Sizing, Dynamic Modelling and Control of a Solar Water Pumping System for Irrigation

Master of Engineering Seminar
By
© Shatadru Biswas

Supervisor
Dr. M. Tariq Iqbal

Department of Electrical & Computer Engineering
Faculty of Engineering & Applied Science
Memorial University of Newfoundland, NL, Canada

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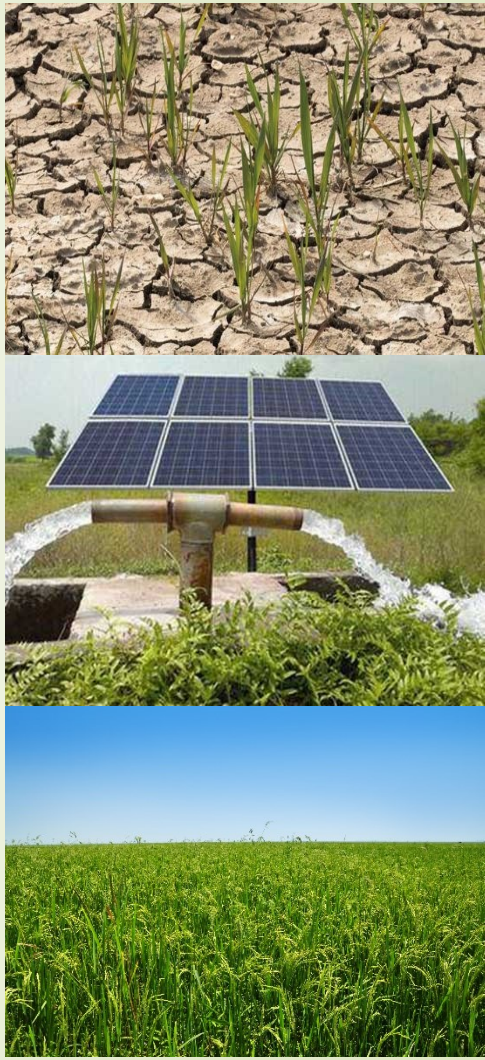
OUTLINE

- Introduction
- Literature Review
- Selected Site Data Analysis and System Sizing
- Dynamic Modelling and Simulation in Simulink
- Sensitivity and Effectiveness Analysis
- Design of Instrumentation and Control System
- Conclusions and Recommendations for Future Work

INTRODUCTION

- Irrigation is highly significant for crop production
- Diesel engine system is costly solution in off-grid areas
- Demand for freshwater in increasing rapidly
- Conservation of water is also important
- Solar water pumping system is widely used renewable source application
- The technology of solar cell is growing fast
- Solar PV system offers unattended operation, low maintenance, easy installation , long life and causes no pollution
- Governments of developing countries have various policies to promote alternative source of energy

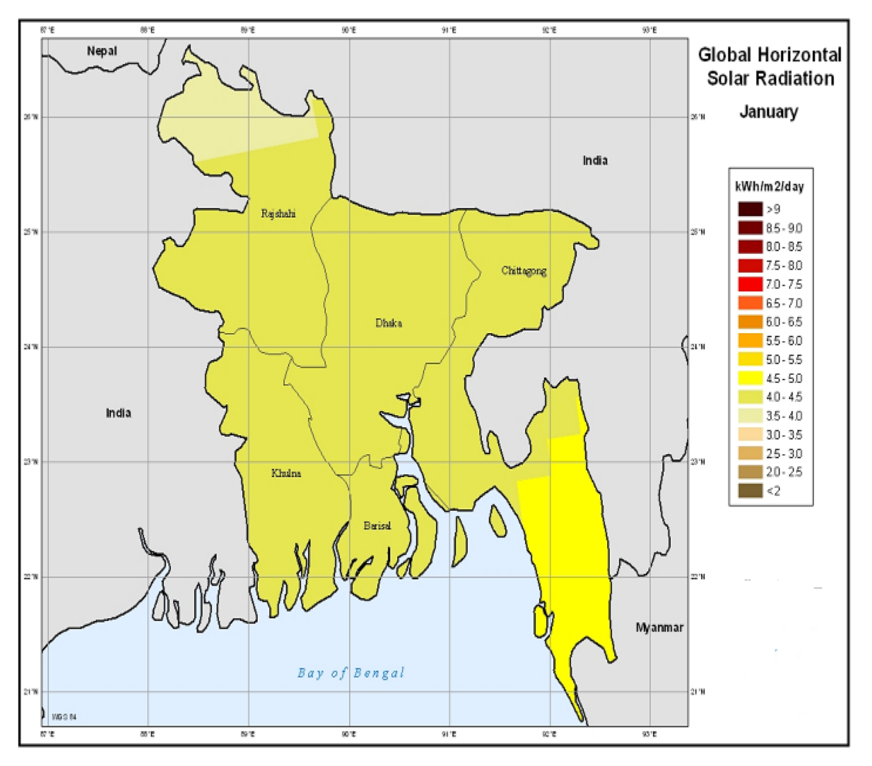


Automated Solar Irrigation Pumping System may be an feasible solution

Introduction

Case Study

- Bangladesh - an agriculture-based developing country
- Main crop – rice
- Land under irrigation – 59%
- Ground water irrigation – 85%
- Main power source - electric power & diesel engine
- Electric power – limited access
- Diesel engine – impacts country's economy
- Average solar radiation:
  - in normal days- 4.0 to 6.5 kWh/m^2/day
  - in bright sunshine- 6.0 to 9.0 kWh/m^2/day
- Projects:
  - Governmental
  - Non-Governmental
- Government policy:
  - subsidies
  - lower bank loan interest rate



