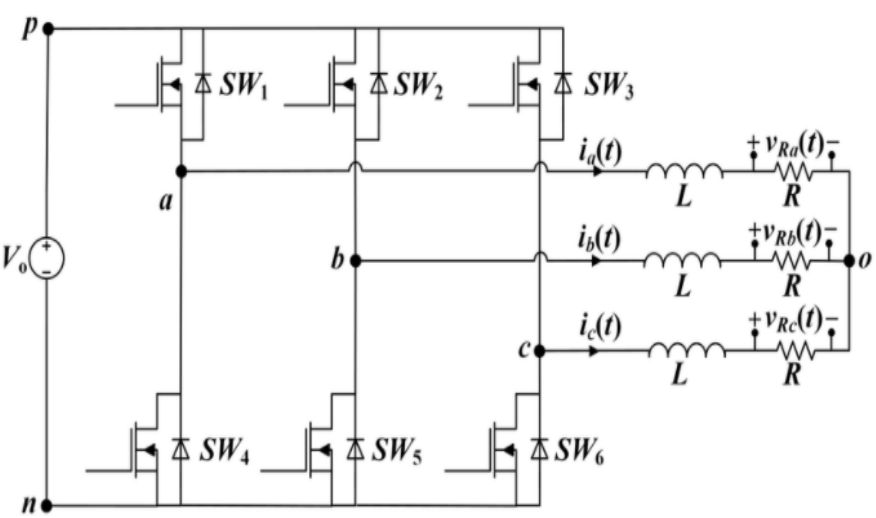


Figure 9: Three Phase Full bridge inverter configuration [16]

1.1.5 Battery (Optional)

Lead Acid Batteries: This battery was invented in 1859 by a French physician named Gaston Plante [17]. It is regarded as one of the most successful and earliest batteries available for commercial purposes. In a typically available 12V battery, 6 lead-acid cells are connected in series. A lead-acid battery can be seen in figure 10 below.

Figure 10: A lead-acid battery [18]

Types of electrodes: Its anode (negative electrode) consists of lead, made of sponge lead; this increases the surface area available to react with the sulphuric acid electrolyte. Its cathode (positive electrode) consists of lead dioxide [19].

Electrolyte: It is a diluted solution of Sulfuric acid, which is usually 40% concentrated. The sulfuric acid solution positively charged H^+ ion and negatively charged SO_4^{2-} ions facilitate in redox reaction [19].

Separator: The function of a separator is to avoid shredded active material from causing a short circuit. There are two types of separators: microporous membrane and absorbed glass mats (AGM) [19].

Working of battery: When a load is applied across the lead-acid battery's positive and negative terminals, a circuit completes. Electrons flow through a redox reaction in the sulfuric acid solution in the electrolyte [19].

$Pb + PbO_2 + 4H+ + 2SO_4^{2-} \rightarrow 2PbSO_4 + 2H_2O$

At Anode, oxidation occurs:

$Pb \rightarrow Pb^{2+}$

$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$

At Cathode, reduction occurs:

$PbO_2 \rightarrow Pb^{2+}$

$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

1.1.6 Types of Water Pumping Systems

There usually are two types of pumps in operation for a solar water pumping system [22].

- Submersible Solar Pumps
- Surface Solar pumps

Submersible Solar pumps: These pumps are used to lift water up to 650 feet and usually are used when the water supply is more than 20 feet deep from the surface [22]. A submersible solar water pump can be seen in figure 11 below.

Figure 11: Submersible Solar water pump [23]

Surface Solar Pumps: These pumps are effective when the water level is less than or equal to 20 feet from the surface. They can lift water up to 200 feet [22]. A surface solar pump can be seen in figure 12 below.

Figure 12: Surface Solar water pump [24]

1.2 Literature Review

Detailed literature is discussed in this section, including manual and computer simulation-based methods for designing and analyzing a solar water pumping system. This section covers the modeling of different components of a solar water pumping system in MATLAB/Simulink and the use of the SCADA (Supervisory control and data acquisition) system for a solar water pumping system.

Choudhary et al. [25] have discussed the evolution of solar water pumping system with time. Throughout the world for some time now, due to fluctuating prices of fossil fuel [26] and due to their environmental hazards, there has been a considerable shift towards PV based water pumping systems and a lot of research and development have been going on in the field of designing and optimization of a PV based water pumping system. Allouhi et al. has discussed in detail PV-based water pumping systems [27], considering their sizing aspects and economic analysis.

There have been many methods used to optimum design a solar water pumping system. These methods can be classified into two broader categories Manual Formulation Methods and Computer simulation-based Methods.

1.2.1 Manual Formulation Methods

Over time many manual computation methods have evolved, which are easy and straightforward to implement as well. One such method [28] used mathematical formulas to calculate the photovoltaic panel requirement considering a fixed tilt angle, the number of batteries required, and the overall system's cost analysis over a fixed life cycle. In the paper [29], different methods for PV sizing based upon the loss of load probability (LLP) are discussed. A method discussed uses simple manual computations and required four coefficients to design a stand-alone PV system throughout Spain. This paper [30] discussed a method that does PV system curve sizing using a simple procedure based upon observed time-series of solar radiation by incorporating simple geometrical concepts curve for sizing, which use data of daily solar insolation.

1.2.2 Computer-based Methods

Computer-based methods are based on computer simulations. There are two types of analysis performed using computer-based software for a PV-based water pumping system. One is the steady-state analysis and the other is the dynamic analysis of the designed system. In a steady-state analysis, the software performs calculations for a PV system sizing, keeping in view a specific time interval. They also help determine the power generated from the source, load mapping, and different parameters related to battery and power converter requirements [31]. Many of these software for steady-state analysis are discussed in [32], but these software are computation-intensive. Few of such software for system sizing are RETScreen [33], PVplanner [34], PVSyst [35], SolarPro [36], SAM (System advisor model) [37] and HOMER (Hybrid Optimization Model for Electric Renewables) [38]. Some of the software for dynamic modeling which help to evaluate the PV system with changing conditions are TRANSYS (Transient System Simulation Tool) [39], LABVIEW[40] and MATLAB [41].

A design for a 6MW PV system, which is also grid-connected, was analyzed for six different states of Nigeria [42] using RETScreen software. In the design, the overall sizing of the system, cost analysis and emission analysis was performed. After the analysis, the Yobe state among all the six states was declared the best option for designing the 6MW PV-based grid-connected system. The writer [43] developed an approach for appropriate site selection for implementing a PV-based system based on the Brown-Gibson model. He used RETScreen software to evaluate the net present value of the proposed system and payback period duration with saving in terms of carbon emission. For a hostel residence in MANIT Bhopal India, a [44] PV-based system of 110kW over a rooftop covering an area of around 1065m^2 was developed using PVplanner software. The system was developed using four different types of PV cells. The best average performance ratio was of amorphous silicon-based PV Panel, which was 79.5.

Feasibility analysis for PV panels installation [45] on the rooftop was conducted for the University of Surabaya campus buildings located in Indonesia. The expected energy output from those panels was evaluated using PVplanner software. A PV-based water pumping system was designed for a location in Karansar, Jaipur, India using software PVSyst [43]. Using PVSyst and based on climatic data, overall system production in terms of water pumped was determined, which came out to be $10629m^3$. Unused PV energy was determined, which came out to be 927kWh, overall system efficiency came out to be 82.5%. Its cost analysis was also performed, which came out to be 230,320 INR as the initial investment, along with an operating cost of 10,000 INR/yr and a specific cost of 3.84 INR/m^3. Chaichan et al. [44] discussed four different design scenarios for solar water pumping systems in Oman using HOMER. Among them, three were powered by PV and one system was powered by a diesel generator. After the economic comparison, the cost of energy for the diesel generator-based water pumping system was US$ 0.6092/kWh, which was greater than the cost of energy for the PV-based water pumping system, which was US$ 0.4743/kWh.

Kazim et al. [48] has done modeling of PV-based solar water pumping for a remote area in Sohar, Oman, which can be used for irrigation purposes. For the PV-based solar water pumping design, he used HOMER. The system requirements for a daily load of 2.22 kWh/ day came out to be 12V,200 Ah four batteries, a PV module network of 0.84kW rating and an inverter of 0.8kW to serve the design purpose. The cost of the system came out to be 0.309 USD/kWh. In this paper [49], four different systems are designed using HOMER for lightning on a 10km long street in Salalah, Oman. The first system was powered solely by the PV network. The second system was powered by a wind source. A diesel generator powered the third system and the last system was designed using a hybrid approach that used an optimized combination of PV and wind. The hybrid solution of PV and wind proved to be the most cost-effective solution that consisted of a wind turbine of 250kW and 80kW PV panel network backed by 200 (200Ah/12V) batteries and a power converter of 55kW size. As per Kammash et al. [50], the Renewable energy center at the University of technology is to be lighted using the PV Panels network, so they used HOMER for the overall system’s sizing. The PV Panel network requirement came out to be 8kW, 20 12V 200Ah batteries, and a power converter requirement of 4kW. The overall system's initial cost came out to be 2000

USD, the net cost of the overall system came out to be 32,015 USD and the per kW cost of electricity produced by the system came out to be 0.903USD. Alkarrami et al. [51] designed a water pumping system for a site in Sirte city, Libya, sourced by hybrid energy sources. He used three different software to design the proposed system, namely HOMER Pro, HOMER Beta and iHOGA. As per his analysis, HOMER Pro gave the best results. This paper [52] discussed designing a PV water pumping system for Bangladeshi conditions in Lalmonirhat, Bangladesh. For PV water pumping system sizing, the software used was HOMER. After analysis, the PV Panel requirement came out to be 15.013kW, battery bank capacity requirement came out to be 2600Ah and the power converter requirement came out to be 21kW.

The dynamic modeling for an overall designed solar water pumping system can be performed in MATLAB/Simulink. In this paper [53], a PV-operated multi-staged centrifugal pump driven by an induction motor was discussed. The pumping system was aided with a battery bank for excess energy storage purposes. In the paper, MATLAB/Simulink was utilized to evaluate the overall system's dynamic behavior. The results were compared with the manufacturer's data and results differed by a small margin. In this paper [54], MATLAB/Simulink is used to evaluate a PV-based water pumping system's dynamic behavior with a brushless DC motor; it has a zeta DC-DC converter which is used for maximum power extraction during its operation. The simulation results were verified with the manufacturer's data. As per simulation results, 83% was obtained at solar insolation of 1000W/m^2 and the overall efficiency of 71% was obtained at solar insolation of 400W/m^2. A PV-based solar water pumping system is modeled in MATLAB/ Simulink in paper [55]. The pumping system is controlled by a vector-controlled permanent magnet synchronous motor. In MATLAB/Simulink, the modeled system was evaluated at starting state and dynamically changing insolation conditions.

Odeh et al. [56] have designed a PV-based solar water pumping system for a site in Ritem, Jordan, using TRANSYS and determined the impacts of the head of the pump, PV array size, and insolation on the PV array on the overall designed system's output. A program called deck file was developed in TRANSYS by the programmer for the system. It was concluded that while optimally designing the system, there is a trade-off between the overall annual efficiency of the system and the optimum overall cost of the system in terms of water unit cost. The writer has discussed [57] control and monitoring of a PV-based water pumping system using a test bench setup in Algerian conditions using LABVIEW. In this, LABVIEW software was used to observe the data accumulated from different sensors to monitor different parameters such as irradiance, power, and current variation with the pump's varying flow rate, varying time and circumstances.

1.2.3 Conclusion regarding suitable computer based method

Considering the above literature review, we chose HOMER for designing and sizing a solar water pumping system for our work. We found it to be the most widely used software and gave the most consistent and reliable sizing results. For dynamic analysis of the designed system, MATLAB/Simulink was chosen. As per literature, many dynamic analysis results from MATLAB were compared with the manufacturer's data and the simulation results were found to be in line with the manufacturer's data. Hence, MATLAB was chosen as a good option for dynamic analysis of the designed solar water pumping system.

Since the ready-made blocks available in MATLAB/Simulink do not allow a large set of data for irradiance and temperature to be processed rapidly. They are complex and reduce computation speed for the analysis of a large set of input data. For this purpose, mathematical modeling of different components of the designed solar water pumping system was done in

MATLAB/Simulink, namely PV Panel, MPPT, Buck-Boost Converter, Battery Bank, Inverter and water pump using 3 phase induction motor.

In this regard, literature was also surveyed for mathematical modeling of different PV-based solar water pumping systems components in MATLAB/Simulink.

1.2.4 Dynamic modeling in MATLAB/Simulink

1.2.4.1 PV Panel Modeling

In literature, many authors have performed mathematical modeling for a PV panel in MATLAB/Simulink. In paper [58], the author considered a single diode equivalent cell model for a PV panel and utilized built-in mathematical blocks to model different equations to develop an overall model for a PV panel. The modeling was done for the PVL-124 solar panel. The PV subsystem's input was irradiance, temperature, series resistance and shunt resistance and the output was panel voltage and current. This author [59] discussed another model of a PV Panel in MATLAB/Simulink for an MSX 64W PV panel. Subsystems for different mathematical equations of a single diode-based equivalent circuit for PV panel were modeled and integrated. The input to the overall PV subsystem is temperature and Irradiance, while the output is the PV Panel current. The entire system was evaluated over various environmental conditions.

In this paper [60], the writer discussed a PV panel TCM-210SB modeled in MATLAB/Simulink. Different mathematical equations for a single diode model for PV panel were modeled. After modeling, the dynamic behavior of the panel was also tested under environmental characteristics in the Bashkortostan Republic (Russia). The computational results at the end were verified with experimental data using a real panel test bench. One of the most detailed and easy to implement modeling was in paper [57]. In this, a DS-100M solar panel is modeled using single diode model equations. The inputs to the overall PV subsystem are only temperature and irradiance, while the output is the PV Panel current. The author took a different approach; instead of making different subsystems, every equation was modeled in a single subsystem. In the final model, six panels were integrated in series and their dynamic behavior was studied under different scenarios. The results were also verified using 2 PV panels connected in series and the results obtained by simulation were found to be accurate.

1.2.4.2 Buck-Boost Model

Literature was also explored for the mathematical modeling of a buck-boost converter in MATLAB/Simulink. In paper [62], different designs for various DC-DC converters considering their mathematical equations were discussed. An open-loop model of Buck-Boost converter was discussed and simulated in MATLAB/Simulink. Its inputs were input voltage and switch control. The outputs were the voltage and current of the power converter. In paper [63], the writer developed a mathematical model for a buck-boost converter in MATLAB/Simulink with sliding mode control. During the simulation, it showed good dynamic behavior even at varying loads and supply.

1.2.4.3 Battery Model

In paper [64], four different techniques were discussed to keep a check on SOC (State of charge of a battery) while the battery is discharging, which can later be utilized while making a mathematical model for a battery bank in MATLAB/Simulink. In this paper [65], the writer discussed different methods for SOC estimation based on traditional methods that include experimentation with batteries, methods based on control theory, and some methods based on modern algorithms for SOC estimation. These methods can also be realized in MATLAB/Simulink to understand the dynamic behavior of the battery. A lithium-ion battery was modeled in MATLAB/Simulink [66] to understand its dynamic behavior. The mathematical equations for Open circuit voltage, SOC, and the RC's parallel combination were modeled to make an overall battery model in MATLAB/Simulink. This system was further validated using practical results through experimentation.

1.2.4.4 Inverter Modeling

In this paper [67], the author discussed designing a three-phase sinusoidal pulse width modulation-based inverter in MATLAB/Simulink. SPWM technique was analyzed and based on the results of the dynamic behavior of the inverter. It was concluded that there is a reduction in total harmonic distortion in a VSI inverter current and voltage. The author in this paper [68] has modeled a three-phase VSI inverter in MATLAB/Simulink. He modeled two modulation techniques, SPWM and space vector-based PWM technique for an inverter design. After performing the dynamic analysis in MATLAB/Simulink, it was concluded that SVPWM is more efficient in terms of THD and reduces switching losses.

1.2.4.5 Motor/Pump Modeling

In this paper [69], a mathematical-based model for an induction motor was developed in MATLAB/Simulink using basic mathematical equations. This model can be used to analyze the dynamic behavior of the induction model. In paper [70], a dynamic model for an induction motor was modeled in MATLAB/Simulink using the d-q modeling technique, which can be used to understand the behavior of different parameters associated with an induction motor.

1.2.5 Supervisory control and data acquisition (SCADA) implementation for a solar water pumping system

As per author [71], an economical SCADA system was proposed for a solar water pumping system, in which a Node-Red was used as an HMI. In this system's voltage, current and solar irradiance data were extracted using respective sensors integrated with Arduino Uno, connected with

Raspberry Pi Zero and a camera module. In this paper [72], the writer implemented a SCADA system for a Portuguese irrigation canal network, which supported in remote monitoring of parameters such as water flow, water levels and was used for remote control of different gates. In the paper [73], the writer presented an idea of using the Xbee and a GSM module to monitor and control a solar drying and water pumping system. Using Xbee, data was collected and sent over a cloud through a GSM module, which can be viewed and controlled over a specialized mobile app.

In paper [74], a 2.4KW solar water pumping system was monitored and controlled using influx DB and Grafana, which are open-source storage database and HMI (Human Machine Interface). Data was acquired with the help of an RS486 bus using ModBus-RTU protocol which communicated with hardware having sensors. In this paper [67], a SCADA system was developed using LABVIEW; a PLC connected with it took values of different solar-powered irrigation system parameters and reflected them on SCADA, easing the overall monitoring of the system. The author [76] discussed a general SCADA system that monitors different parameters and optimizes operation as per a rule-based approach: the water system operator.

1.3 Motivation and Research Objectives of the thesis

In Pakistan, agriculture is a central component of the economy. Growing agriculture is vital for the rapidly increasing population. For this purpose, more and more water resources must be tapped, which are only possible with abundant electricity resources to power the water pumping system. However, Pakistan has been struggling for the past decade to fulfill its electricity requirements. As the country is rich in solar energy, this strengthens the case for powering solar water pumping systems with solar energy.

The research objectives for this thesis were to

- Design a solar water pumping system with a battery bank for a selected site in Pakistan using HOMER, which can be taken as a case study for future scenarios.
- Perform dynamic analysis for the designed solar water pumping system in MATLAB/Simulink to validate the designed system in HOMER. Mathematical modeling of different solar water pumping systems components was to be performed so that a more straightforward overall system can be developed, which is robust, quick and can simulate data for a larger input data set.
- Design a solar water pumping system with a water tank for the same selected site using HOMER. Compare the two designed solar water pumping systems and evaluate which one of the two systems is more feasible for Pakistani conditions.
- Design an Emoncms based SCADA system that can store and reflect environmental, hydro and electrical parameters related to a solar water pumping system.

1.4 Structure of the Thesis

The first chapter of this thesis discusses a detailed literature review; it discusses the need and feasibility of a solar water pumping system in Pakistan. It discusses literature related to different tools used to design and analyze a solar water pumping system and the SCADA system for a solar water pumping system. Chapter one also discusses different components of a solar water pumping system, their modeling and the chapter concludes with the thesis research objectives.

In the second chapter, the design and analysis of a solar water pumping system in HOMER is discussed, including designing solar water pumping water to evaluate ratings of different components. It also includes a detailed cost analysis of the overall proposed solar water pumping solution.

The third chapter is about dynamic modeling of the proposed solar water pumping system in MATLAB/Simulink. Detailed dynamic modeling and analysis of the solar water pumping system is performed to analyze the system to dynamically changing conditions for a sample set of seven days.

The fourth chapter discusses the design and analysis of a solar water pumping system with a water tank in HOMER. Using HOMER software, a solar water pumping system is designed with storage as a water tank. Along with this, a detailed cost analysis for the designed system is also done in HOMER. Towards the end, two designed solar water pumping systems in which one is with a battery bank as a storage system and others have a water tank as a storage system, are discussed and compared with each other based on their cost analysis.

In the fifth chapter, an open-source Emoncms SCADA system is discussed, which is used to monitor different parameters of a solar water pumping system; the parameters monitored are divided into three categories environmental, hydro and electrical parameters.

The sixth chapter discusses concluding remarks, research contributions and improvements that can be incorporated in the already designed solar water pumping system to make the overall system better.

Chapter 2

Design and Analysis of a Solar Water Pumping System in HOMER

2.1 Site Selection

A suitable site was selected where a solar water pumping system can be implemented. For this purpose, an agricultural area was selected, known as "Mustafa Research Farms," located at Wasti Jiuan Shah Tehsil Sadiqabad, Rahim Yar Khan, Pakistan. The coordinates of location are 28°14'24.0"N 69°37'16.0"E [77]. It covers an area of around 239.6 acres of land. The crop cultivated on this land is Rhodes Grass, which is grown for commercial purposes and is exported from Pakistan to many countries of the world.

In figure 13, the Mustafa Research Farms is bordered by a blue line in figure 13. Five water pumping systems irrigate this whole area. The location of the water pumping systems can be seen by circles in blue in figure 14.

Figure 13: Selected agricultural site "Mustafa Research Farms."

Figure 14: The locations of the five water pumping systems

2.1.1 Solar Insolation details of the selected site

The solar insolation details and clearness index can be seen in figure 15, extracted from the National Renewable Energy Laboratory [78] as its database is attached with HOMER. The figure shows that the GHI (Global Horizontal Index) varies from 3.6 to 7.26 kWh/m^2/day and its clearness index varies in the range of 0.601 to 0.69.