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LITERATURE REVIEW

- Anis and Nour [1994], Argaw [1994], Loxsom and Veroj [1994], Katan et al. [1996], Hoque [2001], Pande et al. [2003], Cuadros et al. [2003], Zvonimir and Margeta [2006], Forero et.al [2006], Odeh, Yohanis, and Norton [2006], Hamidat and Benyoucef [2007], Meah, Ula, and Barrett [2008], Bakelli, Arab and Azoui [2011], Mokaddem et.al [2011] worked on system sizing and modelling of solar water pumping system
- Dynamic modeling and simulation of the solar PV system was done by Gad [2009], Akihiro Oi et al. [2009], Malla, Bhende, and Mishra [2011]
- Yunseop, Evans, Iversen [2008], Dursun and Ozden [2011] , Prisilla [2012], Uddin et.al [2012], Li [2013], Pavithra and Srinath [2014], Harishankar [2014], Hussain [2015] provided solutions for automated solar PV system
- The systems were economically analyzed by Pande et al., Kim, Mahir, Harishankar, Hossain, Hassan, Mottalib, Hossain

SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Selected Site

- Name – GS-Gorol project
- Location – Gorol (Kamlertari), Kaliganj, Lalmonirhat, Bangladesh
- Geographical Location – 26°N, 89.28°E
- Installed by – Grameen Shakti
- Technical Support – Sherpa Power Engineering Limited
- Average water discharge - 1700 m^3/d
- Total dynamic head – 12 m
- Solar PV – 26.775 kWp
- Motor capacity – 15 kW
- Water tank size – 3400 L

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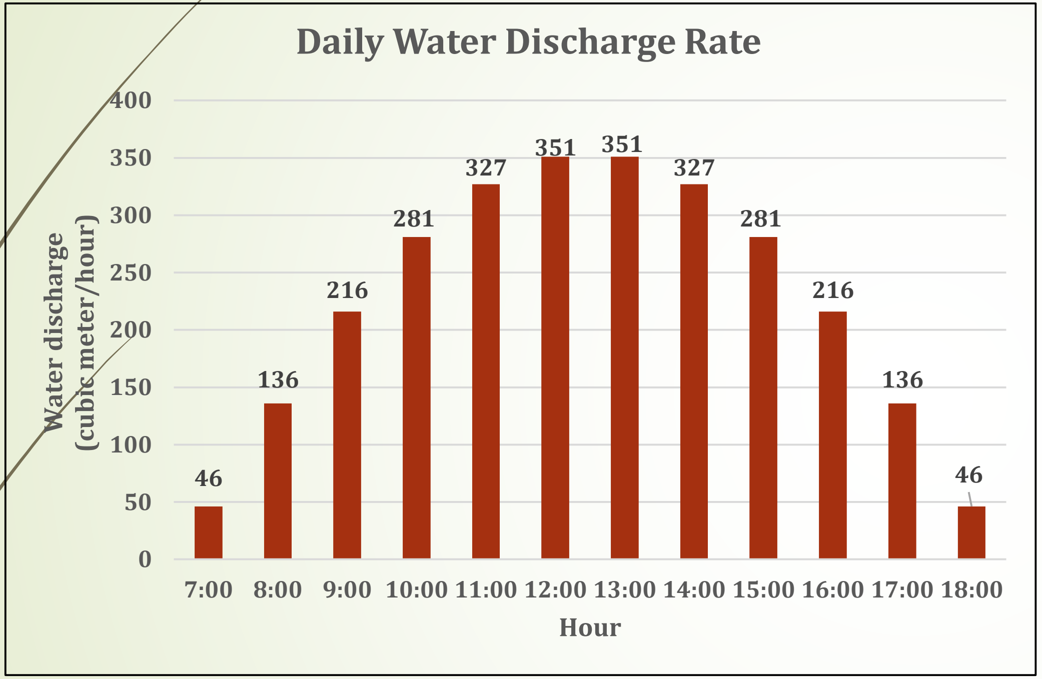
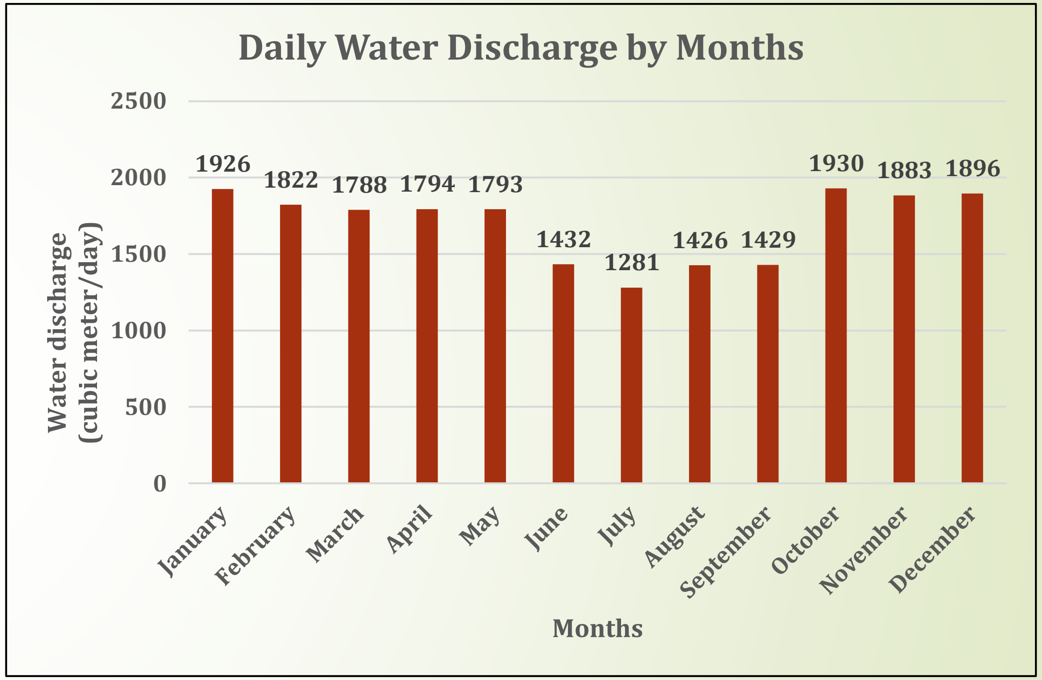
SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Site Output Data