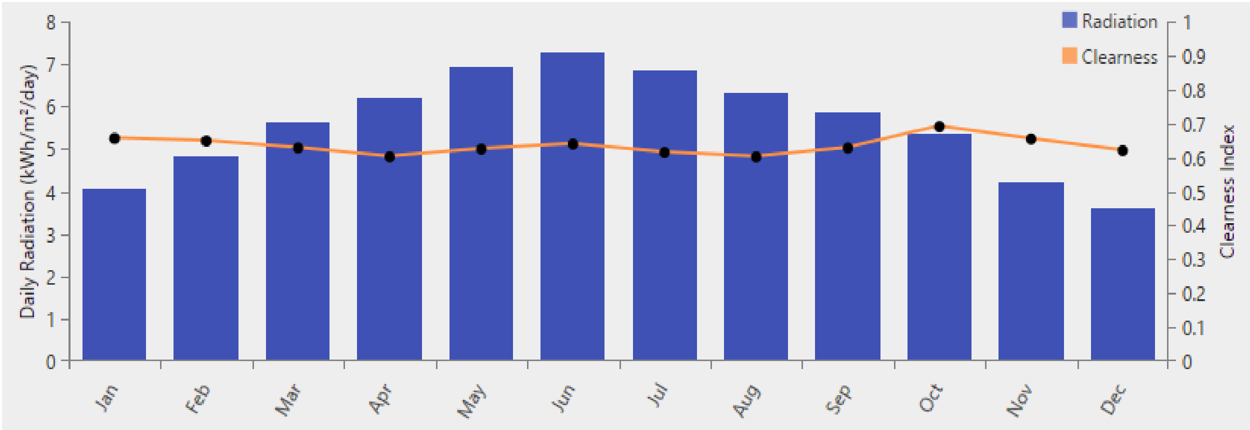


Figure 15: Insolation and clearness index details of the selected site

2.1.2 Data Collected from the Site

The data collected from the selected agricultural site for motor/pump load calculation is as follows and the yearly operation of the motor is summarized in table 1.

Water level = 25ft = 7.62m

Dynamic head = 35ft = 10.668m

Water flow requirement = 2 cusec (cubic feet/sec) = 204m^3/hr = 898.2 gpm

Table 1: Details of operation throughout the year

Months	Days of Full Operation (24 x 7)	Days of idle operation
January	First 7 days of the month	Next 24 days of the month
February	First 10 days of the month	Next 18 days of the month
March	First 11 days of the month	Next 20 days of the month
April	First 14 days of the month	Next 16 days of the month
May	First 17 days of the month	Next 14 days of the month
June	First 20 days of the month	Next 10 days of the month
July	First 22 days of the month	Next 9 days of the month
August	First 24 days of the month	Next 7 days of the month
September	First 18 days of the month	Next 12 days of the month
October	First 14 days of the month	Next 17 days of the month
November	First 10 days of the month	Next 20 days of the month
December	First 0 days of the month	Next 31 days of the month

The brand selected for the water pump/motor is Wilo. It has an online tool [79] that was used to evaluate the motor and pump size. The required data (flow rate and total dynamic head of the motor) was incorporated in the online tool. The motor rating came out to be 11kW, which is equivalent to 15hp. The details regarding the motor/pump are in figure 16. Details led to the selection of Atmos GIGA-N 125/200-11/4 [80]. The further details regarding motor/pump are summarized in figure 17 [79].

Motor data
Mains connection: 3~400V/50 Hz
Voltage tolerance: ±10 %
Motor efficiency class: IE3
Rated power: 11 kW
Rated speed: 1470 1/min
Rated current: 20,9 A
Power factor: 0,77
Motor efficiency: 91,1 %
Motor efficiency: 91,8 %
Motor efficiency: 91,6 %
Protection class: IP55
Insulation class: F

Installation dimensions
Pipe connection on the suction side: DN 150 , PN16
Pipe connection on the pressure side: DN 125, PN16

Figure 16: Details of Motor/Pump for the selected site

Most of the solar water pumping systems are battery-less. Still, in this scenario, the system chosen was battery-based because of the water requirements for the site. It required a system designed to operate for 24 hours a day and for that, there had to be a storage system so that continuous operation of motor/pump is not compromised. This is because excess solar energy is only available for a specific segment of the day.

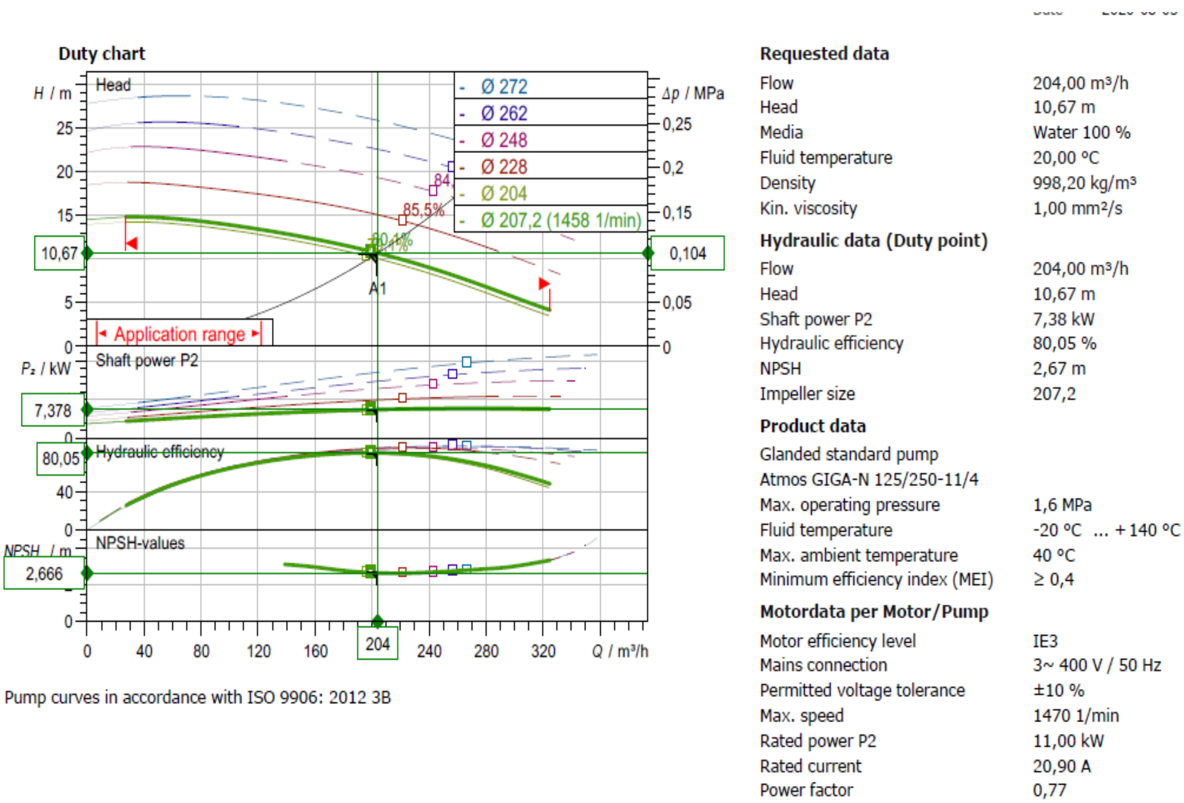


Figure 17: Selection parameters that led to motor selection

2.2 Sizing of the proposed system using HOMER

The next step was to map the load details in HOMER as per the motor operation table summarized in table 1 and the calculated motor/pump load. Then the simulation in HOMER was performed to get the optimum ratings of different design components of the proposed solar water pumping systems. The diagram of the overall proposed PV-based water pumping system can be seen in figure 18.

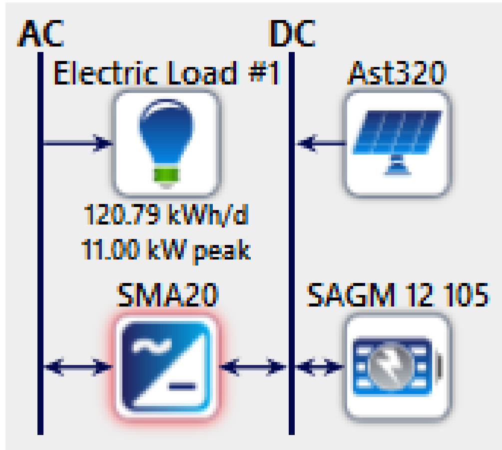


Figure 18: Proposed PV based water pumping system

After the simulation was performed in HOMER, the sizing results were summarised in figure 19. The PV panel network was composed of Astronergy ASM6612P-320 solar panels [81]. Its requirement came out to be 73.8kW. The battery-bank composed of Trojan SAGM 12 105 [82] came out to be 450. The inverter requirement came out to be 16.7KW and for that purpose, an SMA Sunny Tripower 20000TL-30 [83] was selected.

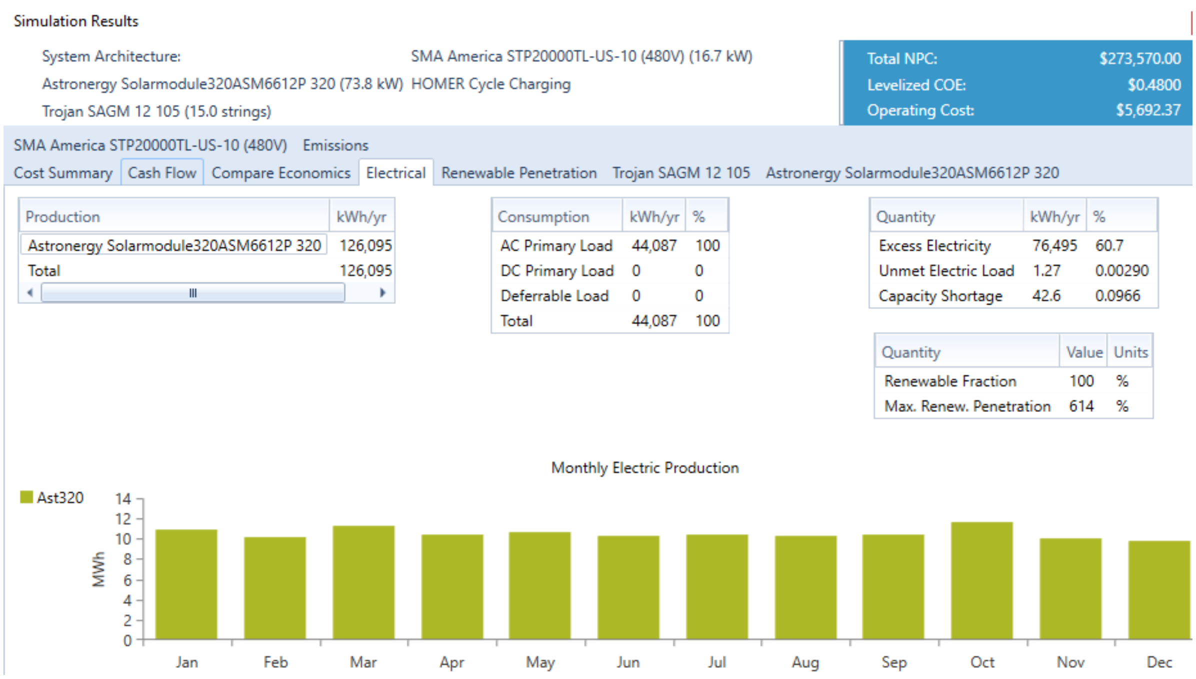


Figure 19: Simulation results for the proposed system

The overall proposed system can be seen in figure 20. As the PV panel network requirement came out to be 73.8kW, 240 24V panels were required to fulfill the requirement with 16 panels in series and 16 such strings in parallel. The battery-bank requirement of 450 was fulfilled by 30 batteries connected in series and 15 such strings connected in parallel. The purpose of having 16 PV panels in series and 30 batteries in series per string was to maintain a dc bus voltage of 360V. The inverter used was of 20kW.

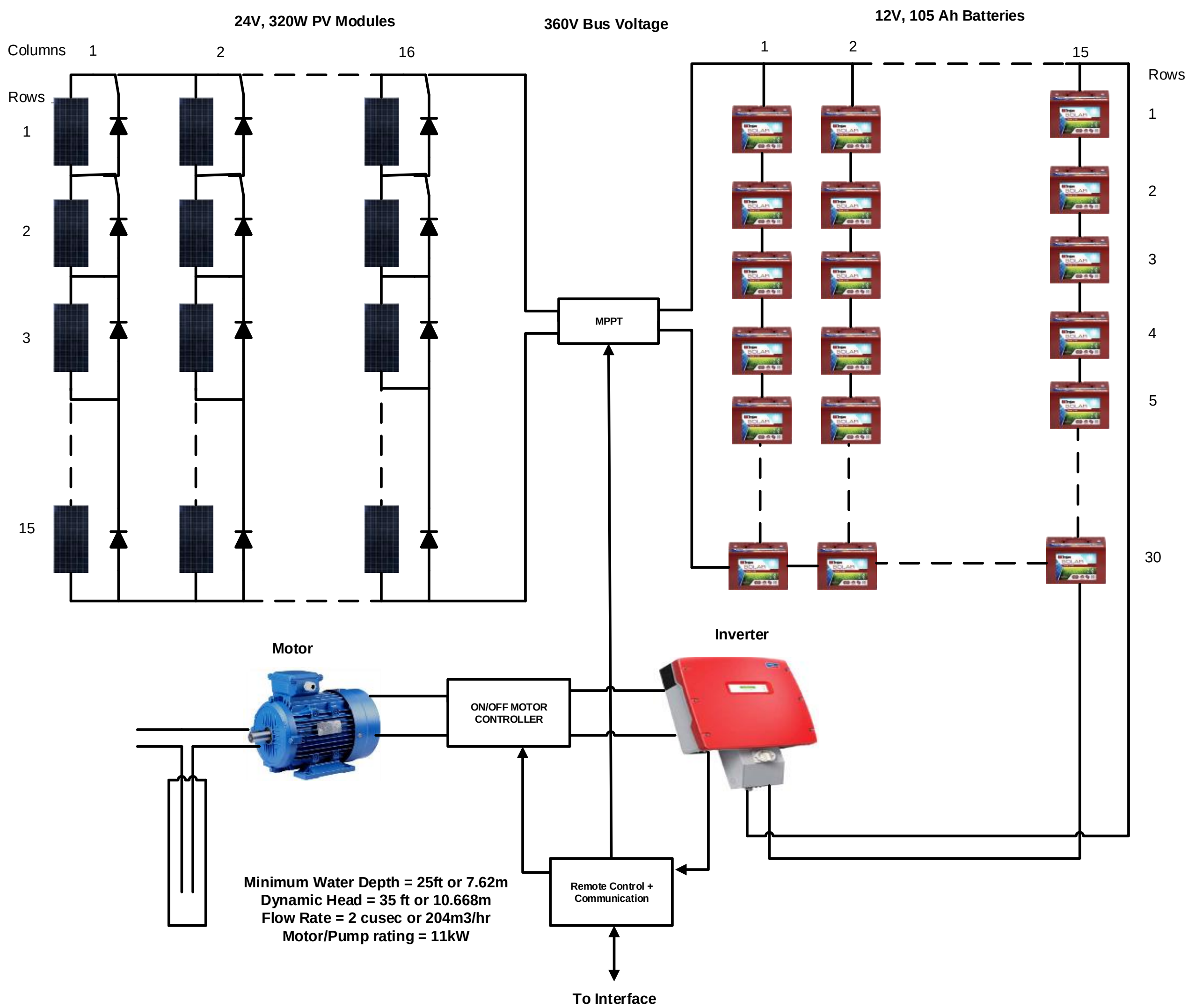
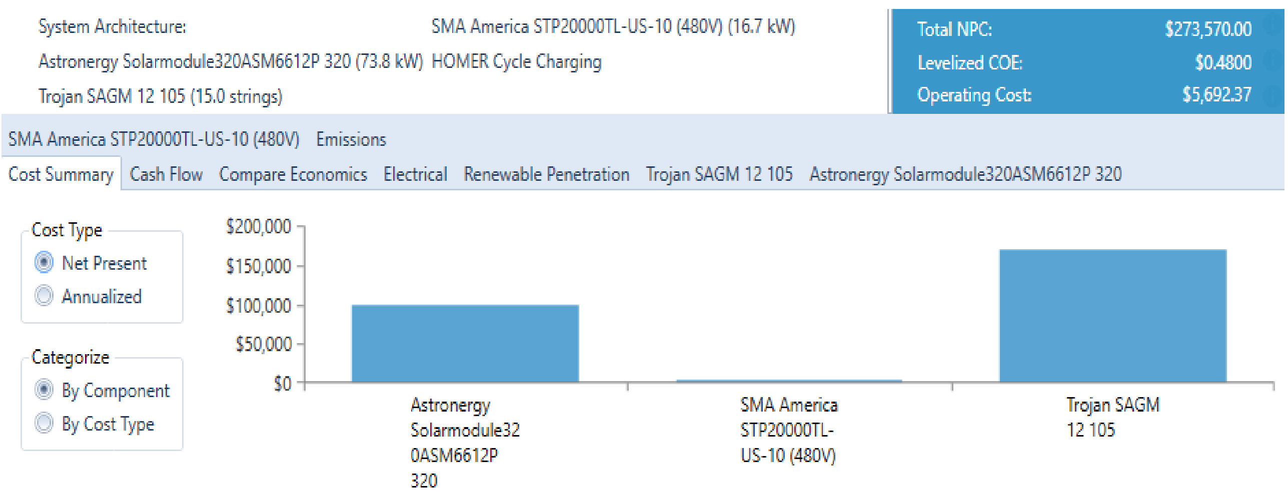


Figure 20: Overall proposed solar water pumping system with a battery bank.

2.3 Economic Analysis of the proposed system using HOMER

The economic analysis of the overall proposed system over its life cycle of 25 cycles was also done using HOMER. The cost summary of the overall proposed system is summarised in figure 21. It can be seen that the total net present cost of the overall system is $273,570. The system's levelized cost of energy comes out to be $0.48 and operating cost, which is $5692.37 per year.

As per cash flow over the life cycle of 25 years for the proposed system, which can be seen in figure 22. The initial investment required is $199,981.86, then an annual investment of $4,615.22 is required from the 1st year of its operation to the 25th year of its operation. In the 21st year, a further investment of $99,000 is required to keep the system running. After the end of the cycle of 25 years, a salvage value of $76,681.52 is available for the overall system.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Astronergy Solarmodule320ASM6612P 320	$39,713.02	$0.00	$59,663.29	$0.00	$0.00	$99,376.31
SMA America STP20000TL-US-10 (480V)	$2,768.84	$1,174.75	$0.00	$0.00	($221.10)	$3,722.49
Trojan SAGM 12 105	$157,500.00	$31,119.79	$0.00	$0.00	($18,148.56)	$170,471.23
System	$199,981.86	$32,294.53	$59,663.29	$0.00	($18,369.66)	$273,570.03

Figure 21: Cost Summary of the proposed system.

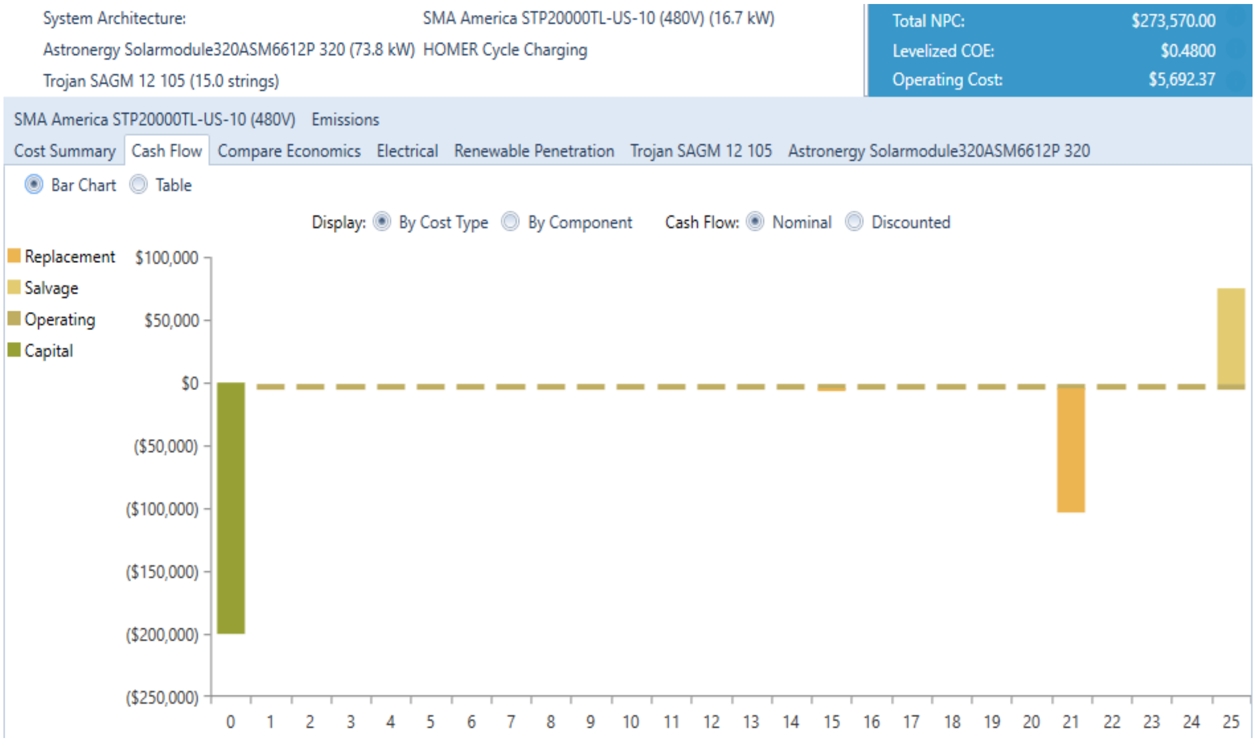


Figure 22: Cash Summary of the proposed system

2.4 Summary of the overall designed solar water pumping system

In the table below, a detailed summary of electrical component ratings and cost is given below.

Table 2: Detailed Summary of electrical component ratings and cost of the proposed system

Electrical Component	**Ratings of Electrical Components**
PV Panel	73.8 kW
Inverter Rating	16.7 kW
Battery requirement	450
Cost Parameter	**Cost ($)**
Net Present Cost	273,570
Levelized Cost of Energy	0.48
Operating Cost	5692.37

2.5 Conclusion

This chapter's content covered site selection for a solar water pumping system with a battery bank followed by its design in HOMER. After the design, the design parameters for different components of a solar water pumping system were evaluated. A detailed cost analysis was also performed for the designed solar water pumping system using HOMER.

Chapter 3

Dynamic Modeling of the Proposed Solar Water Pumping System in MATLAB/Simulink

For the dynamic analysis of the designed solar water pumping system with a battery bank in HOMER, MATLAB/Simulink was chosen. The purpose of the dynamic modeling was to analyze the designed system's behavior with changing solar insolation and temperature to verify if the designed system is feasible for the selected site.

3.1 Dynamic System Modeling in MATLAB/Simulink

As the ready-made blocks in MATLAB/Simulink library were complex and a system composed of them is not suitable for dynamic analysis for prolonged time intervals. In contrast, our objective was to perform dynamic analysis for the designed system for lengthy intervals to verify the system comprehensively. Hence, the proposed system's dynamic modeling was done in MATLAB/Simulink using models based on their mathematical equations. The mathematical modeling of different design components enabled speedy simulation, which resulted in a robust design. The model of the proposed system can be seen in figure 23.

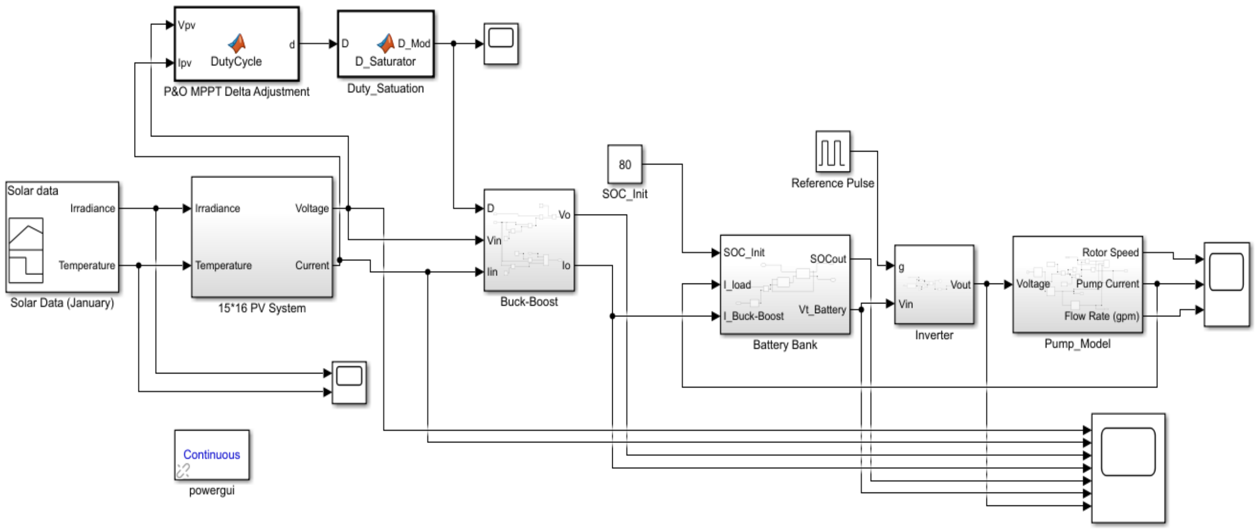


Figure 23: Dynamic Model of proposed PV based water pumping system with battery bank

3.1.1 Details of Blocks for Dynamic model

This section discusses in detail the subsections of the model for dynamic analysis in figure 23.

3.1.1.1 PV Panel Network Modeling

The PV Panel requirement was 15 panels in series and 16 such panels strings in parallel. It can be seen in figure 24 that a panel output is multiplied by 15 to serve the correct voltage level and the output of the second panel is multiplied by 16 to serve the correct current level.

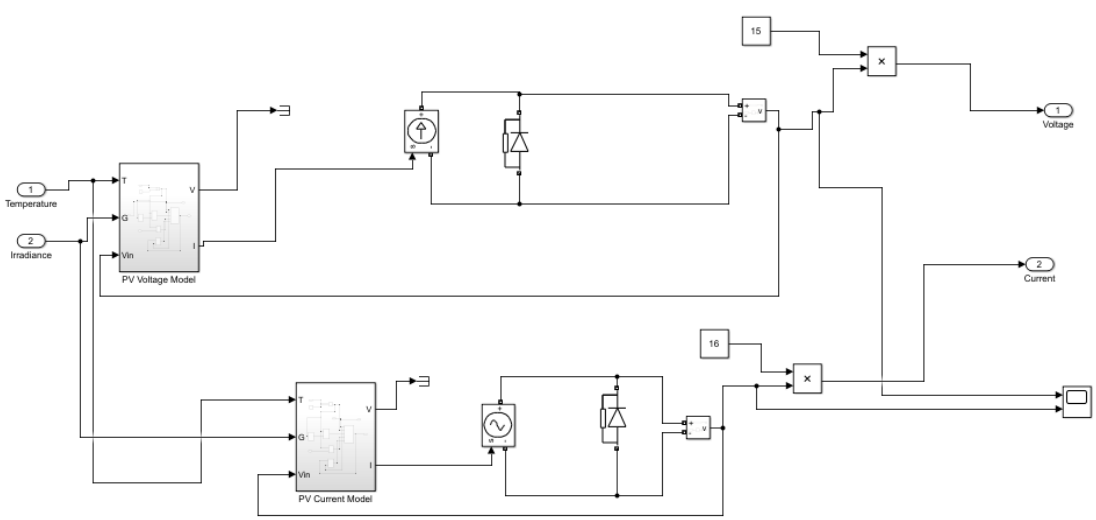


Figure 24: Depiction of 15 x 16 PV Panel setting requirement

PV Panel modeling included modeling mathematical equations that depict a single diode PV Cell Model seen in figure 25.

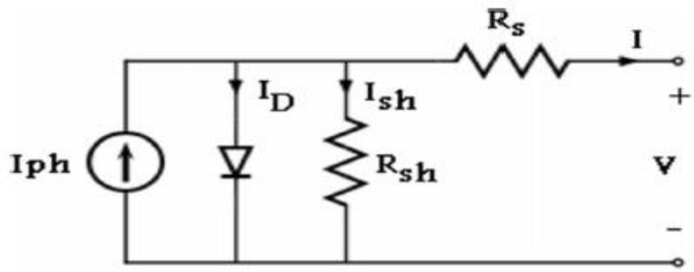


Figure 25: Single diode PV Cell Model

The modeled equations are as follows.

The Photo-current equation is written as 1. The saturation current equation is written as 2. Reverse Saturation current is written as 3. Current through shunt resistor is written as equation 4 and the Output current is given by equation 5.

$$I_{ph} = \left[I_{sc} + k_i.(T - 298).\frac{G}{1000}\right] \qquad (1)$$

In equation (1); I_{ph} means photo-current in A, I_{sc} means short circuit current in A, K_i means short-circuit current of the cell at 25 °C and 1000 W/m^2, T means operating temperature (K); I_r: solar irradiation (W/m^2).

$$I_0 = I_{rs}.\left[\frac{T}{T_n}\right]^3.\exp\left[\frac{q.E_{go}.\left(\frac{1}{T_n}-\frac{1}{T}\right)}{n.k}\right] \qquad (2)$$

In equation 2; I_0 is saturation current, I_{rs} is the reverse saturation current, q is the electron charge, Tn: nominal temperature = 298.15 K; Eg0: bandgap energy of the semiconductor, = 1.1 eV; n: the ideality factor of the diode; k: Boltzmann’s constant, = 1.3805 × 10−23 J/K.

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q.V_{oc}}{n.N_S.k.T}\right)}-1} \qquad (3)$$

In the equation 3; V_{oc} is open circuit voltage

$$I_{sh} = \left[\frac{V+I.R_s}{R_{sh}}\right] \qquad (4)$$

In equation 4; V is the output voltage, I is the output current, R_s is the series resistance, R_{sh} is the shunt resistance

$$I = I_{ph} - I_0 \left[\exp\left[\frac{q.(V+1.R_s)}{n.k.N_s.T}\right] - 1\right] - I_{sh} \qquad (5)$$

For the modeling of the above equations and final system in MATLAB/Simulink; reverse saturation equation modeled can be seen in figure 26, saturation current equation modeled can be seen in figure 27, photocurrent equation modeled can be seen in figure 28, shunt current equation modeled can be seen in figure 29, Output PV current model can be seen in figure 30. The overall PV cell model can be seen in figure 31.

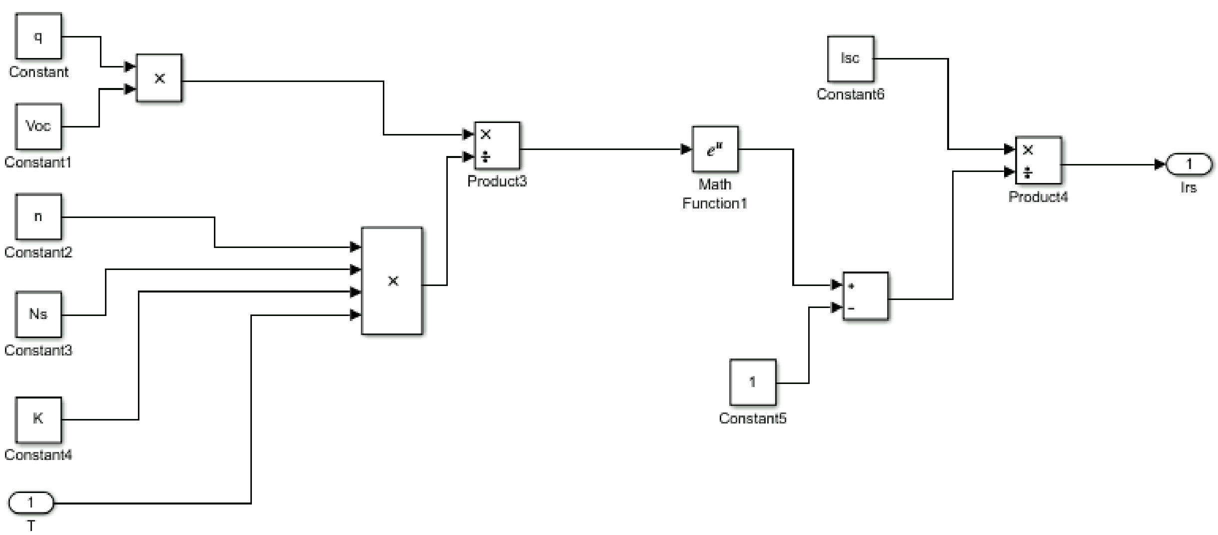


Figure 26: Reverse Saturation equation modeled in MATLAB/Simulink

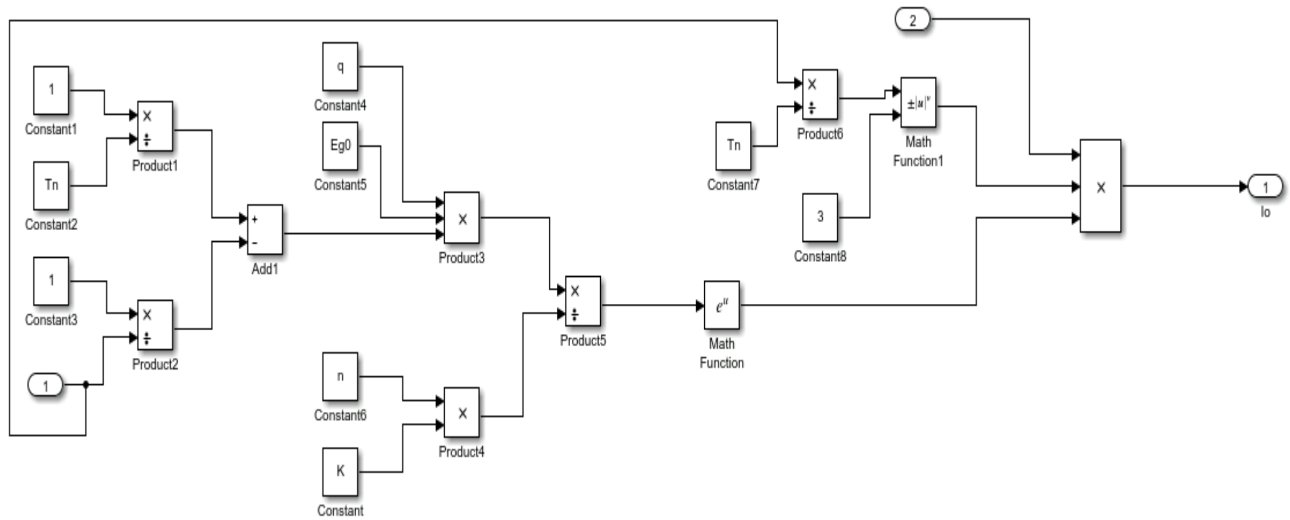


Figure 27: Saturation Current Equation modeled in MATLAB/Simulink

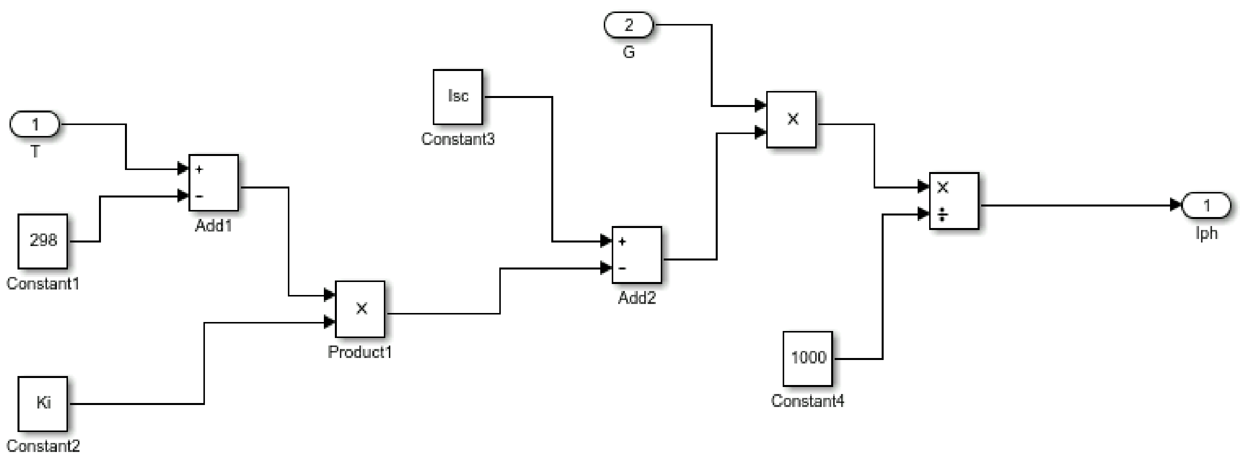


Figure 28: Photo-Current Equation modeled in MATLAB/Simulink

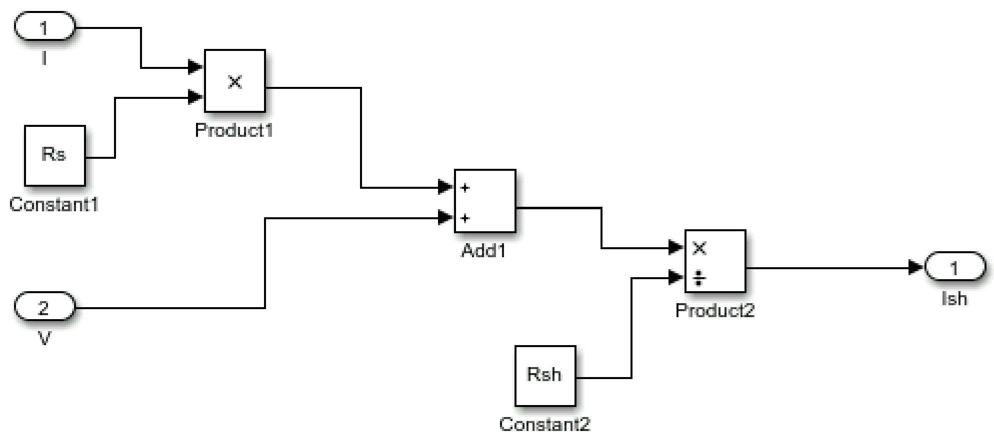


Figure 29: Shunt Current Equation modeled in MATLAB/Simulink

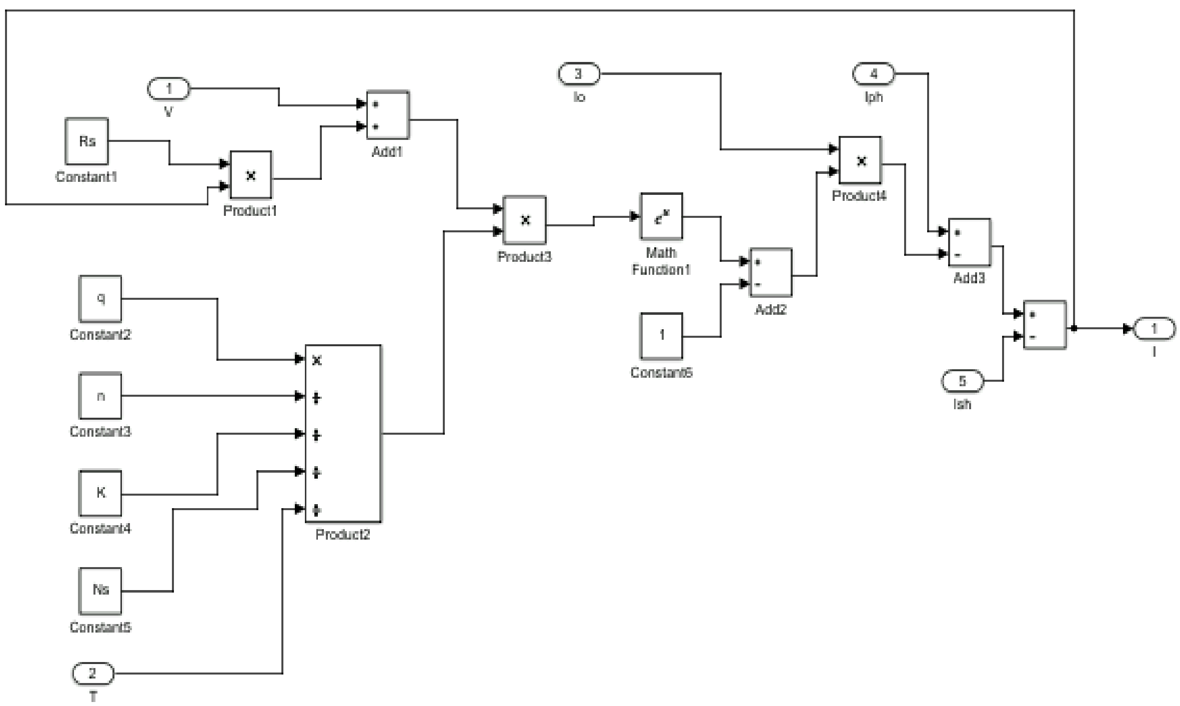


Figure 30: Output PV current modeled in MATLAB/Simulink

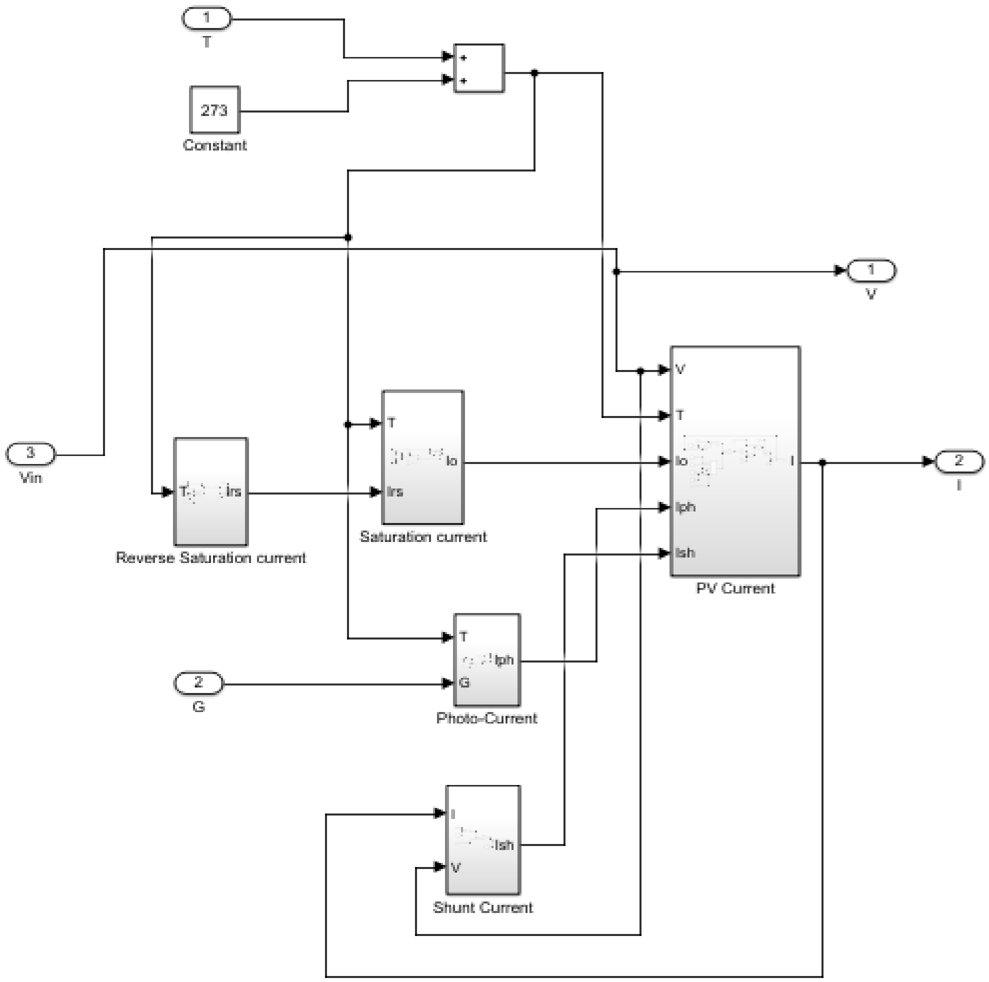


Figure 31: the Overall PV cell model in MATLAB/Simulink

3.1.1.2 Buck-Boost Modeling

The mathematical equations for the buck-boost converter were modeled in MATLAB/Simulink.

The equations modeled are as follows in equations 6 and 7.

$$V_o = -\frac{V_i k}{1-k} \qquad (6)$$

In this equation above, V_o is the output voltage, V_i is the input voltage and k is the duty cycle.

$$I_i = \frac{I_o k}{1-k} \qquad (7)$$

In the equation above; I_o is the output current, I_i is the input current

The equations modeled MATLAB/Simulink can be seen in figure 32.