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SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

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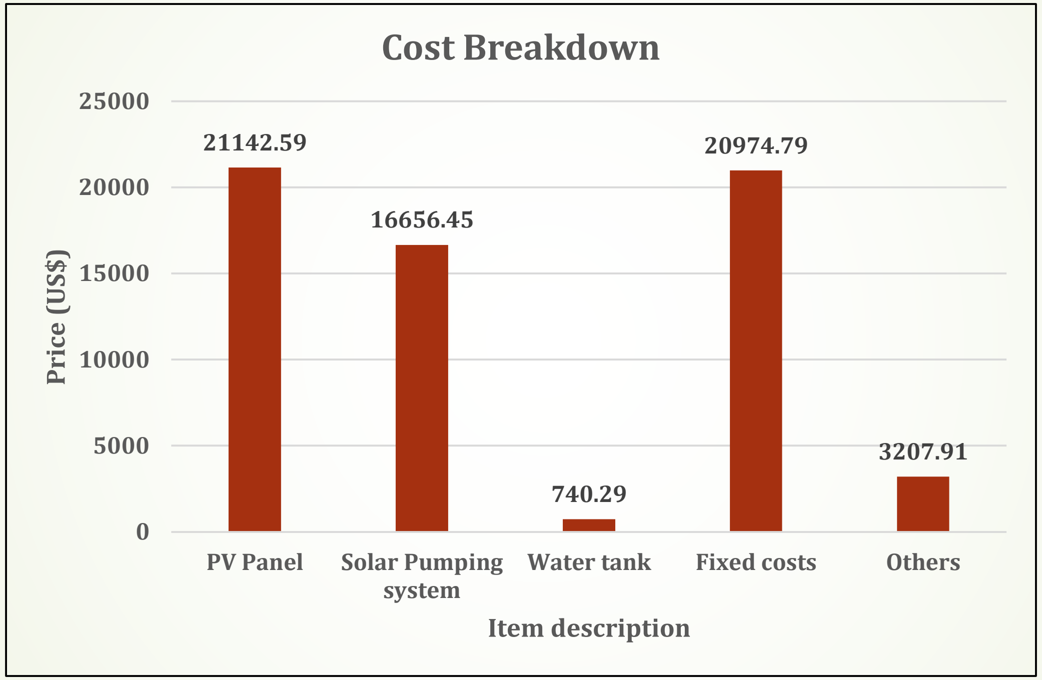
Cost Breakdown of GS-Gorol Project



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SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

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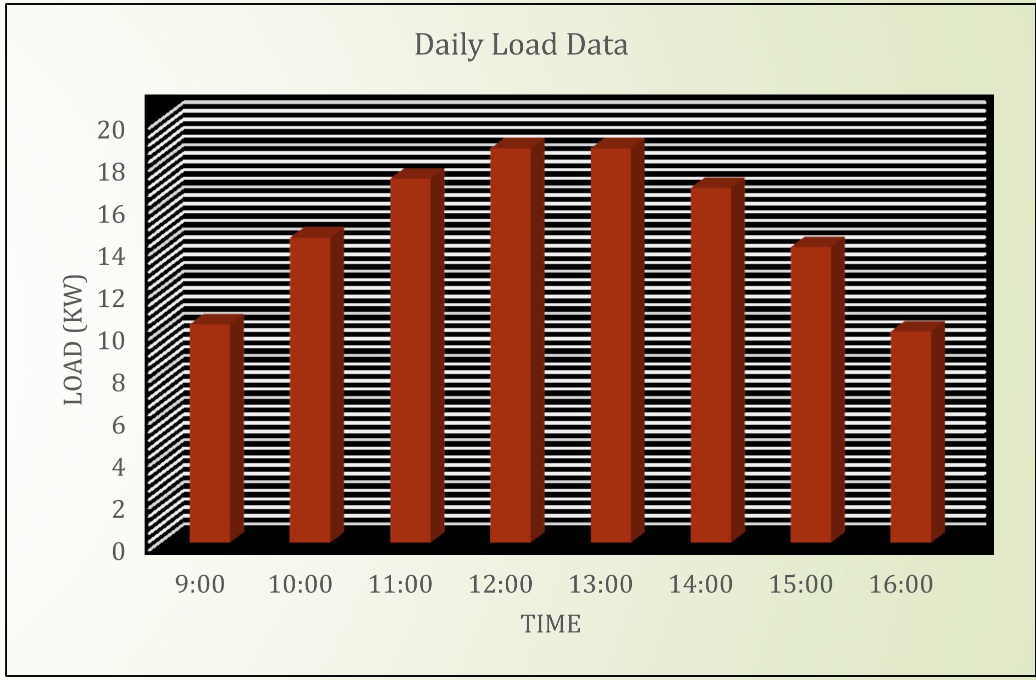
Proposed Solar Irrigation Pumping System