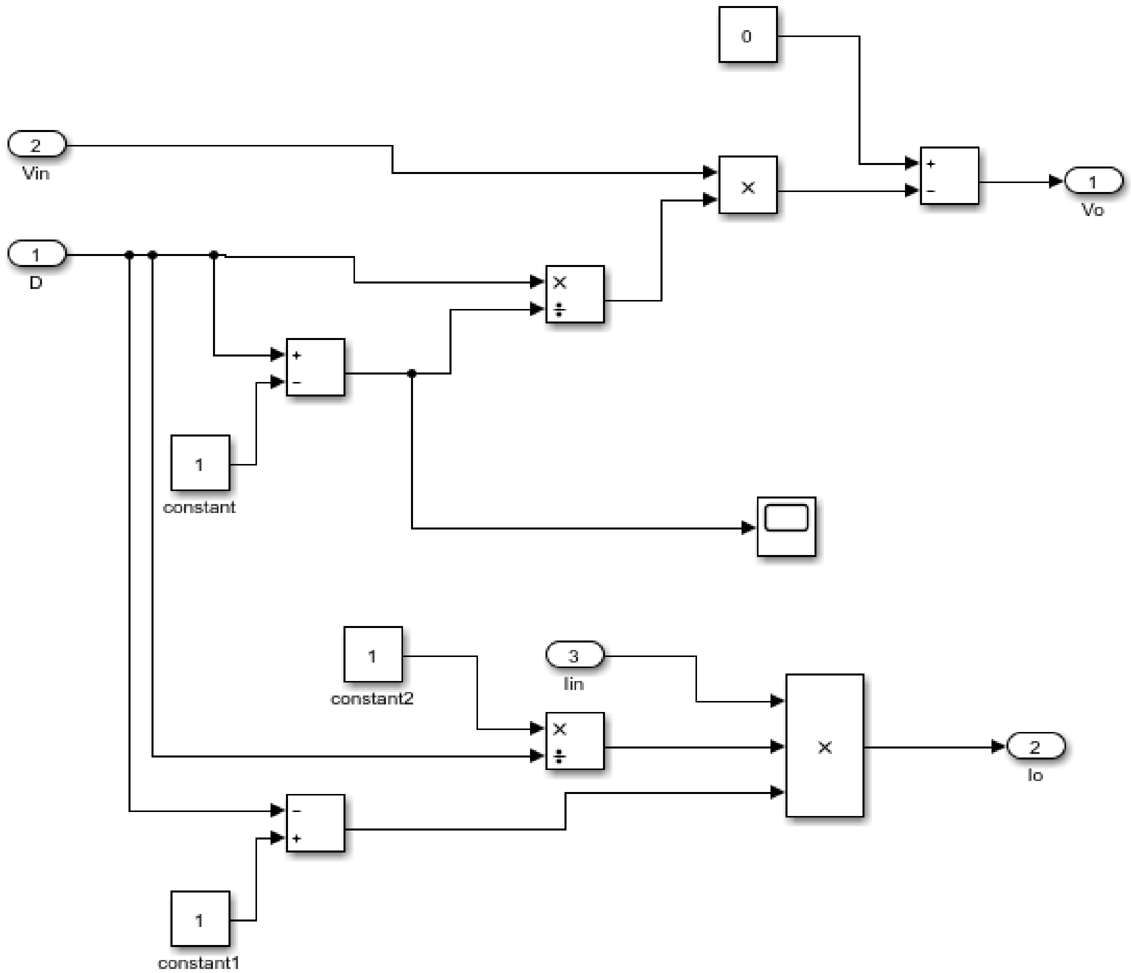


Figure 32: Buck-Boost voltage and current equations modeled in MATLAB/Simulink

3.1.1.3 Battery Bank Modeling

Figures 33 and 34 show scenarios when the battery is discharging and charging respectively.

As shown in figure 33, when a battery is discharging, the switch with the solar panel is open. In this scenario, the load voltage (V_L) is less than the open-circuit battery voltage (Voc). The open-circuit voltage depends on SOC (Value of AH of the battery at that time) and the SOC (State of Charge) can be calculated on I_B (battery current), which is equal to I_L (load current). The equations for V_T or terminal voltage and load current I_L can be seen in equations 8 and 9. The equation for SOC is in equation 10.

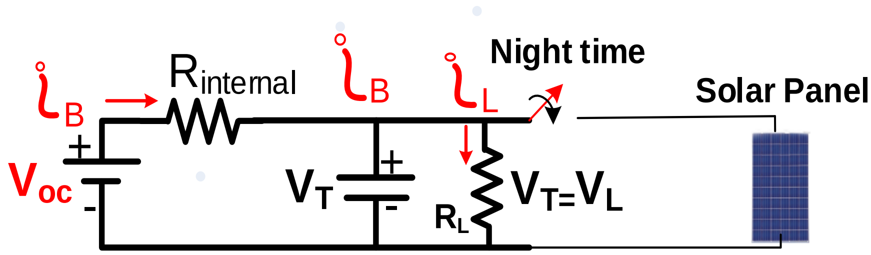


Figure 33: Battery feeding the load

$$V_T = V_{oc} - I_B R_{internal} \quad (8)$$

$$I_L = I_B = \frac{V_T}{R_L} \quad (9)$$

$$SOC(t) = SOC_{(t=o)} - \frac{1}{3600}\int_0^{t(Sec)} I_B \, dt \quad (10)$$

In the equations above, I_B is the battery current, R_L is the load resistance

When the solar panel is charging the battery, as shown in figure 34, the V_T and I_B equations can be seen in equations 11 and 12.

$$V_T = V_{oc} + I_B R_{internal} \quad (11)$$

$$I_B = I_{Solar\ panel} - I_L = I_{Solar\ panel} - \frac{V_T}{R_L} \quad (12)$$

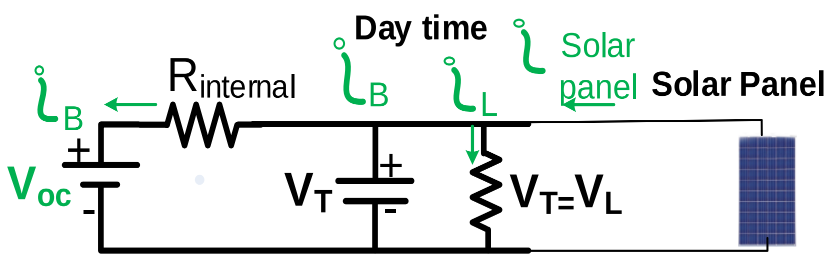


Figure 34: Solar panel feeding the load and battery

Now, SOC can be calculated on I_B, which is difference $= I_{Solar\ panel} - I_L$. The load voltage is more than the open-circuit battery voltage in this scenario. Open circuit voltage depends on SOC (Value of AH of the battery at that time) which can be calculated from equation 12.

$$\mathrm{SOC(t)} = \mathrm{SOC}_{(t=o)} + \frac{1}{3600}\int_{0}^{t(Sec)} I_B \, dt \qquad (12)$$

Since the battery to be modeled was Trojan 12V with 105 Ah. The batteries were set up as 30 in series to have a bus voltage of 360V and 15 such strings were set up to meet the system load requirement.

The data for charging current from Trojan 12V, 105Ah datasheet is summarized in table 3.

Table 3: Trojan battery data for maximum charge current from the datasheet.

12V, 105AH=100% SOC

Maximum Charge Current (A) 20% of C20	21A
Absorption Voltage (2.40 V/cell)	14.4V
Float Voltage (2.25 V/cell)	13.5V

The data for internal resistance and capacity from Trojan 12V, 105Ah datasheet is summarized in table 4.

Table 4: Trojan battery data for internal resistance and capacity from the datasheet.

12V, 105AH=100% SOC of single battery

INTERNAL RESISTANCE (mΩ)	4.8 m ohm
CAPACITY A AMP-HOURS (Ah)	105

The data for SOC with V_{oc} from Trojan 12V, 105Ah datasheet is summarized in table 5.

Table 5: Trojan battery data for SOC with Voc from the datasheet.

12V, 105AH=100% SOC of single battery

SOC %	**Cell V**	**V open Circuit**
100	2.14	12.84

75	2.09	12.54
50	2.04	12.24
25	1.99	11.94
0	1.94	11.64

The data for the designed battery bank for different parameters is summarized in tables 6, 7 and 8.

Table 6: Trojan battery bank data for maximum charge current based on the datasheet.

12V, 105AH=100% SOC of single battery of battery bank 30x15

Maximum Charge Current (A) 20% of C20	21x15=315A
Absorption Voltage (2.40 V/cell)	14.4x30=432V
Float Voltage (2.25 V/cell)	13.5x30=405V

Table 7: Trojan battery bank data for internal resistance and capacity based on the datasheet.

Battery Bank

12x30=360V, 105x15=1575AH=100% SOC of battery bank 30x15

INTERNAL RESISTANCE (mΩ)	4.8x30/15=9.6 m ohm
CAPACITY A AMP-HOURS (AH)	105x15=1575

Table 8: Trojan battery bank data for SOC with Voc based on the datasheet.

12x30=360V, 105x15=1575AH=100% SOC of battery bank 30x9

SOC %	**Cell V**	**V open Circuit**	
100	2.14	12.84x30	385.2
75	2.09	12.54x30	376.2
50	2.04	12.24x30	367.2

25	1.99	11.94x30	358.2
0	1.94	11.64x30	349.2

The model for the battery-bank in MATLAB/Simulink can be seen in figure 35. In this figure, a SOC with Voc lookup table based on table 8 was built and internal resistance was incorporated based on the result summarised in table 7.

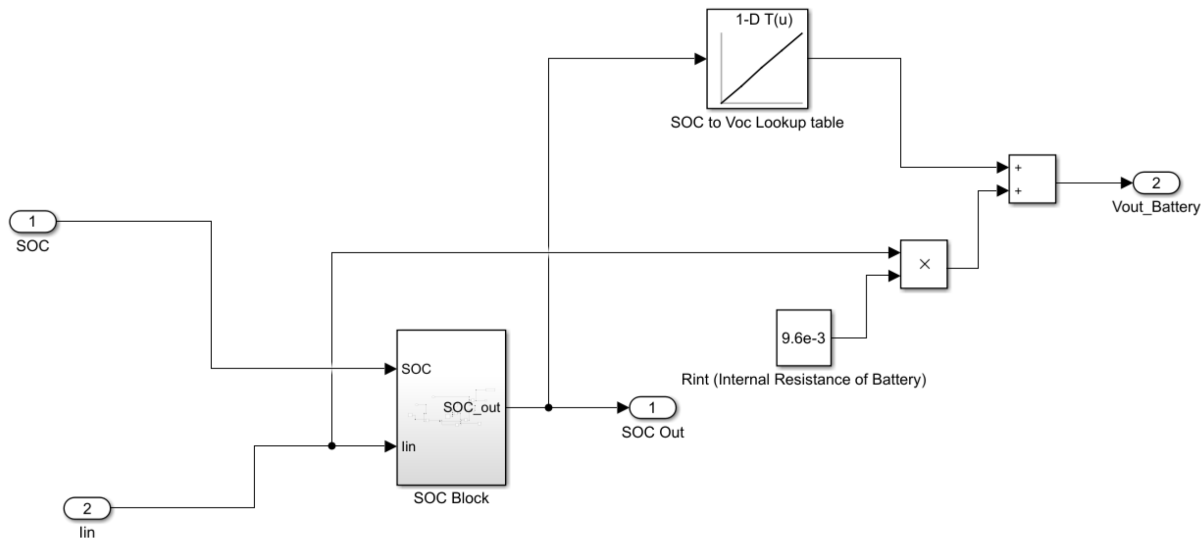


Figure 35: Battery Model in MATLAB/Simulink

The SOC block model can be seen in figure 36, was modeled based on equations 10 and 12.

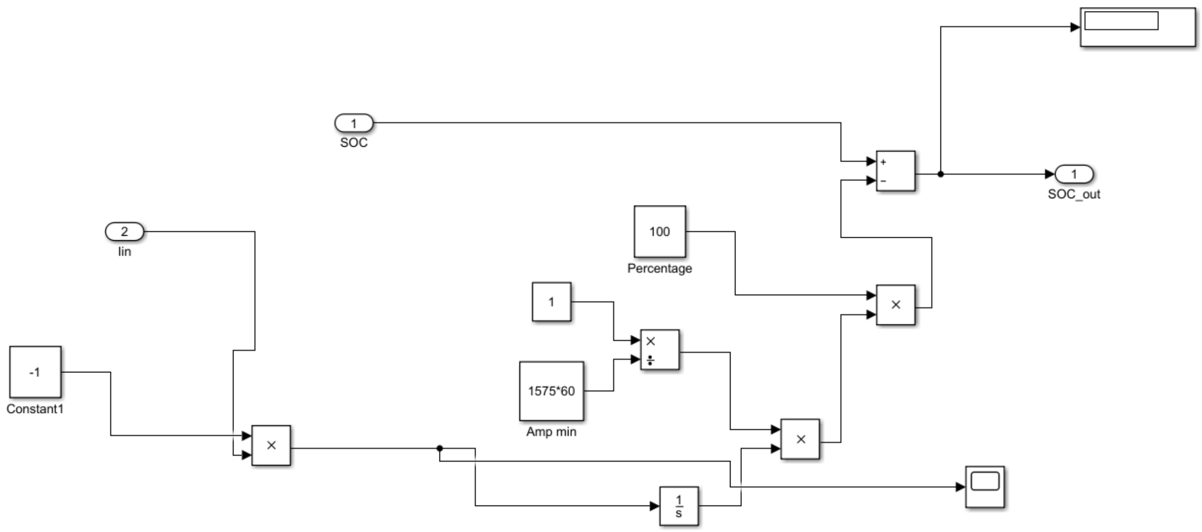


Figure 36: SOC block for modeled battery bank

In figure 37, inputs and adjusted input given to the battery-bank model can be seen.

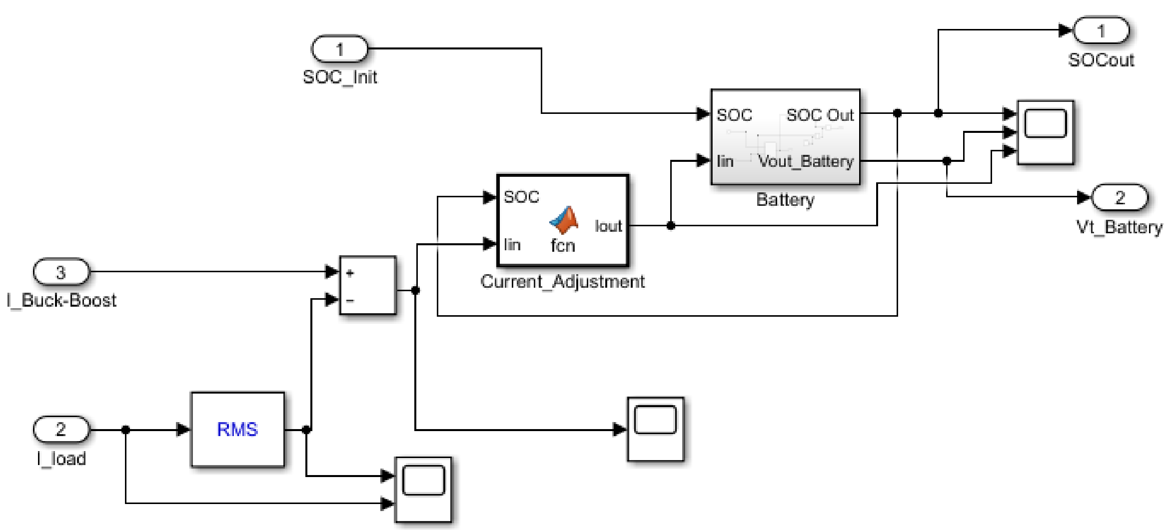


Figure 37: Inputs fed to battery bank Model

3.1.1.4 Inverter Modeling

The inverter model is in figure 38. In this figure, it can be seen that there is a switch for the switching purpose of an inverter, followed by a filter and gain adjust to get the smooth output. Small **g** represents a reference wave to compare with the input dc to help with the switching.

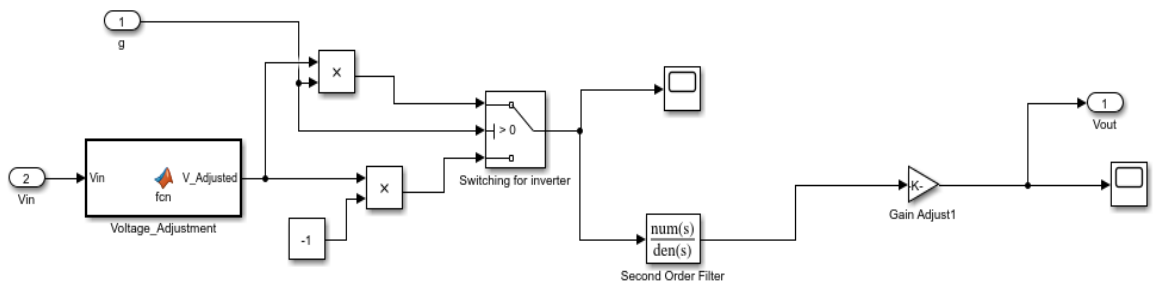


Figure 38: Inverter model in MATLAB/Simulink

3.1.1.5 Motor/Pump Modeling

As per data:

Power of the motor was 11kW

Rated Voltage = 3 phase 400V/50Hz

Rated Current = 20.9 A

For 1 phase voltage is

$V_{peak} = (400/\sqrt{3})^* \sqrt{2} = 326.6$

It is equal to 326.6 cos θ

Current for single phase is

Current = 20.9* √2 =29.6 A

The final current is equal to 29.6 cos (θ-36.6), as the motor is inductive, so the current lags. 36.6 is the angle for power factor as per the datasheet, equal to 0.77, as in figure 16.

As for the modeling in MATLAB/Simulink, a simplified equivalent model of induction motor was considered in figure 39. The mathematical equation for the equivalent model can be seen in equation 13.

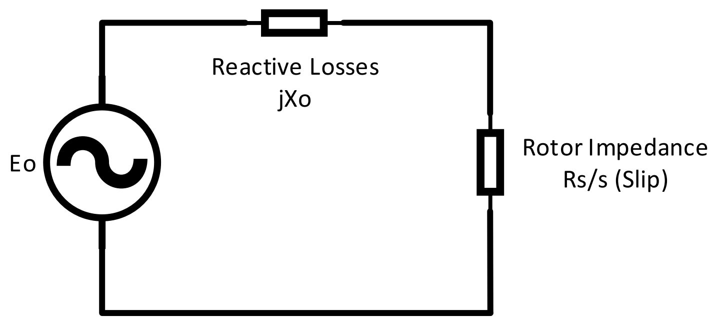


Figure 39: Equivalent model for Inductive Motor

$$E_0 = I(jX_o + \frac{R_s}{s}) \qquad (13)$$

In this equation; Eo is the input voltage, I is the load current

Design assumptions:

Inrush current was taken to be 6 times rated peak current (29.6 x 6 = 177.6), and the inrush current settles after 25 seconds.

The equation for rated current

$$\frac{R_s}{s} + jX_o = \frac{E_o}{I} = \frac{329.6}{29.6} \qquad (14)$$

The rated current slip was 0.02 as rotor rated speed was 1470 rpm and synchronous speed was 1500 rpm.

$$\text{Slip} = \frac{1500 - 1470}{1500} = 0.02$$

Simplifying equation 14, which was for rated current, we came up with equation 15

$$50Rs + jX_0 = 11.034 \qquad (15)$$

Deriving equation for inrush current from equation 13

$$\frac{R_s}{s=1} + jX_o = \frac{E_o}{I} = \frac{329.6}{177.6} \qquad (16)$$

After solving equations 15 and 16 simultaneously the results calculated were

Rs = 0.18976 and jX_o=1.6513

These values were used while modeling in MATLAB/Simulink for induction motor, as shown in figure 40.

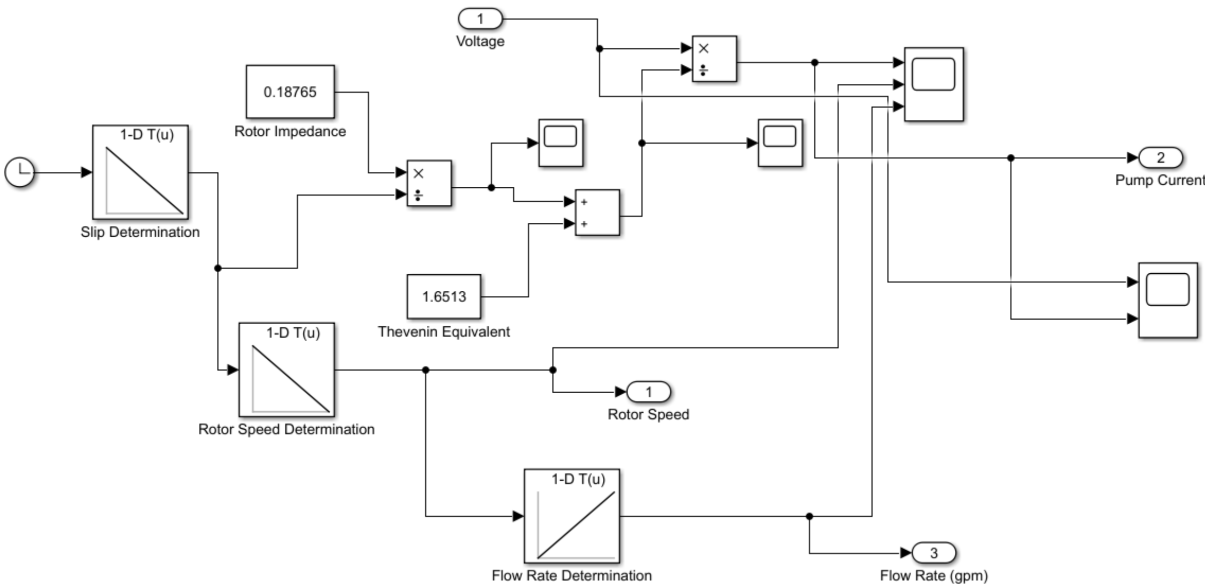


Figure 40: Modeling of Induction Motor in MATLAB/Simulink

3.1.2 Input Irradiance and Temperature

The data was simulated for the first seven days of April when the motor is in operation to evaluate the proposed PV-based water pumping system's dynamic behavior. The solar data included solar irradiance and temperature for the first seven days of April, making it a total simulation for 10080 minutes, shown in figure 41. The irradiance varied from 0 to 1021 W/m^2. The temperature varied from 25 to 49.5^{o}C during the whole week of simulation.