- HOMER - Hybrid Optimization and Multiple Energy Resources
- HOMER Optimization tool – gives feasible solution of battery based system
- Battery less system – manual calculation of tank size equivalent to battery storage
- Load input into HOMER – Daily load data was calculated form the site data



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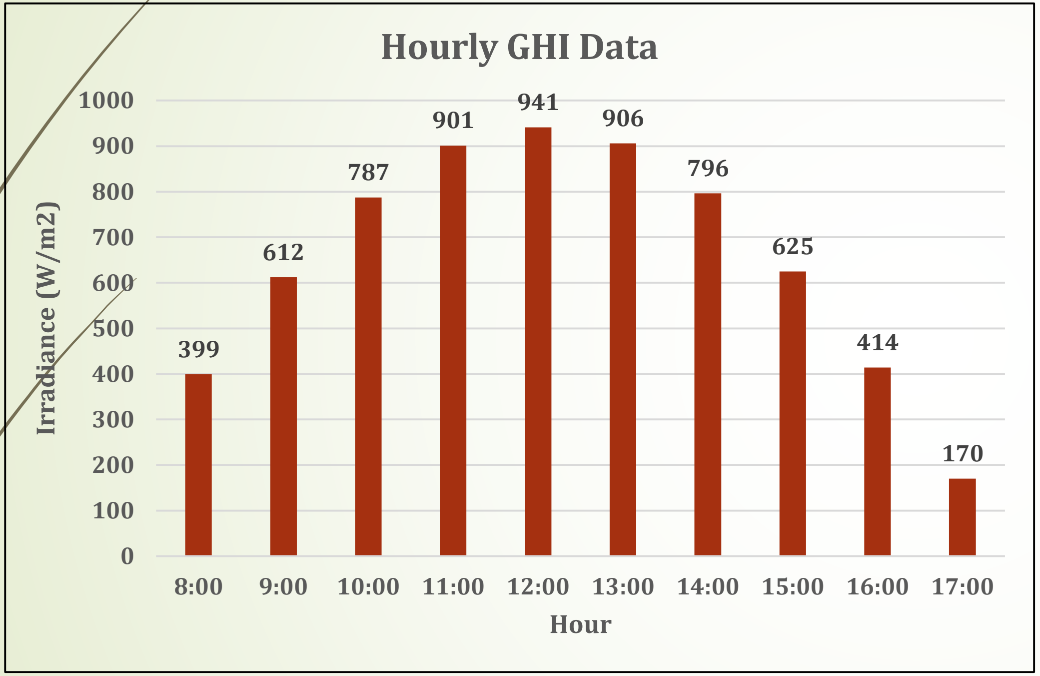
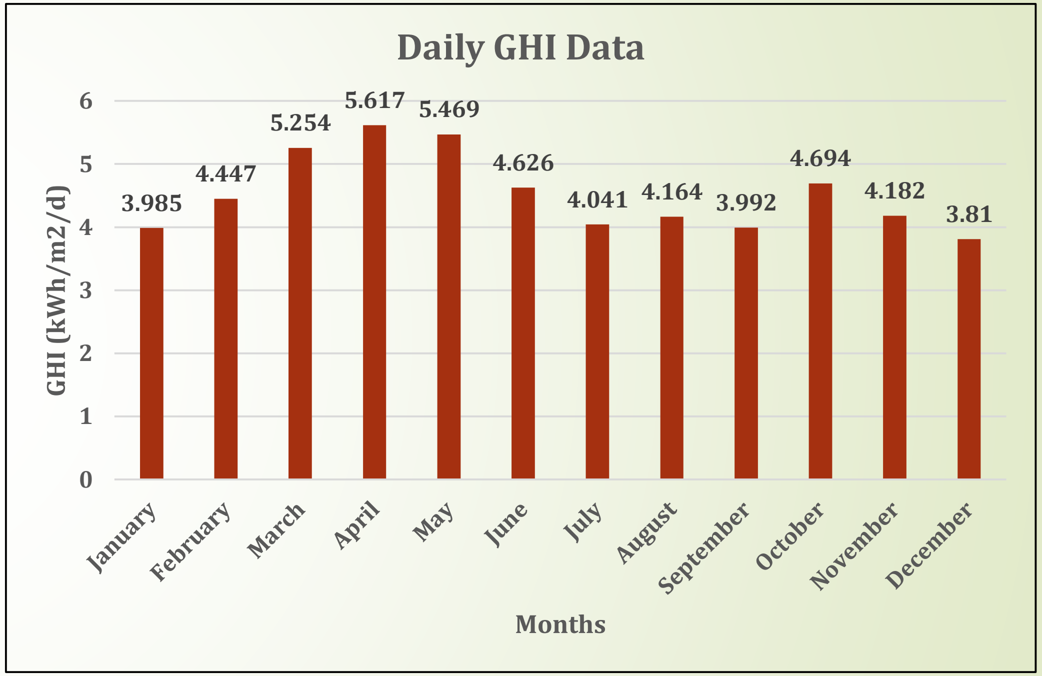
SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Solar GHI Data



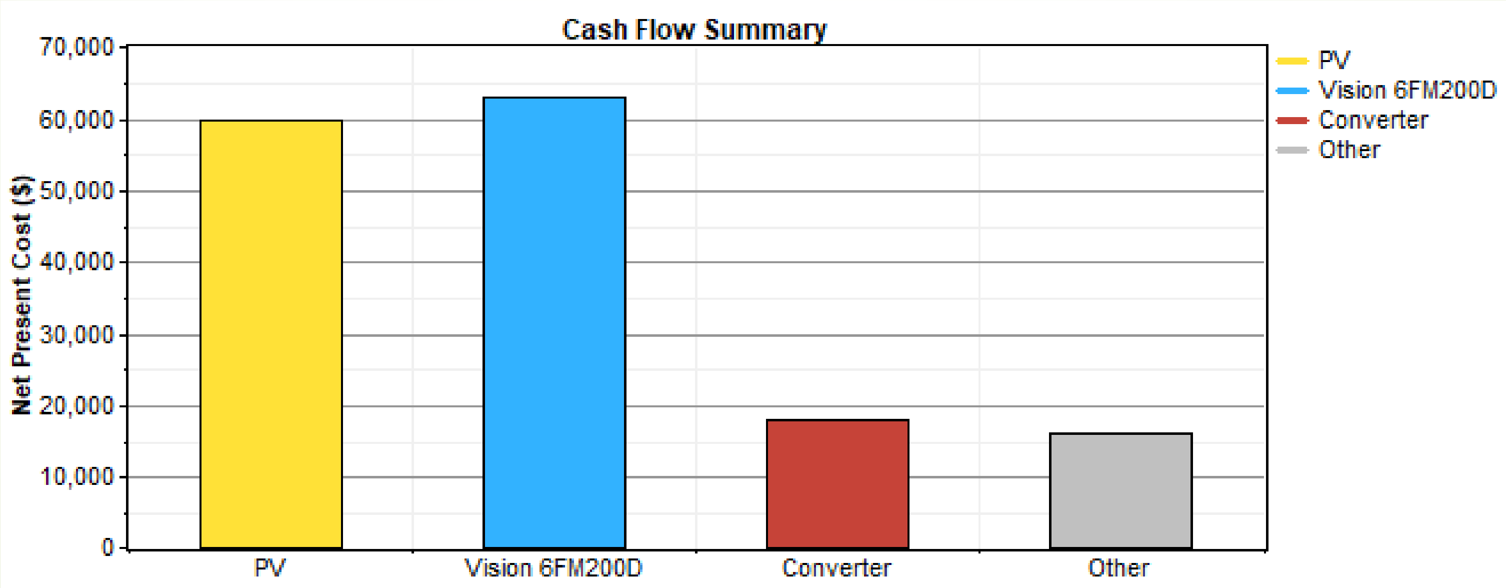


SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Homer Simulation Result for Battery Based system

System Component

System component	Rating
PV [kW]	38.4 (310 Wp each)
Battery Storage [No]	60 (12V, 200 Ahr each)
Inverter [kW]	20.7



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SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Homer Simulation Result for Battery Based system

Economic Cost Breakdown

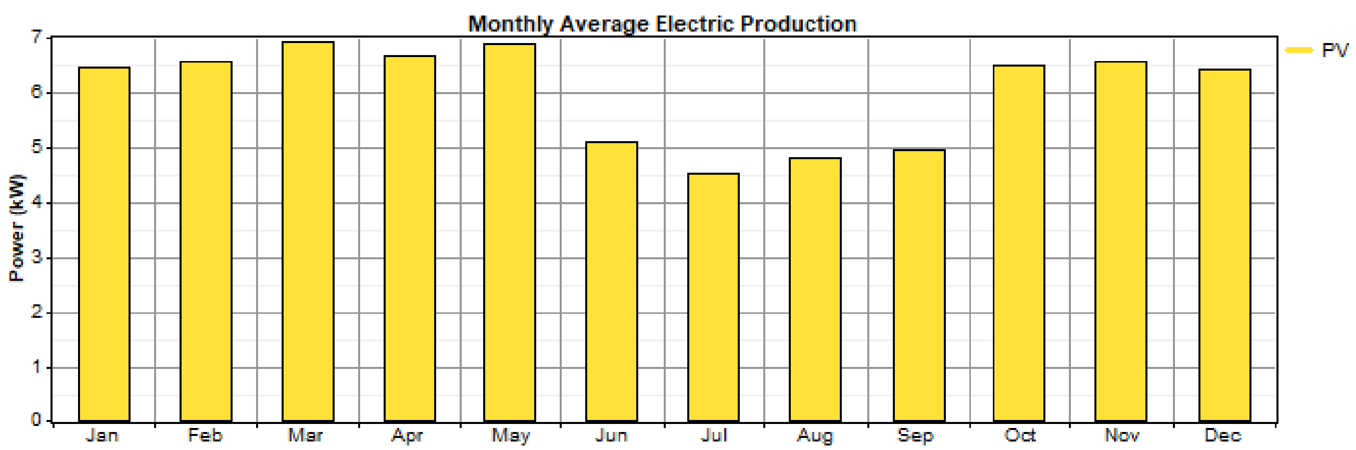
Component	Capital (US$)	Replacement (US$)	O&M (US$)	Salvage (US$)	Total ($)
PV	55,242	4,977	1,876	-2,318	59,777
Battery Storage	42,000	21,513	0	-554	62,960
Inverter	14,003	3,193	1,174	-410	17,959
Other	7,000	0	9,077	0	16,077
System	118,245	29,683	12,127	-3,282	156,773