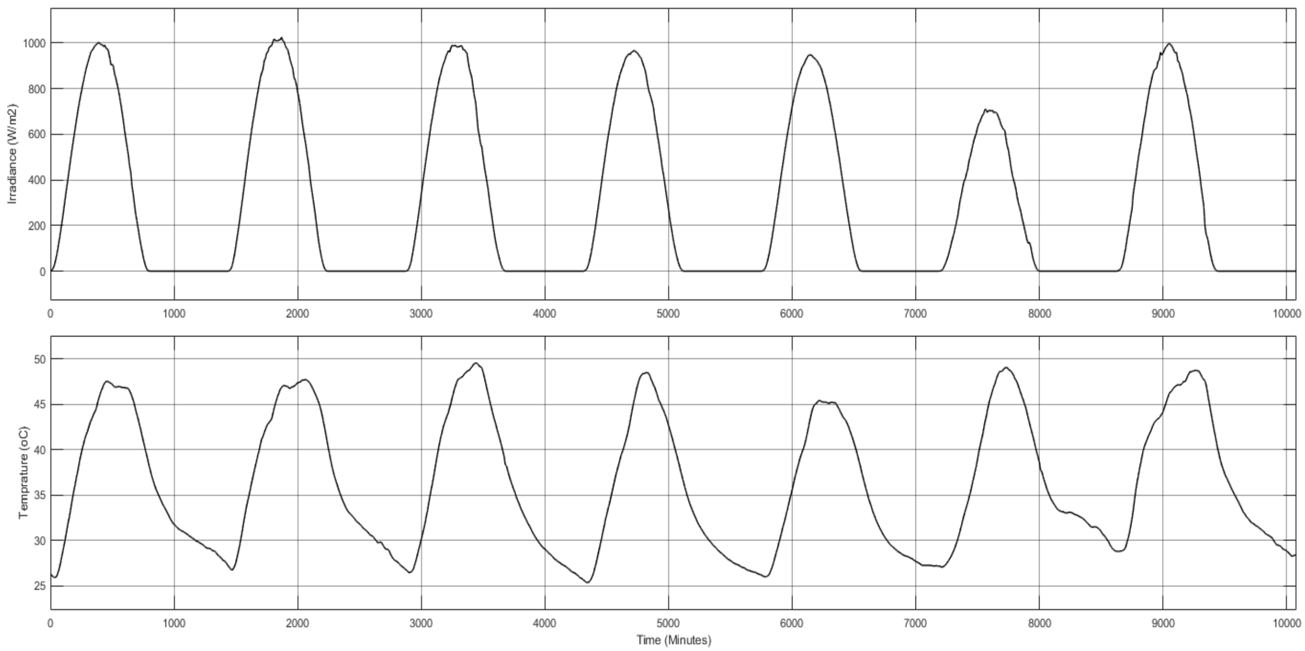


Figure 41: Irradiance and Temperature during 1st week of April

3.1.3 Simulation Results of the proposed designed system

Simulation results are split into two figures (A and B) for the proposed system, seen in figures 42 and 43. It can be seen in figure 42 that, as far as PV panel output is concerned, the output varied throughout the week with varying irradiance and temperature. The voltage output varied from 0 to a maximum of 658V and the current varied from 130A to 0 A. This output in the next step is fed to the buck-boost converter controlled by the duty cycle, which is controlled by Perturb and Observe MPPT technique block. The voltage output from the buck-boost converter varies from 0 to 987V and current output varied from 0 to 87A.

The initial SOC (State of Charge) of the battery was 80%, which declined to 79% after 1st discharge, remained between 84 and 100% afterward throughout the simulation, as shown in figure 43. The output voltage was only once 377.5V during 1st discharge, but other than that it varied from 385.6V to 379.5V. The momentarily pointed peak in battery voltage at the top as it reaches an SOC of 100% is because during the charge it takes into consideration the battery's internal resistance, but once it stops charging since the battery has reached 100% of SOC, it no longer takes into consideration the battery's internal resistance hence, there is a slight decrease in overall battery's output voltage.

The voltage output of the inverter varied from +326.6V to -326.6V, as can be seen in figure 43. In our system, phase to neutral voltage is considered, which is equal to $(400/\sqrt{3})*\sqrt{2} = 326.6V$. It is essential to know that we have considered 4 wire, three-phase bridge inverter which can supply a voltage from phase to neutral, and we have shown only one phase for the inverter stage.

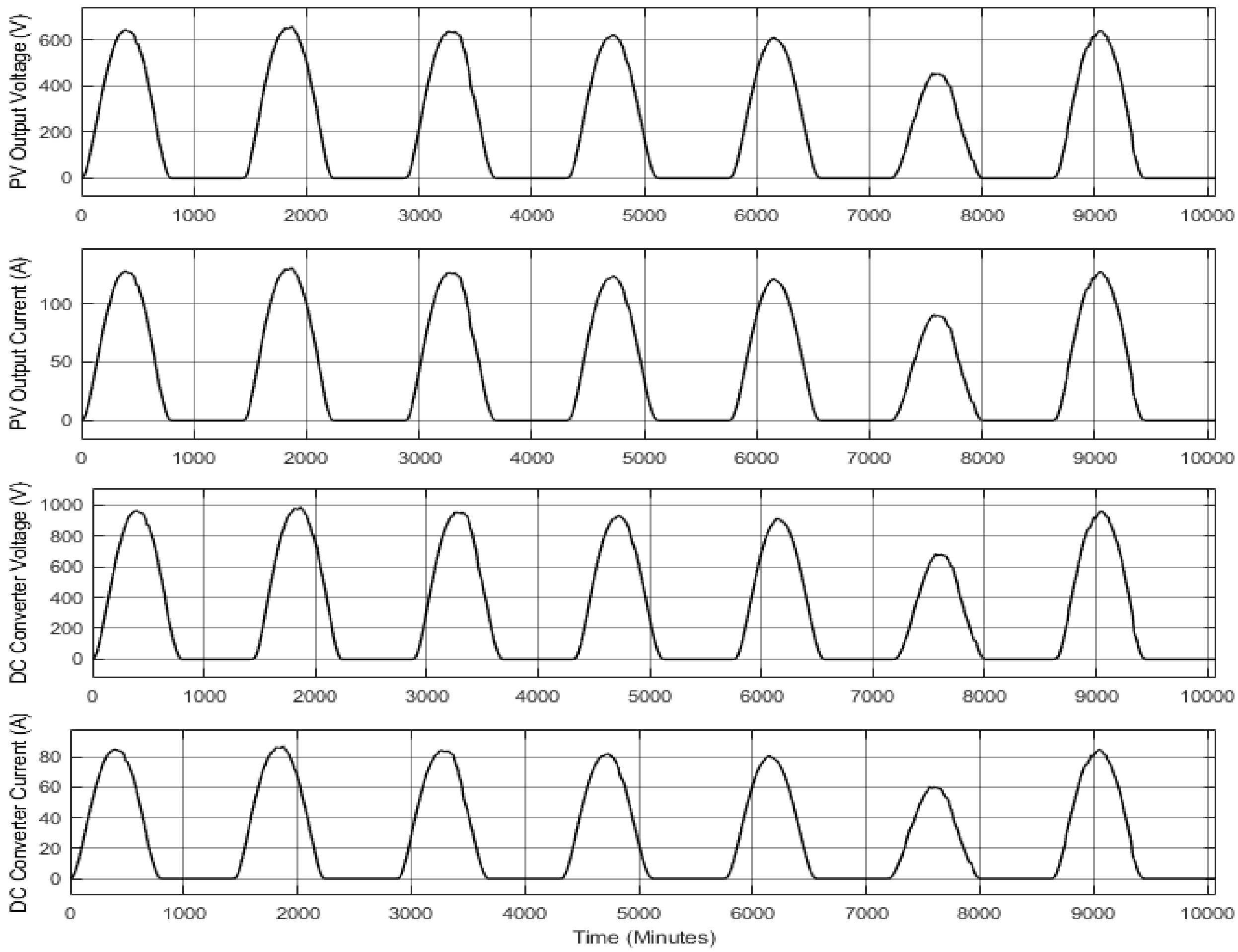


Figure 42: Simulation results for Dynamic Modeling; A

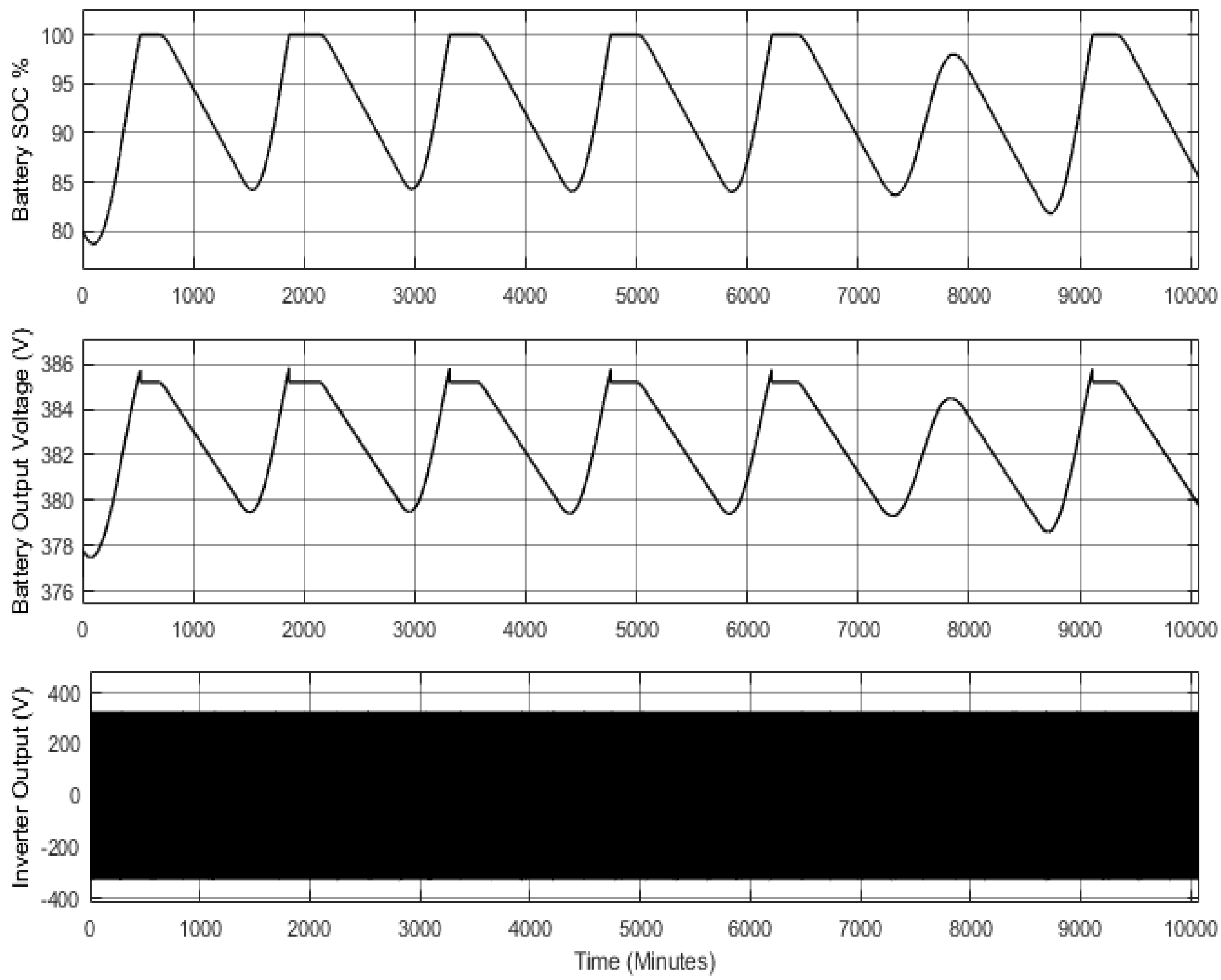


Figure 43: Simulation results for Dynamic Modeling; B

The detailed simulation results for the first seven days of April for the motor/pump can be seen in figure 44. It can be seen from the simulation results in the figure that it took about 15 seconds to get to steady-state and after that continuous operation of the motor was at 1470 rpm, which is in accordance with the datasheet. After the initial surge for 25sec, which is characteristic for the induction motor, the current stabilises from 326.6 A to 29.6A within 15 seconds. The current for phase to neutral current is equal to 20.9A (As per motor datasheet)*√2 = 29.6A.

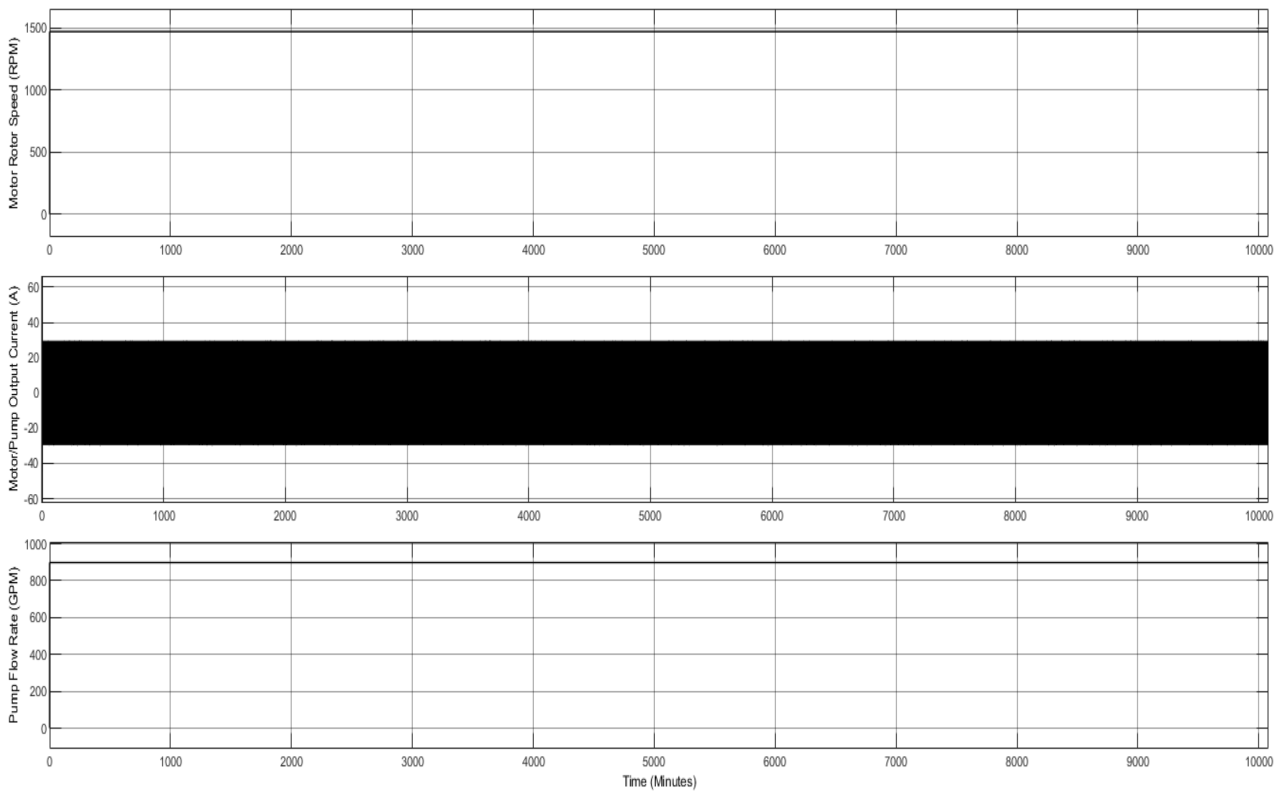


Figure 44: Simulation Results for Dynamic Modeling of Motor/Pump

Based on the simulation results, it can be concluded that the designed system in HOMER was optimally designed, which was verified by the detailed modeling in MATLAB/Simulink after performing a dynamic analysis of the system for 1 week's data of April. It was further observed that there was no total drain-out of the battery bank and continuous overall system operation was observed.

3.2 Conclusion

In this chapter, the mathematical equations based models for different components of a solar water pumping systems were developed in MATLAB/Simulink to speed up and optimize the overall system. It helped during the dynamic analysis of the system for a prolonged period. Based on the simulation results of dynamic analysis, it can be safely concluded that the designed system in HOMER was feasible and can be safely implemented on the selected site.

Chapter 4

Design and Analysis of a Solar Water Pumping System with Water Tank in HOMER

4.1 Introduction

Solar water pumping systems usually require a storage system to aid for their operation, usually during nighttime or when the solar energy is not available in excess to feed the system. One of the storage systems discussed in this thesis was battery-bank storage. Their design and costing were discussed in the previous two chapters in detail.

Another option of storage system which is explored in this chapter is water tank storage. One of the most popular options as a storage system in Pakistan is a water tank, which is usually a common site in rural areas of Pakistan where agriculture is practiced, as shown in figure 45 [84]. It can be seen that there are two outlets for water, among which one is to irrigate the land and second is to put excess water in storage which is a water tank on the right-hand side.

Figure 45: Solar water pumping system with water tank in Pakistan

One of the reasons this option was explored (other than being a common practice in Pakistan), so that a comparison of solar water pumping systems with battery bank and other with a water tank can be obtained. So that a more feasible option among the two could be concluded for Pakistani conditions.

4.2 Design of a Solar Water Pumping System with Water Tank in HOMER

4.2.1 Load determination for the Proposed System

Before proceeding with the design, the first step was to determine an optimum size of a tank that could be enough to keep water storage for 1 day. For this purpose, the flow rate for 1 day was calculated, as shown below.

$204m^3/hr \times 24 = 4896m^3$

$4896m^3$ is the flow rate for one day. Hence, if the motor runs for 5 hours each day during active days of the month (when continuous water flow is required). The flow rate required out of the motor is $4896/5 = 979.2\ m^3/hr$.

Hence, using an online source for Wilo pump [79] and using the previously known data regarding the total dynamic head and calculated flow rate requirement, the size of the motor came out to be 55kW and the motor selected for this purpose was CronoNorm-NLG 250/360-55/4 [85]. The details regarding the motor can be seen in figure 46. The further details regarding the graph can be seen in figure 47.

Operating data
Fluid media: Water 100 %
Fluid temperature: 20,00 °C
Fluid concentration: 100,00 %
Requested flow: 979,20 m^3/h
Requested head: 35,00 ft
Min. fluid temperature: -20 °C
Max. fluid temperature: 120 °C
Maximum operating pressure: 16 bar
Max. ambient temperature: 40 °C
Minimum efficiency index (MEI): ≥ 0,4

Motor data
Mains connection: 3~400V/50 Hz
Voltage tolerance: ±10 %
Motor efficiency class: IE3
Rated power: 55 kW
Rated speed: 1480 1/min
Rated current: 98,6 A
Power factor: 0,85
Motor efficiency: 0,0 %
Motor efficiency: 0,0 %
Motor efficiency: 0,0 %
Protection class:
Insulation class: F

Installation dimensions
Pipe connection on the suction side: DN 300 , PN16
Pipe connection on the pressure side: DN 250 , PN16

Figure 46: Details of Motor/Pump selected

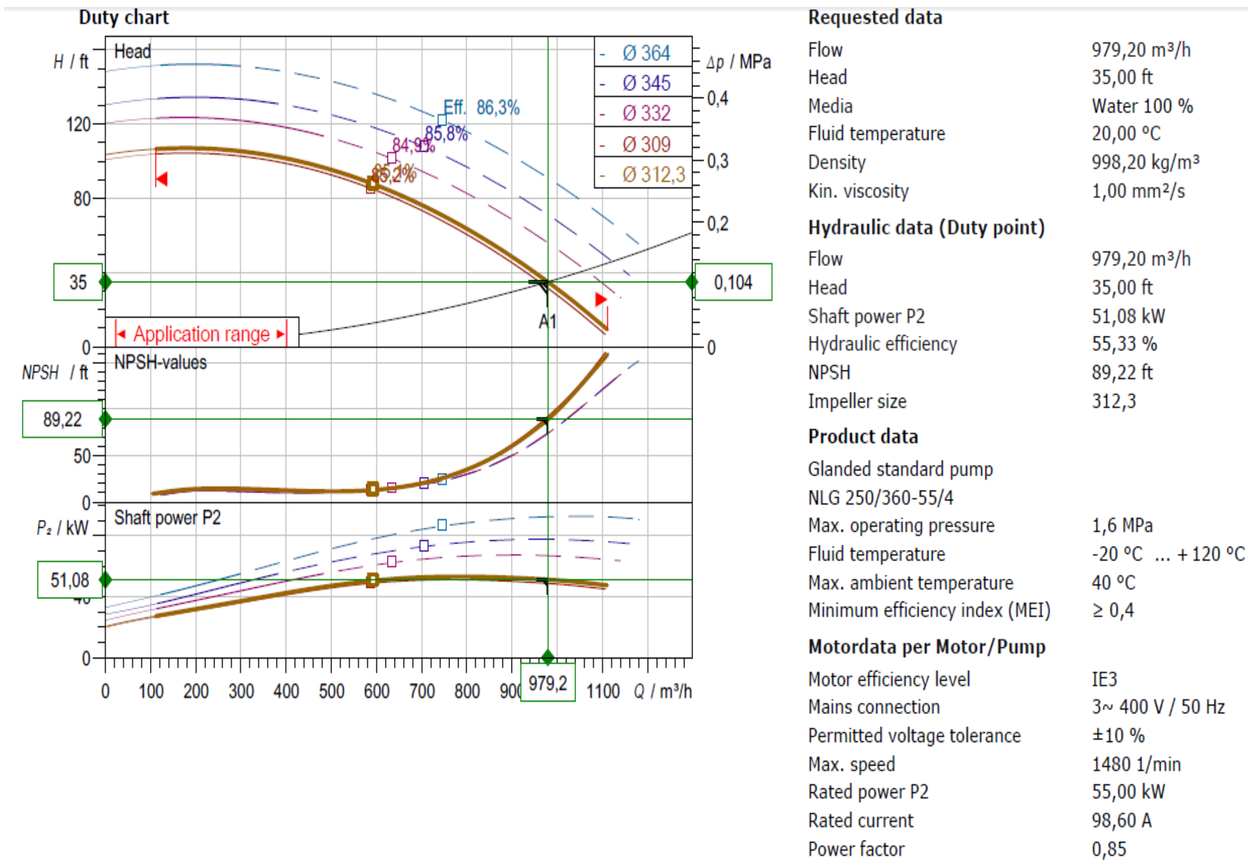


Figure 47: Parameters that led to the motor/pump selection.