Total Net Present Cost (NPC) of the system : US$156,773
The levelized Cost of Operation (COE) : US$0.442/kWh
Total operating cost : US$4,245/yr

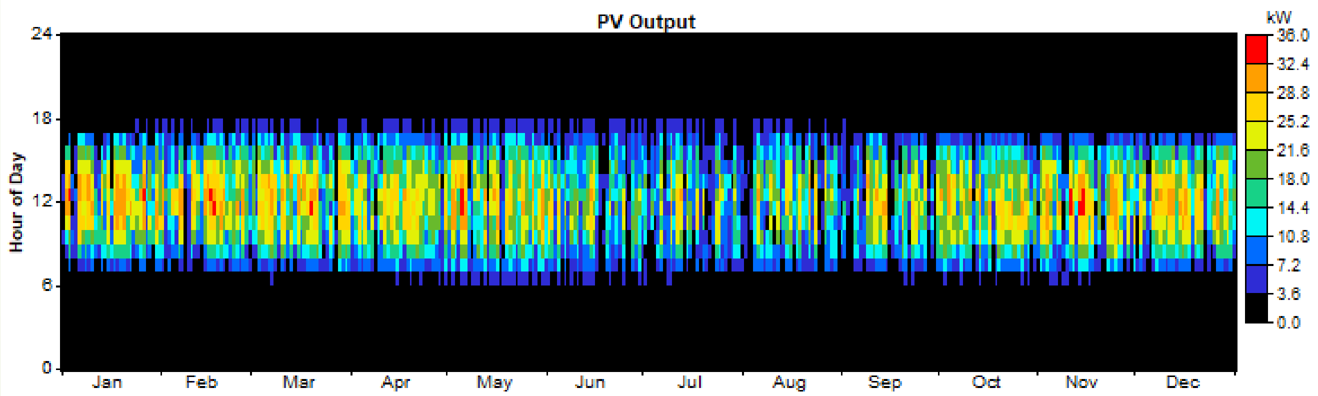
SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Homer Simulation Result for Battery Based system