A generic block diagram for the overall possible system with a water tank can be seen in figure 48 [86]. A more elaborated diagram with system parameters for our designed system with a water tank is discussed later in the chapter.

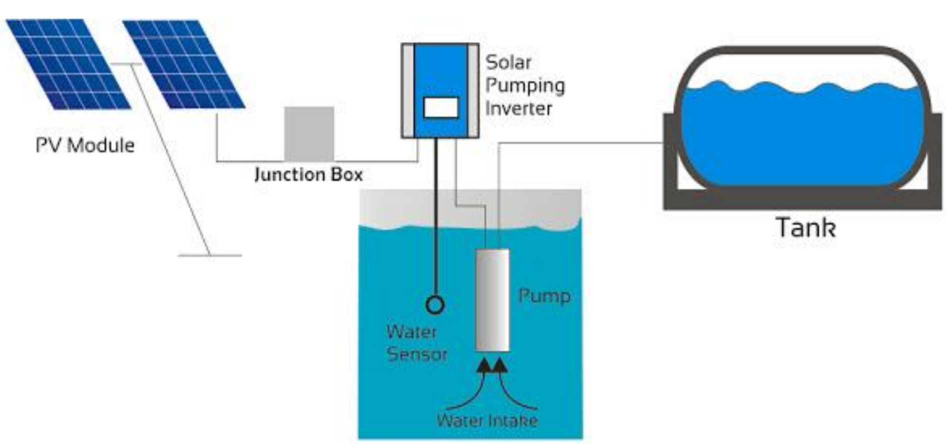


Figure 48: Generic block diagram of solar water pumping with the water tank

4.2.2 Sizing of the Proposed System using HOMER

After the size of the motor was evaluated, the load was mapped to keep the motor's operational hours to be 5 hours. As the load of the motor was associated with a water tank storage, so a deferrable load was used in HOMER and as the motor is running for 5 hours, so 55 x 5 = 275kWh is the storage capacity required. The detailed load mapping in the deferrable load in HOMER can be seen in figure 49.

Figure 49: Load Mapping in HOMER.

The overall proposed system with a water tank in HOMER appears as shown in figure 50. The PV panel used was Astronergy ASM6612P-320 solar [81] to design a PV panel network. The inverter used was SMA American STP60-US-10 [78] which is a 60kW inverter.

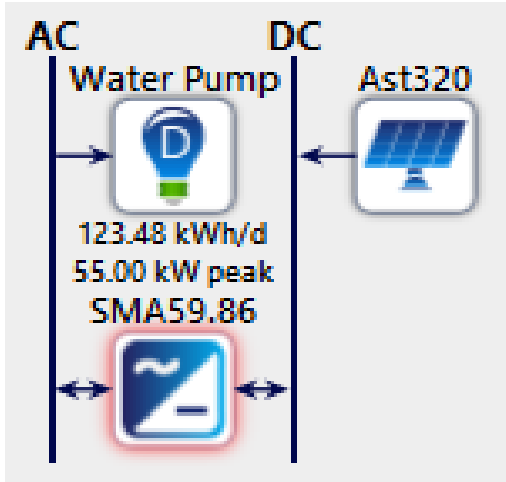


Figure 50: Proposed PV based water pumping system with Water Tank

After the simulation of the overall proposed PV-based solar water pumping system was performed. The PV Panel network requirement came out to be 72.3kW and the inverter requirement came out to be 59.9kW, which was fulfilled by a 60kW SMA American STP60TL-US-10. The overall result can be seen in figure 51.

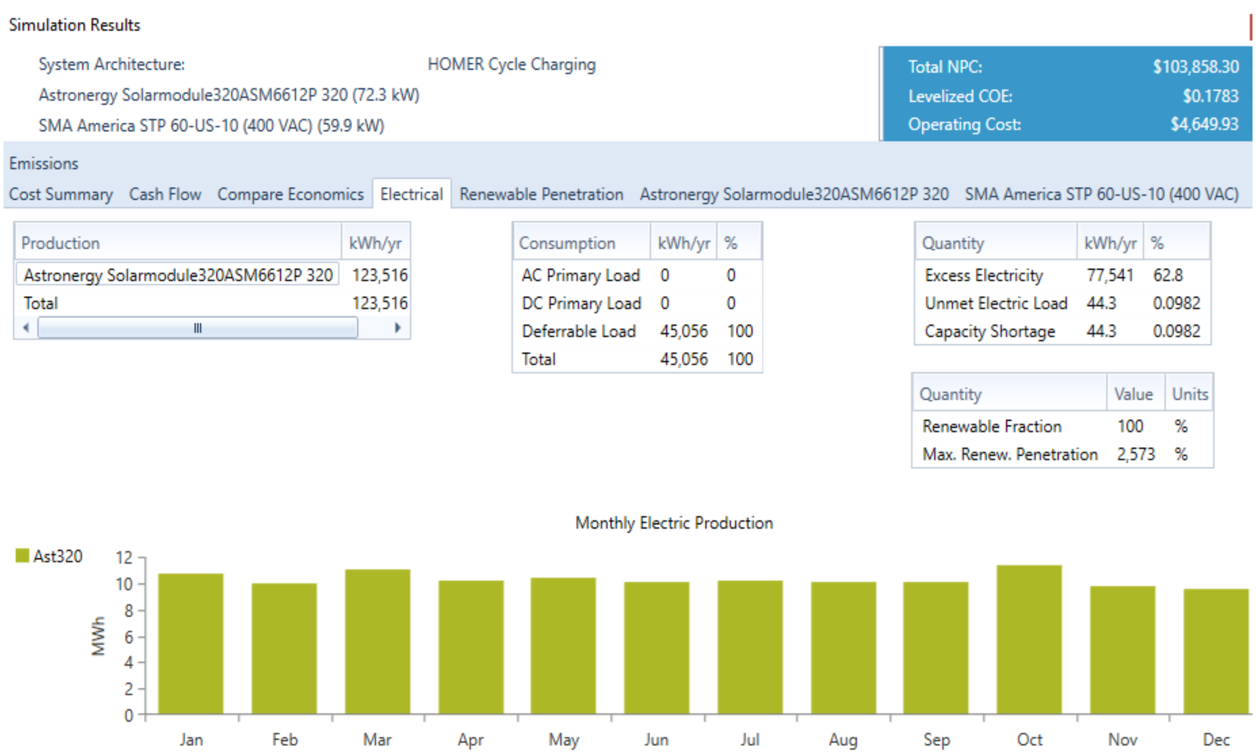


Figure 51: Simulation details for the proposed system with a water tank

The overall proposed system with a water tank can be seen in figure 52. To fulfill the 72.3 kW PV Network requirement, 240 panels were used, as the bus voltage was 360V.

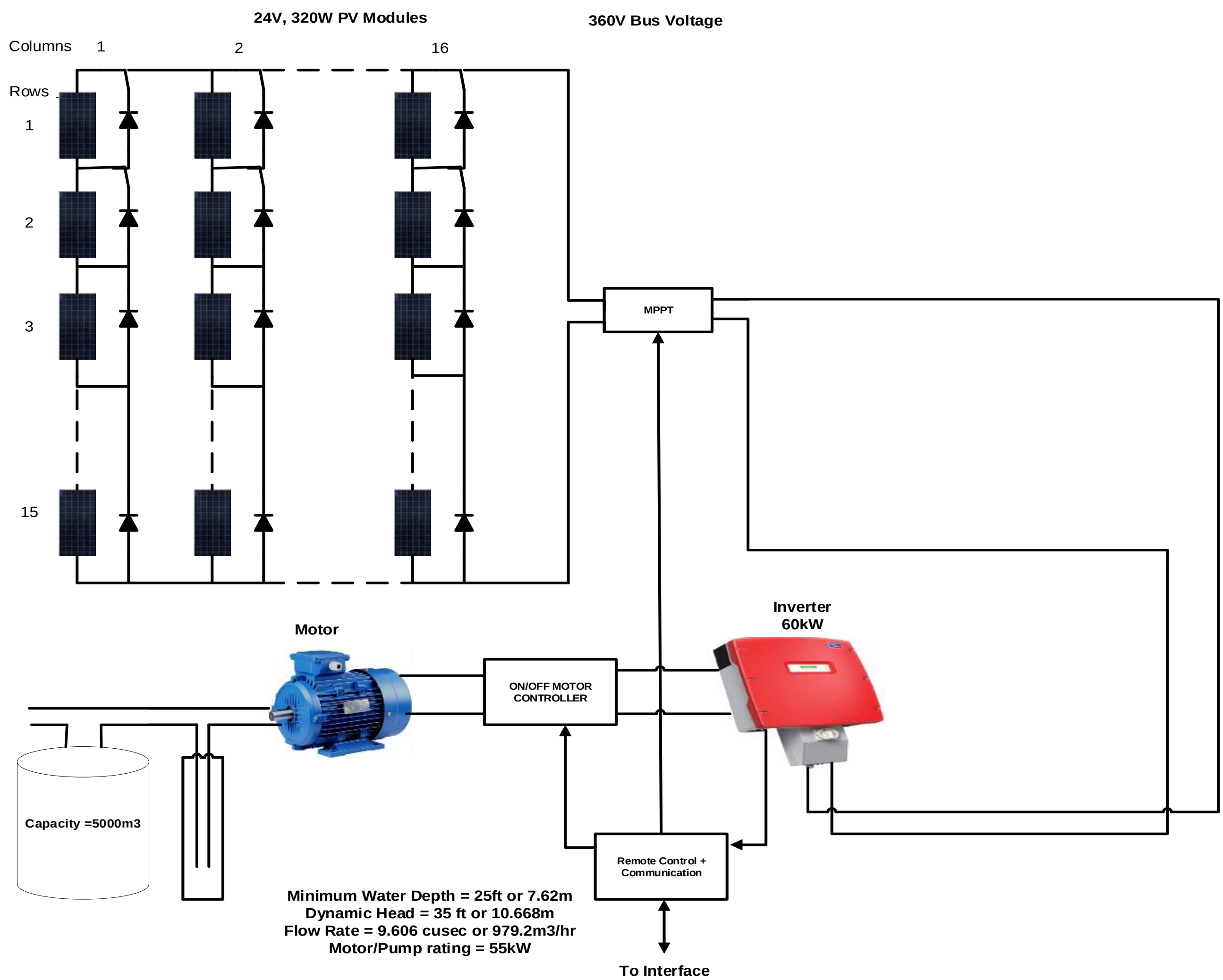


Figure 52: Proposed solar water pumping system with water tank.

4.3 Cost Analysis of the Proposed System with Water Tank using HOMER

The overall cost summary for the proposed system was performed in HOMER, as shown in figure 53. The total net present cost of the proposed system came out to be $103,858.30, levelized cost of energy was $0.1783 and the operating cost of the proposed system was $4,649.93 per year.

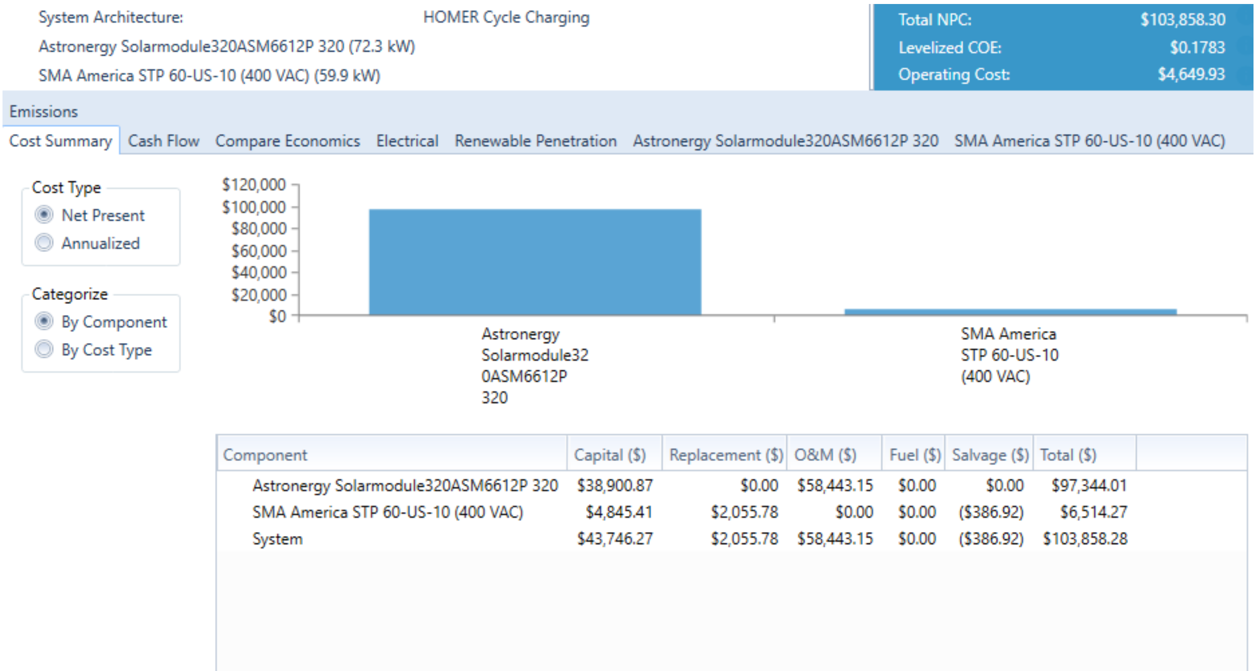


Figure 53: Cash Summary for the proposed system without a battery-bank

The cash flow for the proposed system over the 25 years lifetime can be seen in figure 54. It can be seen that an initial investment of $43,746.27 is required and, then an annual investment of $4,520.83 is required to keep the system running. A further injection of $4,845.41 in the 15th year of the 25 years project life is required. After 25 years of the project's life cycle, the system would have a salvage value of $1,615.14.

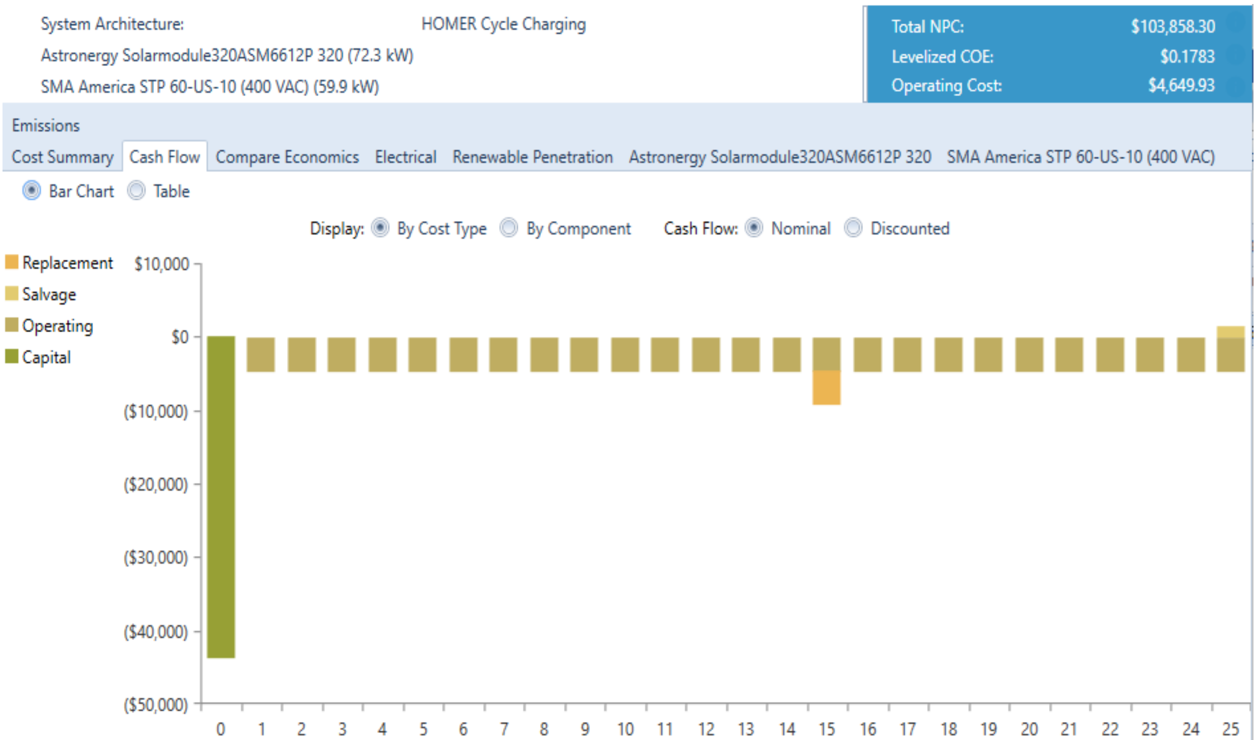


Figure 54: Cash Flow for the proposed system without a battery bank

4.4 Sizing of the Water tank

As the total water discharge in one day was 4896m^3, so a tank of 5000m^3 was planned. For this purpose, the mathematical details are as follows.

Considering a cylindrical tank of 5000m^3 with a height of 2m. The radius of the tank can be calculated using equation 1

$V = \pi \text{ x } r^2 \text{xh}$ (1)

Here V is for volume in m^3, r is radius of the cylinder in meters, h is the height of the tank in meter

5000= 3.142 x r^2x 2

r= 28.21m

Hence, the radius of the tank is 28.21m

4.5 Costing of the Water tank

The local rate for construction, including material, labor, digging and supervision lumped together, cost Rs300/ft^2.

As the tank is open from the top, so the total surface area can be calculated using equation 2.

$$Surface\ Area = \pi \times r^2 + 2\, x\, \pi \times r \times h \qquad (2)$$

Surface area = 3.142 x 28.212 + 2 x 3.142 x 28.21 x 2

Surface area = 2854.6m^2 = 30726.6587ft^2

Overall price for tank is 30727 x 300 = Rs 92,181,00 = $54,540.88

4.6 Comparison of Solar Water Pumping Systems with Battery Bank and with Water Tank

To compare both the designed PV-based water pumping system designs, their economic analysis was considered. It can be seen from the results that the overall net present cost of the system with a battery bank was $273,570. In contrast, NPC for the system with a water tank was 103,858.30 + 54,540.88 = $158,399.18, which was less than the NPC of the PV system with the battery bank. The levelized cost for the system with the battery bank was $0.48, which was as per levelized recorded cost in papers [44],[31],[33]. The levelized cost for the system without a battery bank was $0.1783, which went again in favor of the system without a battery bank. Operating costs per year were $5,692.37 and $4,649.93 for systems with battery and without battery respectively, which again favored the system without a battery bank. The last parameter was the initial investments which were $199,981.86 and 43,746.27 + 54,580.88 = $98,327.15 for systems with battery bank and without battery bank respectively, which again went in favor of system without battery-bank. This factor was less for the system with water tank because the construction of a water tank is relatively cheaper in Pakistan due to less expensive labor.

Hence, it can be concluded that the solar water pumping system based on a water tank is less expensive as compared to the solar water pumping system based on a battery-bank for Pakistani conditions.

4.7 Conclusion

In this chapter, an option of a water tank storage system for solar water pumping systems was discussed for Pakistani conditions in detail. A solar water pumping system solution with a water tank was designed for the same selected site. Its economical results were compared with earlier proposed solar water pumping systems with battery bank for the same site. It was concluded that a solar water pumping system with a water tank is a more feasible solution than a solar water pumping system with a battery bank for Pakistani conditions.

Chapter 5

Supervisory Control and Data Acquisition (SCADA) for a Solar Water Pumping System

5.1 Introduction

To control a solar water pumping system that is primarily located in a remote area, keeping a person 24/7 is not only challenging but costly as well. To control a solar water pumping system, incorporating a Supervisory Control and Data Acquisition (SCADA) technology plays a vital part. Supervisory Control and Data Acquisition (SCADA) is a technology that involves reflection of data on an HMI (Human Machine Interface) taken from different sensors, which are deployed on different locations; this help to get information regarding different parameters of the site, that data is then stored in a cloud or some local storage which can range from a small SD card to a server depending upon the data size and then it can be viewed at an HMI [88]. This technology has many applications which range from business to personal use [89].

SCADA systems are generally used to monitor different parameters of the system to which it is attached. It also eases the control issues for the system as every control is available on the HMI of the SCADA. The advantage of this system is that it has every parameter and control available on-screen, enhancing the monitoring and control of the overall system as a virtual interface enables convenience. It involves minor to massive hardware attached with it as per need. It involves sensors to intermediate circuitry, used for data acquisition and processing so that the right set of data acquired is reflected upon the HMI of a SCADA.

5.2 Emoncms SCADA based system for Solar Water Pumping System

An open sources Supervisory Control and Data Acquisition (SCADA) Emoncms application for a solar water pumping system is discussed in this thesis. We discussed detailed capturing and reflection of parameters like solar panel voltage, battery voltage, load current, water level of the tank, flow rate into the tank and environmental parameters like humidity, temperature and solar insolation. Different sensors were integrated with Arduino Mega 2560. From there, data was pushed to a raspberry pi using serial communication on which open source SCADA Emoncms was running; upon its dashboard, data was reflected. This overall system can be seen in a block diagram in figure 55.