Monthly average electric production



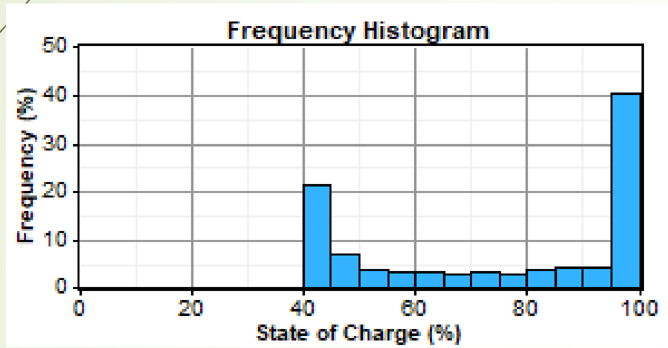
PV output

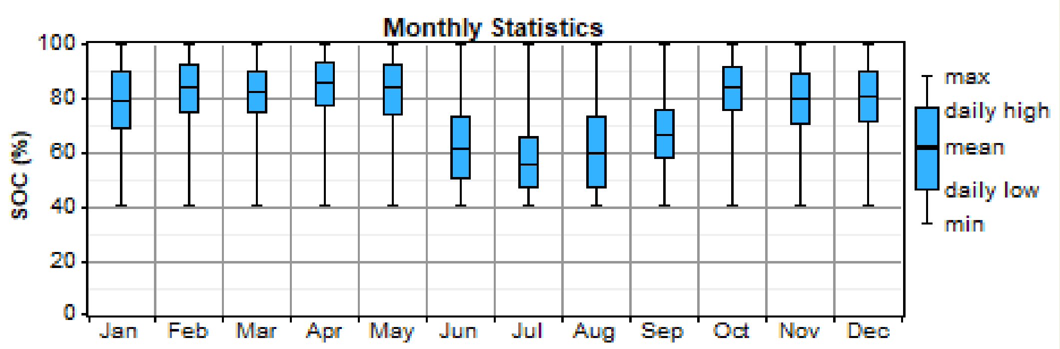


SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

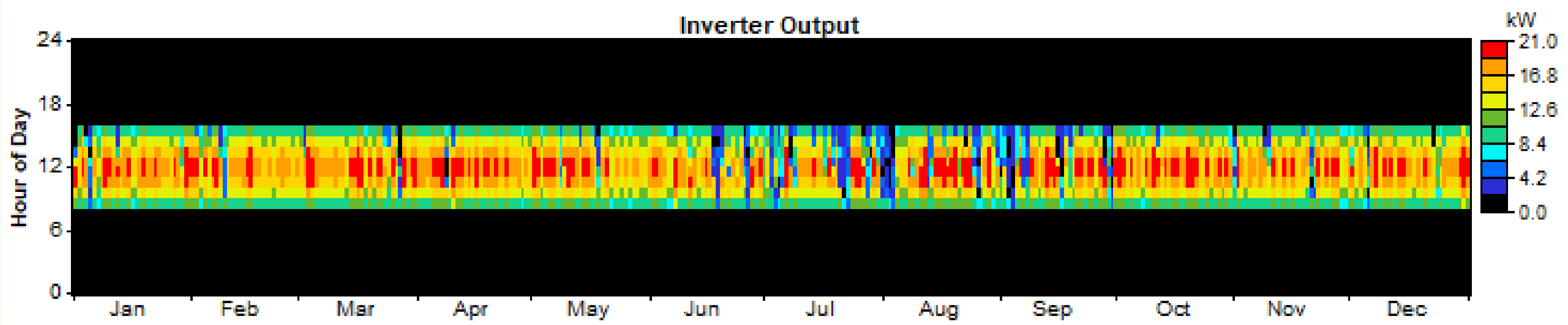
Homer Simulation Result for Battery Based system

Battery Storage



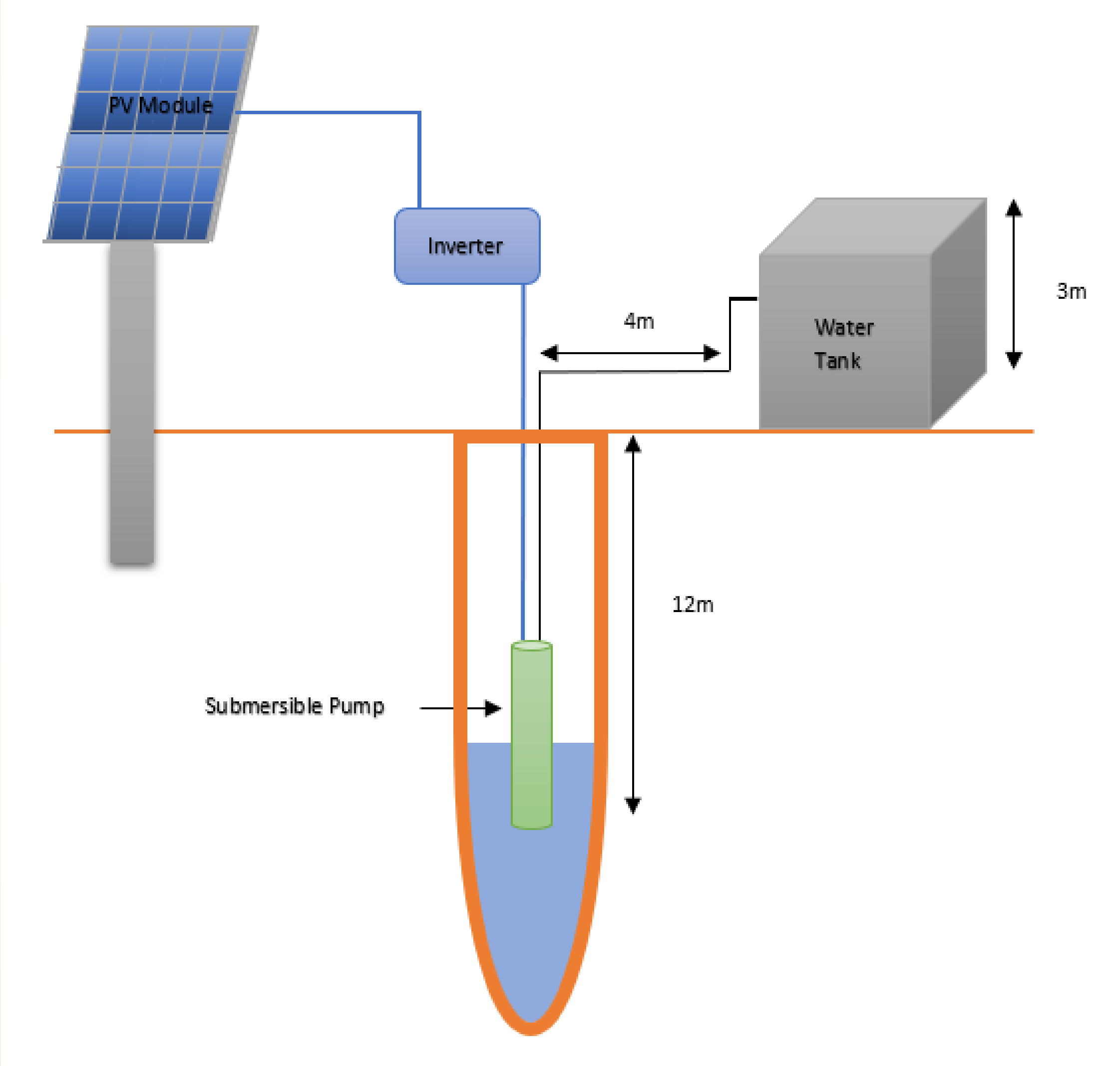


Inverter output



SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Battery Less System



Water Tank Equivalent Battery Storage

Battery ampere hour: 200Ah
Bus voltage: 48V
Number of strings: 15
Total watt-hour = (48×200×15) = 144,000

Calculation of Total Dynamic Head (THD):