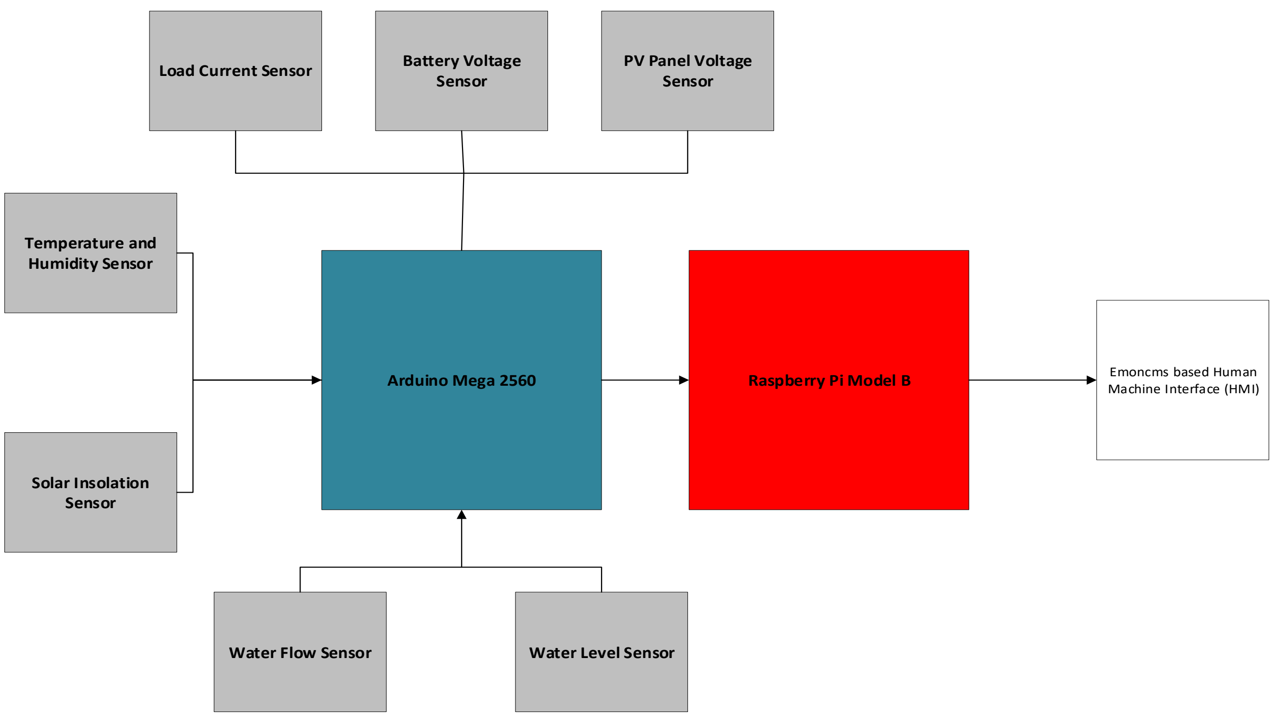


Figure 55: Proposed SCADA system for Solar Water Pumping System

5.2.1 Components used for the SCADA for a Solar Water Pumping System

In table 9 below is the list of all the components, which were used in our SCADA system.

Table 9: Components used to realize the SCADA system for a solar water pumping system

Serial Number	Component Name	Use
1	Raspberry Pi Model 4 B	It has Emoncms installed, which serve as an HMI
2	Arduino Mega 2560	It acts as a hub for sensors, which takes the data from sensors and push it forward to Raspberry Pi
3	Current Sensor Module (ACS712)	Used to sense load current
4	Water flow Sensor (YFS-201)	Used to sense water flow in liters/minute
5	Water Level Sensor	Used to sense the water level in the tank
6	Temperature and Humidity Sensor (DHT-22)	Used to sense temperature and humidity of the surroundings
7	Photo-resistor	Used to sense solar irradiance of the surrounding
8	Set of Resistors used	These are used to set up potential dividers for voltage measurement of PV panel and battery

5.2.1.1 Raspberry Pi Model 4 B

The Raspberry Pi Model 4 B [90] is one of the latest models of Raspberry Pi. It acted as the brain of the overall Emoncms SCADA system employed with our solar water pumping system. It processed the raw data being fed to it from Arduino Mega 2560 and reflected it onto the Emoncms dashboards.

5.2.1.2 Arduino Mega 2560

The Arduino Mega 2560 [91] is a microcontroller-based board with 54 digital and 16 analog pins. It acted as a hub in this overall Emoncms SCADA system. All the sensors were connected to it via wires. It gathered the data from sensors and pushed it through to the Raspberry Pi.

5.2.1.3 Current Sensor Module (ACS712)

A current sensor module was (ACS712) [92] also used in the overall network. The module can measure current up to 30A of current and was used to measure the load current. The current readings from this sensor were fed into Arduino and eventually logged into the emoncms.log file and reflected upon the Emoncms dashboard.

5.2.1.4 Water Flow Sensor (YFS-201)

The water flow sensor (YFS-201) [93] was used in the overall network to measure the flow of water from the solar water pump into the water pump. This water flow sensor can measure up to 30 liters/min of flow and can work at a maximum of 2MPa. The water flow readings were fed into Arduino and eventually logged into emoncms.log file and were reflected upon the Emoncms dashboard.

5.2.1.5 Temperature and Humidity Sensor (DHT-22)

The temperature and humidity sensor (DHT-22) [94] was used to measure the surrounding environment's temperature and humidity around the solar water pumping system. It can measure temperature from -40 to 80 ^{o}C with great accuracy. The sensor was connected with Arduino Mega 2560, which took the readings and pushed the data through serial communication to Raspberry Pi, which was eventually logged into the emoncms.log file and is reflected on the Emoncms dashboard.

5.2.1.6 Photo-resistor

The Photo-resistor connected in the system helped sense the solar irradiance and feed the readings to Arduino Mega 2560, which were further fed to Raspberry Pi through serial communication. On Raspberry Pi, the solar irradiance readings were eventually logged into the emoncms.log file and were reflected upon the Emoncms dashboard.

5.2.1.7 Set of Resistors

Two sets of resistors were used as a potential divider to measure voltages across the PV panel and battery. Since the voltage was measured by Arduino Mega 2560, so a pair of resistors fulfilled the purpose of a potential divider for PV panel voltage measurement and battery voltage measurement.

5.2.2 Overall Circuit Diagram

An overall circuit diagram of the proposed SCADA system can be seen in figure 56.

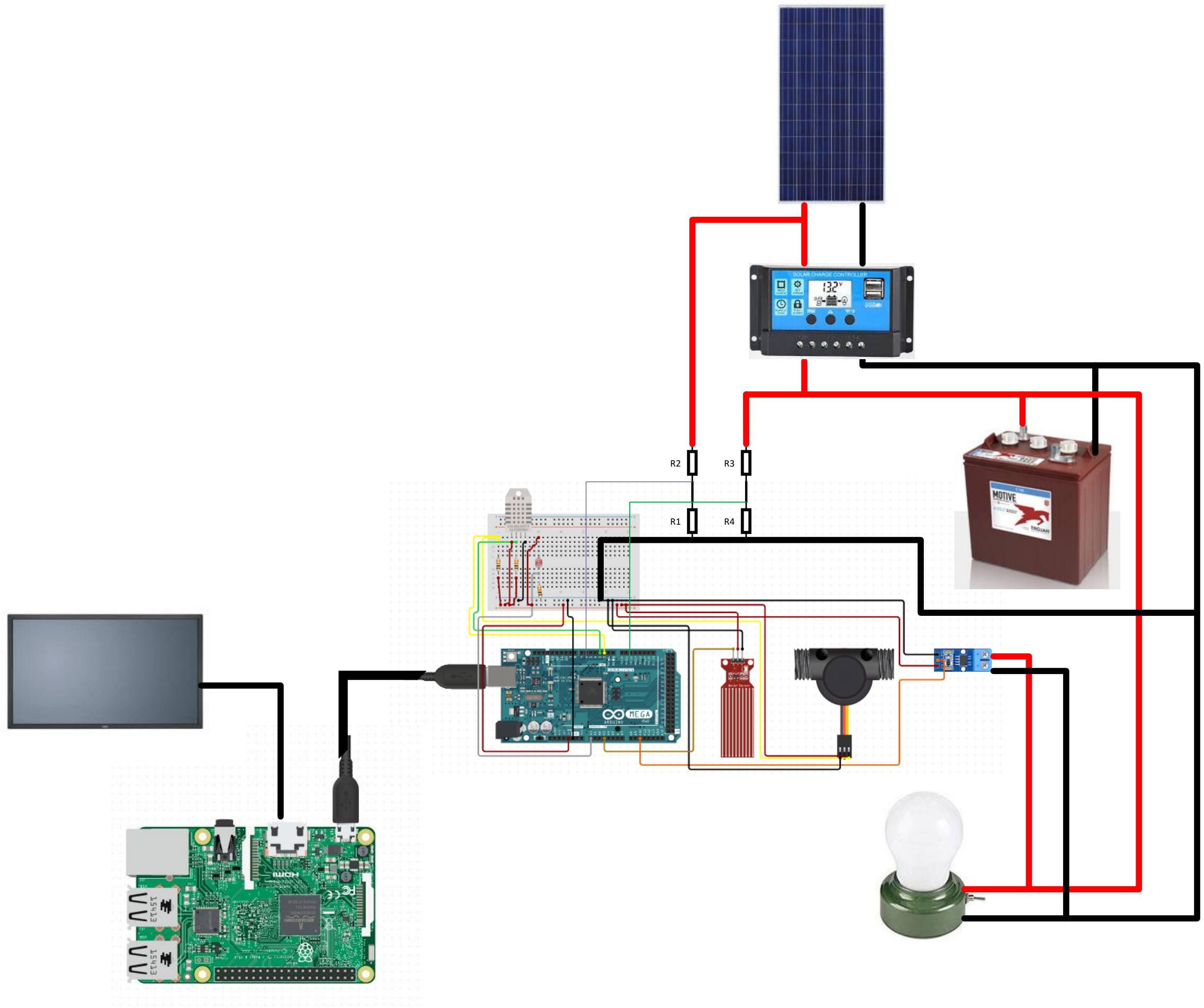


Figure 56: An overall circuit diagram of proposed SCADA system

5.3 Methodology

5.3.1 Emoncms

The platform used as SCADA for the solar water pumping system in this thesis was Emoncms [95]. It is a powerful open-source tool installed as a local host over Raspberry Pi in our scenario. It was used to reflect the environmental, hydro and electrical parameters of the solar water pumping system. Their logs were maintained in emoncms.log. It logged data after every 30 seconds.

5.3.2 Proposed Emoncms SCADA system for Solar Water Pumping System

The proposed local host-based open-source Emoncms SCADA system for the solar water pumping system can be seen in figure 57. In the figure, locations of different sensors in an actual scenario which are in turn connected with Arduino Mega 2560 can be seen; which piles up all the data and sends a string of parameters as data in a defined format that is compatible with Emoncms to Raspberry Pi through serial communication.

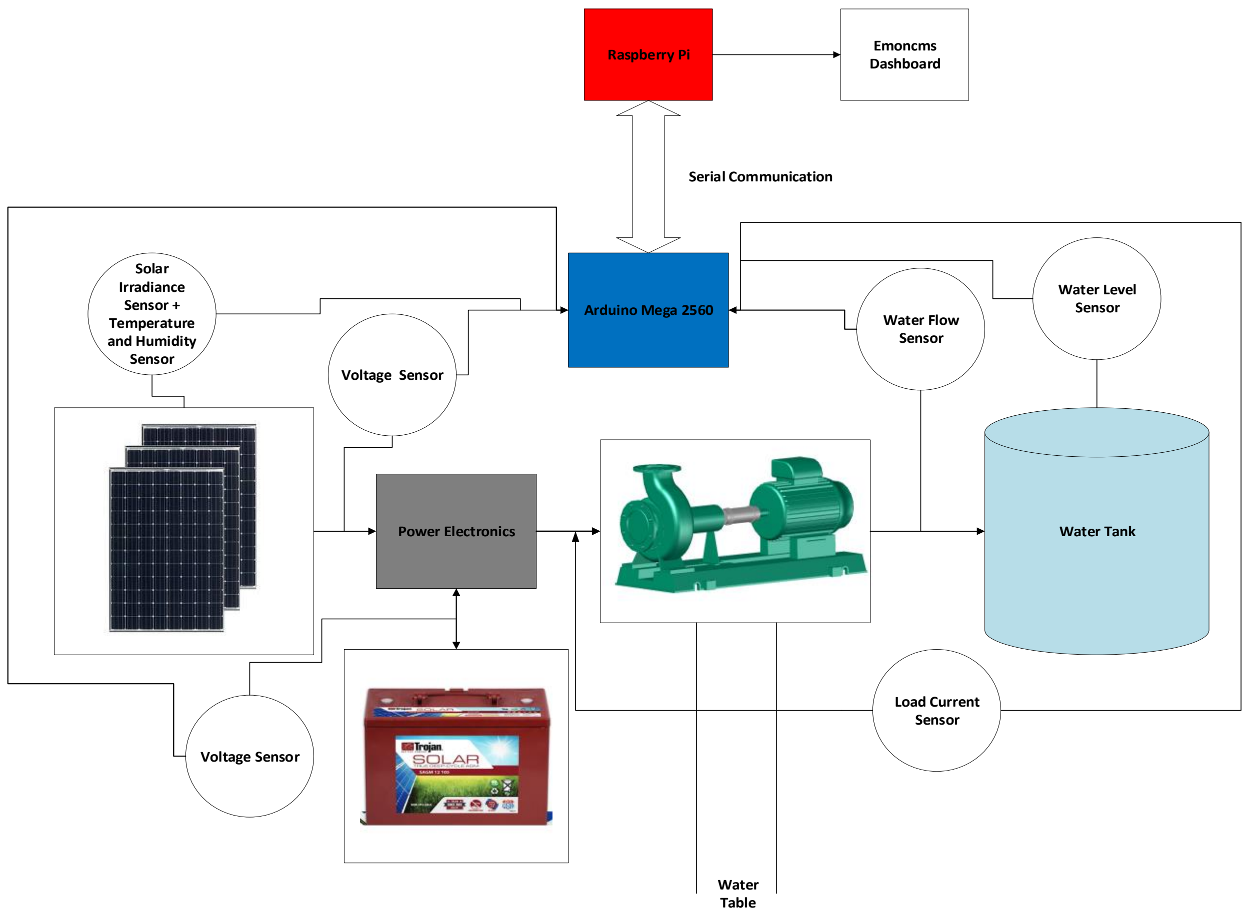


Figure 57: Proposed SCADA system

5.3.3 Prototype of Emoncms SCADA for Solar Water Pumping system

A prototype for the Emoncms based SCADA system for the solar water pumping system was set up in the lab, as shown in figure 58.

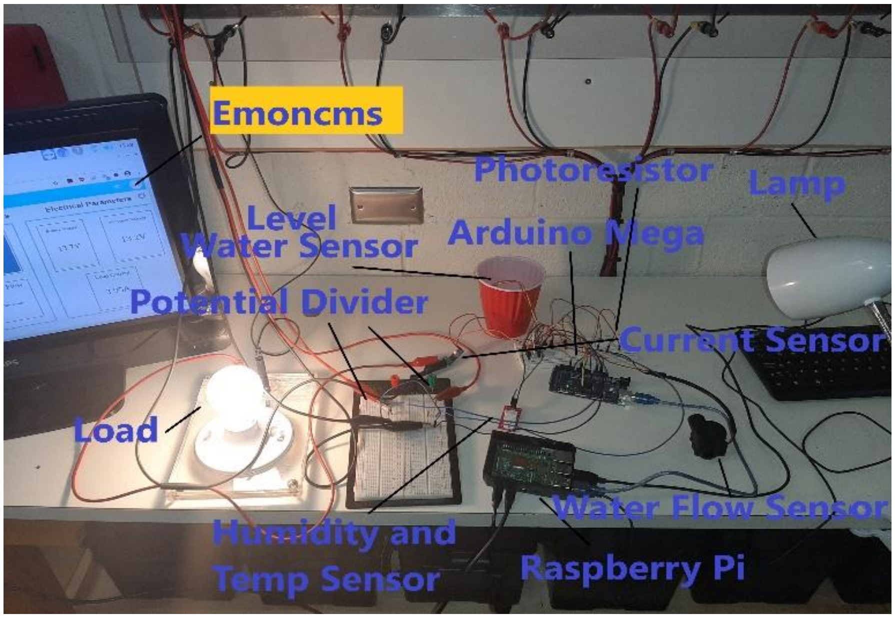


Figure 58: Prototype of Proposed SCADA system in Lab

In the prototype, different sensors can be seen, namely water flow sensor, water level sensor dipped into a red cup (simulating a tank filled with water), humidity and temperature sensor, photo-resistor, a lamp (to simulate the sun); that was directed on to photo-resistor to vary the light intensity and verify its working, two potential dividers; one on the left was used to measure PV Panel voltage and one on the right was used to measure battery voltage, a bulb of 12V; was used as a load which simulated a solar water pump, and a current sensor which helped to measure the load current.

In figure 59, photovoltaic panel connections coming from the ceiling and battery can be seen. In our scenario single battery and single panel were used to keep the overall system simple. The PV Panel and battery used were surrounded by two different black rectangles, as can be in the figure.

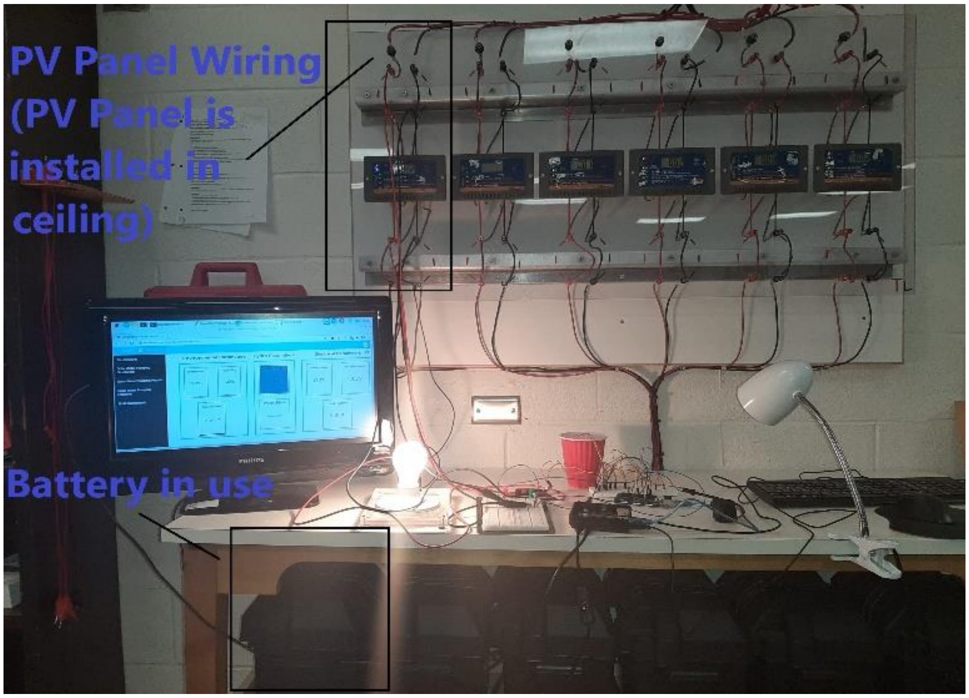


Figure 59: Prototype of Proposed SCADA system in Lab (With Lab setup)

5.3.4 Working of the Prototype

As shown in figure 60, the string that was pushed from Arduino was discovered in the form of inputs as different parameters numbering from 1 to 9.

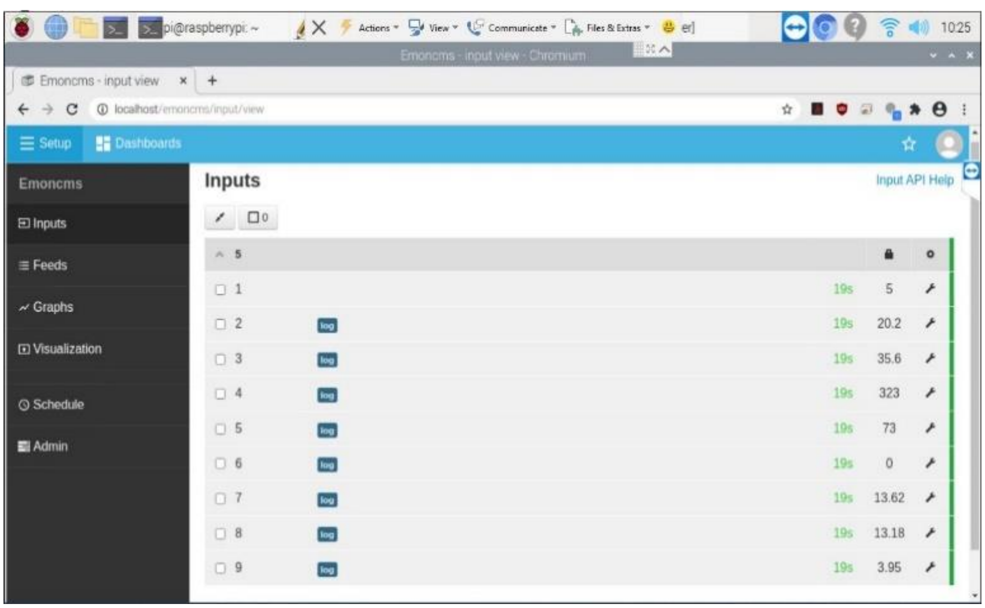


Figure 60: Inputs discovered in Emoncms

They were then locked and their feeds were developed, which logged them and gave them proper units like V for voltage, A for Amperes, as can be seen in figure 61.

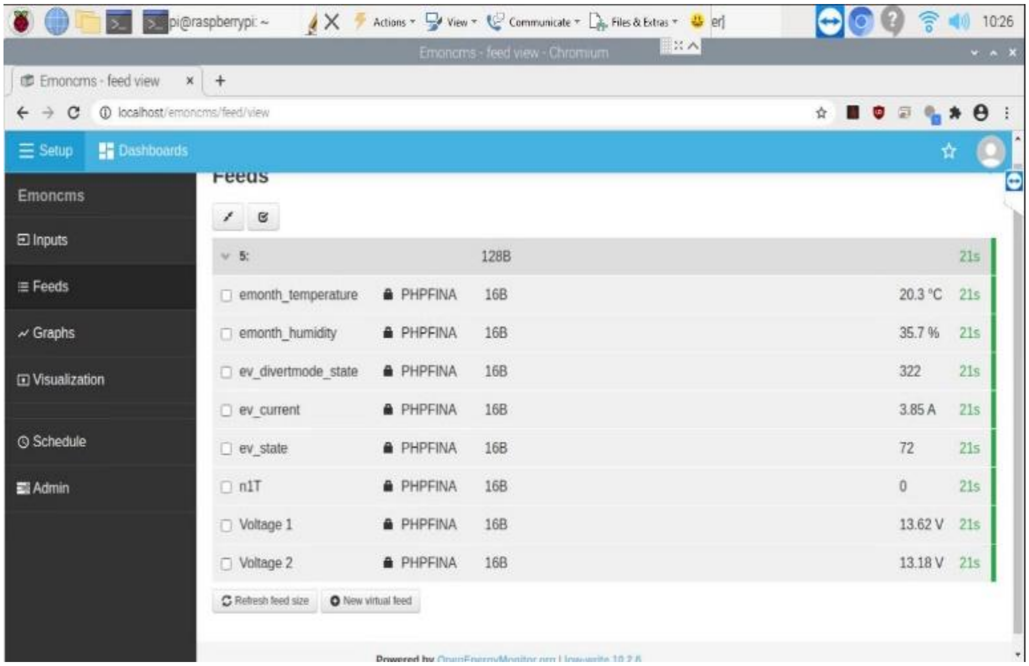


Figure 61: Feed for the inputs discovered in Emoncms

Inputs with their actual input number name and feed name are summarised in table 10.

Table 10: Inputs with discovery number, name and feeds

Input Number	**Input Name**	**Feed name**
1	Node Number	Not logged (No feed)
2	Temperature	emonth_temperature
3	Humidity	emonth_humidity
4	Water Level	ev_divertmode
5	Solar Irradiance	ev_state
6	Water Flow Sensor	n1T
7	Battery Voltage	Voltage 1

8	Panel Voltage	Voltage 2
9	Load Current	ev_current

Towards the end, 3 dashboards based on logged data in feeds were displayed on the dashboard, as shown in figures 62, 63, 64, 65 and 66.

In figure 62, a live dashboard can be seen for easy monitoring. The dashboard gave all the live values for solar irradiance, temperature and humidity under the environmental parameters box. Under hydro parameters, two parameters can be seen: water flow; which was 0 for most of the time except when the air was blown through it, and water level. Live electrical parameters can also be seen, giving live PV panel voltage level, battery voltage level, and load current parameters.

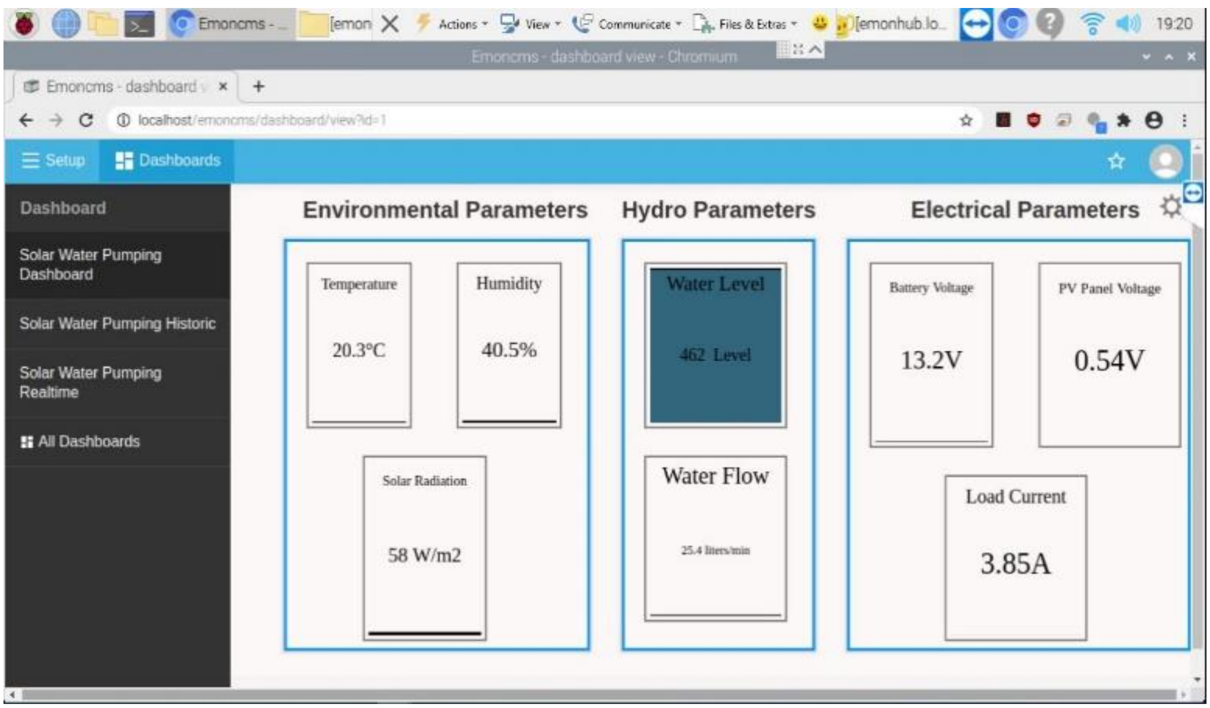


Figure 62: Live Emoncms Dashboard for a solar water pumping system

In figures 63 and 64, real-time graphs for all the discovered parameters can be seen. In figure 66, real-time graphs for environmental and hydro parameters can be seen. In figure 67, real-time electrical parameters can be seen. The time resolution can be modified, ranging from 1 minute to 1 hour for real-time graph displays. In figure 65 and 66, historic logged data for environmental, hydro and electrical parameters can be seen. The data logging was performed for only 3 hours and 40 min in our case. In figure 65, logged data for environmental and hydro parameters can be seen. In figure 66, logged data for electrical parameters can be seen. It can also be seen that when the lamp was turned off, there was a decrease in solar radiation, which was visible in logged data. The resolution of logged data can be set, ranging from a day to a year.

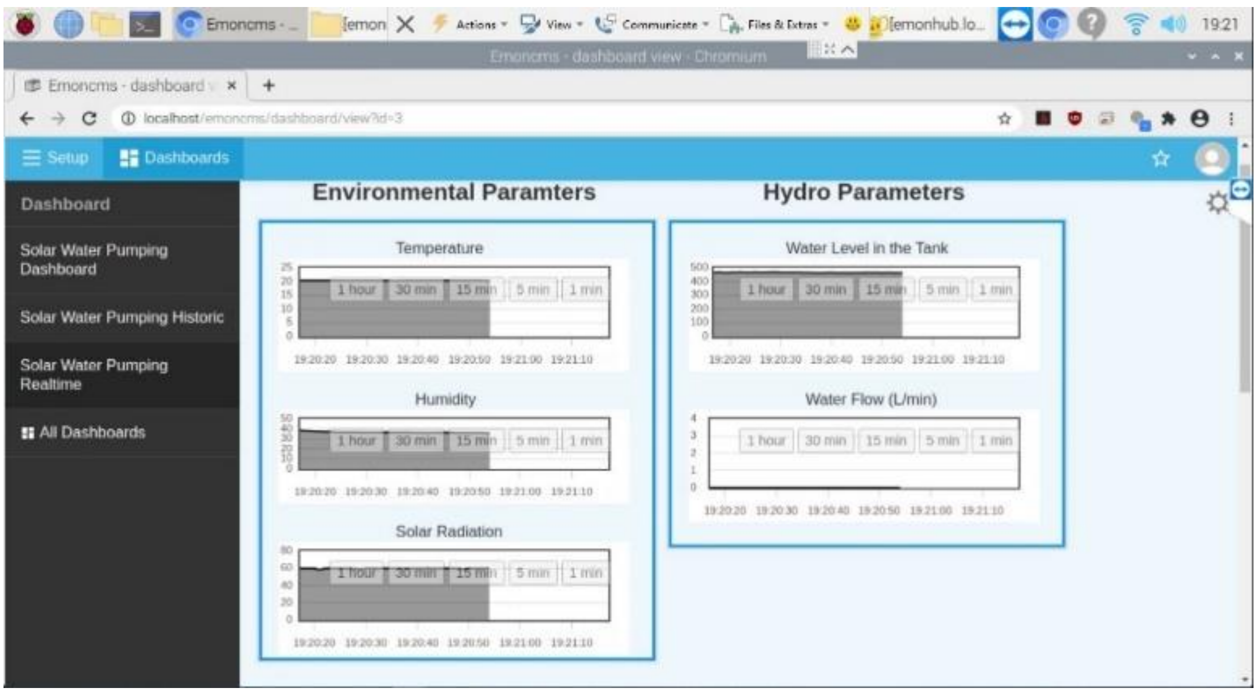


Figure 63: Real time Emoncms Dashboard for a solar water pumping system (Environmental and hydro Parameters)

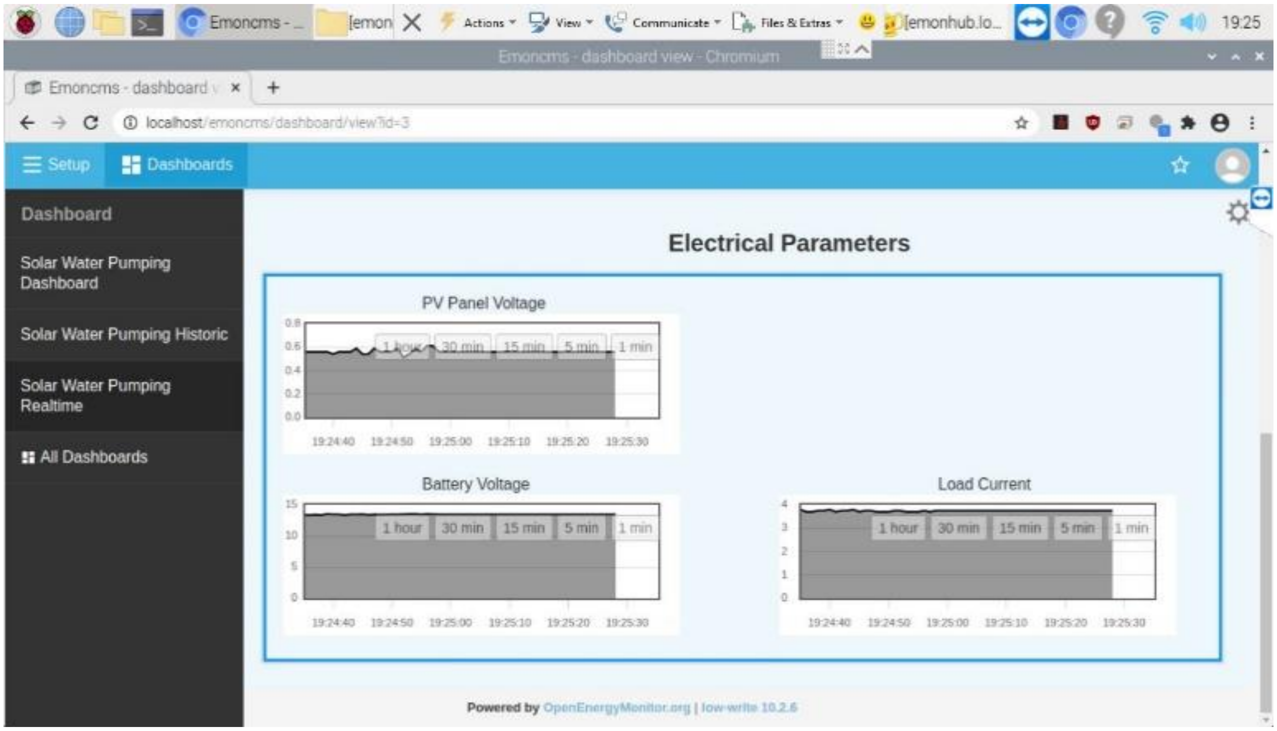


Figure 64: Real time Emoncms Dashboard for a solar water pumping system (Electrical Parameters)

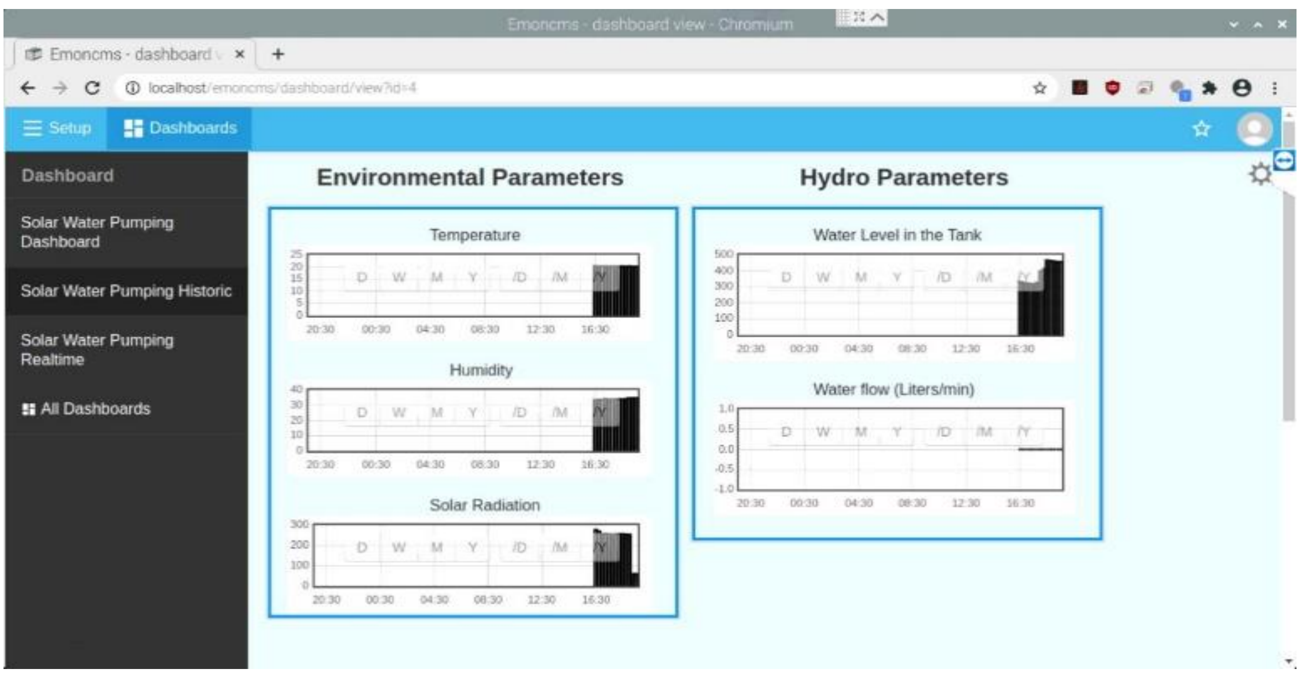


Figure 65: Historic or logged data in Emoncms for a solar water pumping system (Environmental and hydro Parameters)

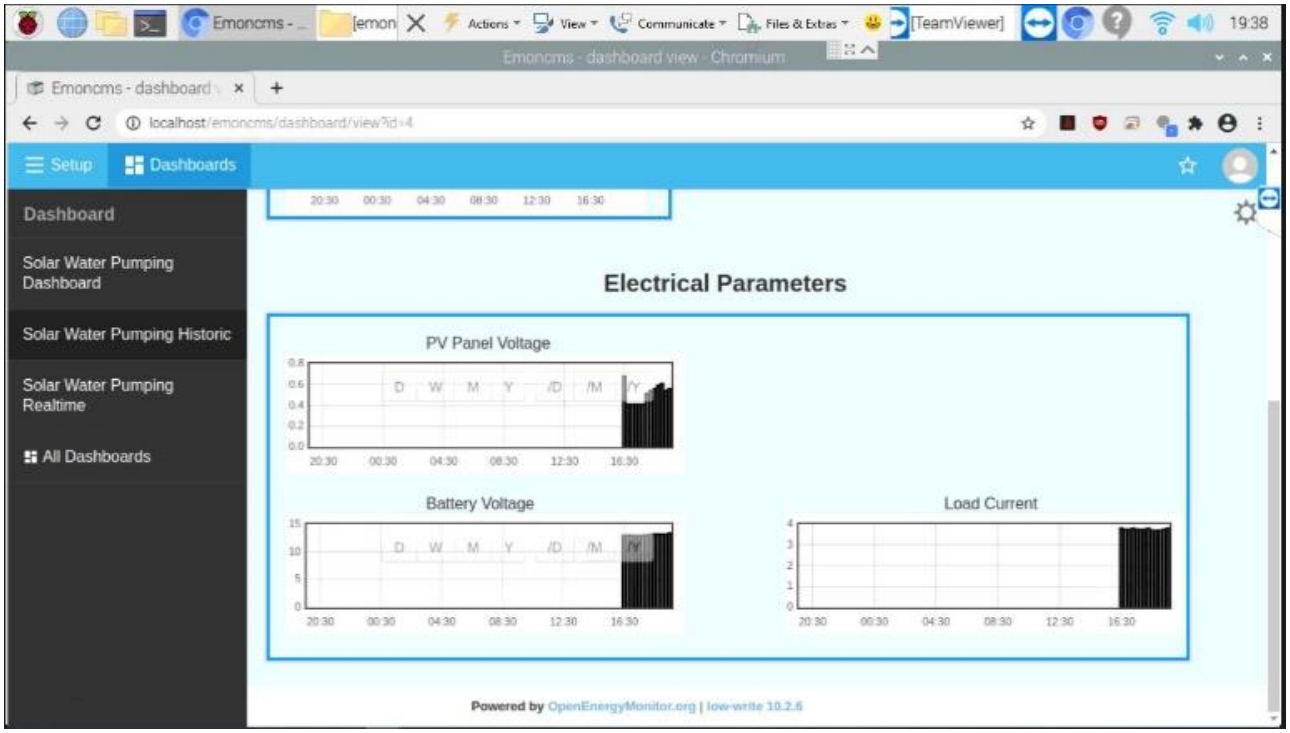


Figure 66: Historic or logged data in Emoncms for a solar water pumping system (Electrical Parameters)

5.4 Conclusion

An open-source SCADA system known as Emoncms was adapted for a solar water pumping system. The process of taking data from sensors and pushing it to Arduino and then to Raspberry Pi in the form of data sting through serial communication was explored. Different parameters for a solar water pumping systems were discovered on Emoncms, which included temperature, humidity, solar insolation, the water level in the storage water tank, flow rate of water into the tank, PV panel voltage, battery voltage, and load current. Data was reflected in 3 dashboards ranging from live to real-time to historic data for convenient monitoring.

The advantages of such monitoring systems are that they are open-source and easy to implement compared to other monitoring systems, which are expensive and require licensing.

Limited testing was possible due to the COVID-19 pandemic, as lab access was limited. Hence, data was logged for a limited number of hours. Further development of the SCADA system was also hampered due to Newfoundland and Labrador being at Level 5 due to the latest ramped-up number of cases of COVID-19.

Chapter 6

Conclusion and Future Work

6.1 Conclusions

For this thesis, a detailed design and cost analysis for a solar water pumping system with battery bank was performed in HOMER. The system requirements came out to be 73.8 kW for the PV panel network, the inverter rating came out to be 16.7 kW, and the battery requirement came out to be 450. The net present cost for the overall system came out to be $273,670, the levelized cost of energy came out to be $0.48 and the operating cost for the system came out to be $5,692.37.

Then, for the designed system, a detailed dynamic analysis was conducted in MATLAB/Simulink, which validated the HOMER software results.

In third part of the thesis, a detailed design and cost analysis for a solar water pumping system with water tank was performed in HOMER. The system requirements came out to be 72.3 kW for the PV panel network and the inverter rating came out to be 59.9 kW. The net present cost for the overall system came out to be $158,399 with tank cost, levelized cost of energy came out to be $0.1783 and operating cost for the system came out to be $4,649.93. Then, based on the economical analysis results for solar water pumping systems with battery bank and water tank, it was concluded that the water tank system was a more feasible solution for Pakistani conditions.

For the last part of the thesis, an Emoncms based SCADA system was implemented to monitor three different categories of parameters for the solar water pumping system: environmental, hydro, and electrical parameters. The data was reflected on three different custom-made dashboards ranging from live to real-time to historic dashboards.

6.2 Research Contribution

Extensive research work on a selected agricultural site of Pakistan was performed for a solar water pumping system.

- A comprehensive design and cost analysis for a battery-based solar water pumping system for a selected site in Pakistan was performed in HOMER.
- Detailed dynamic modeling for designed solar water pumping system in HOMER was performed in MATLAB/Simulink to evaluate the system's feasibility with changing conditions.
- A comprehensive design and cost analysis for a water tank-based solar water pumping system for the same selected site in Pakistan was performed in HOMER.
- The economical results for both the designed solar water pumping systems were compared to evaluate the most feasible solar water pumping system for Pakistani conditions
- An open-source Emoncms based SCADA was designed to monitor different parameters of a solar water pumping system.

6.3 Future Work

As part of the future work, dynamic analysis for a solar water pumping system with water tank in MATLAB/Simulink can be performed for the already designed system in HOMER to validate the proposed system in a more consolidated manner.

The open-source Emoncms based SCADA system can be improved for a wireless system so that that the data could be controlled and monitored wirelessly. An email alert system can be incorporated in the already developed SCADA system using Swift-mailer. A button control can be added to control the motor's ON/OFF from the SCADA system.

6.4 Publications

Articles in Refereed Publications

- Usman Ashraf, M. Tariq Iqbal, Optimised Design and Analysis of Solar Water Pumping Systems for Pakistani Conditions, Energy and Power Engineering Energy, Volume 12, pp 521-542; doi:10.4236/epe.2020.1210032

Refereed Conference Publications

- Usman Ashraf, M. Tariq Iqbal, An Open Source SCADA for a Solar Water Pumping System Designed for Pakistani Conditions, presented at IEEE computing and communication workshop and conference, CCWC 2021
- Usman Ashraf, M. Tariq Iqbal, Feasibility Analysis of a Solar Water Pumping System in Pakistani Conditions: A Case Study, presented at IEEE CCECE 2020

Regional Conference Publications

- Usman Ashraf, Andrew Peddle, Uday Khadodra, M. Tariq Iqbal, Design and analysis of a solar water pumping system for two hectares farm in India, presented at The 29th Annual IEEE NECEC conference St. John's, November 19th, 2020.

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