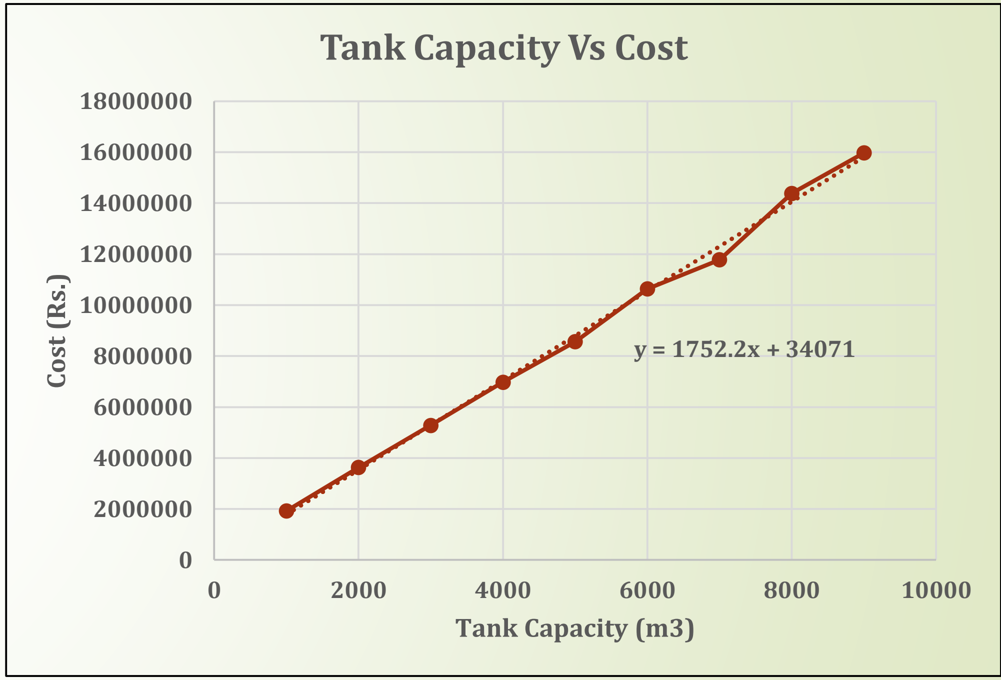
- Elevation head = 15m
- Friction head loss for fittings = 1.71 m
- Friction head loss for pipe = 0.44m
- Total frictional head loss = 2.15m
- Total dynamic head = 17.15m
- Total volume of water needed to be stored in the water tank = 3081 m^3

Decided Tank Size : **3100 m^3**

SELECTED SITE DATA ANALYSIS AND SYSTEM SIZING

Cost of the Tank

Size of the tank: (40m×26m×3m)
Construction cost : US$ 83,087.06
Land cost : US$ 5000



MATLAB and Simulink

- MATLAB - fourth-generation programming language developed and introduced by MathWorks in 1984
- Simulink - graphical programming environment for modeling, simulating and analyzing multi-domain dynamic systems also introduced by MathWorks in 1984

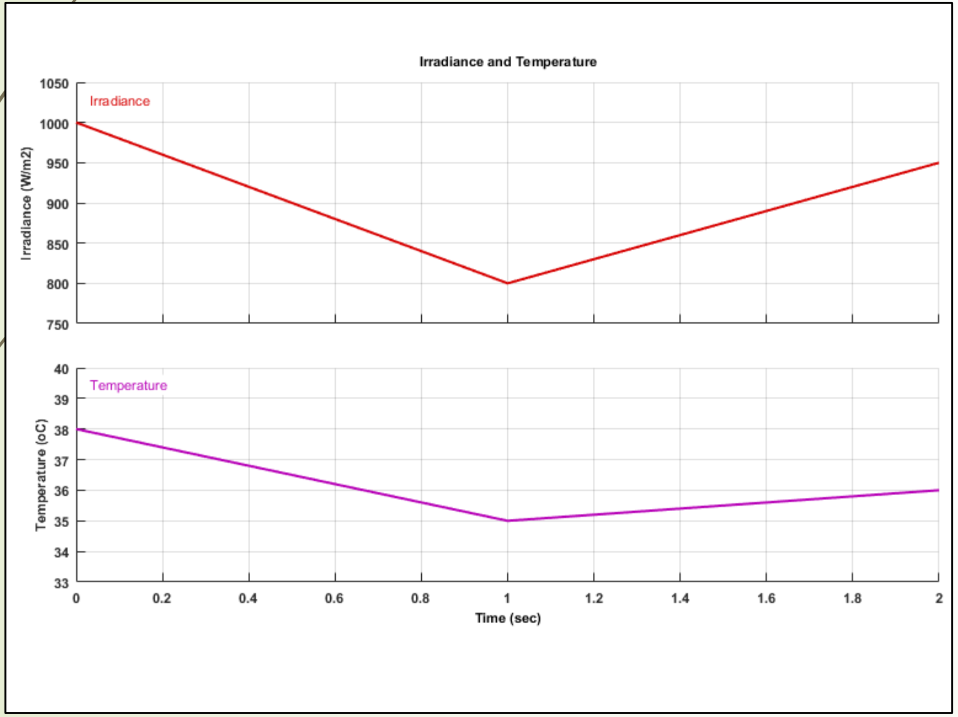
Dynamic Modeling

- Dynamic modeling and simulation of both battery based and battery less system
- Dynamic modeling and simulation of combined storage system
- To observe the dynamic behaviors of the system components
- Find out a feasible solution

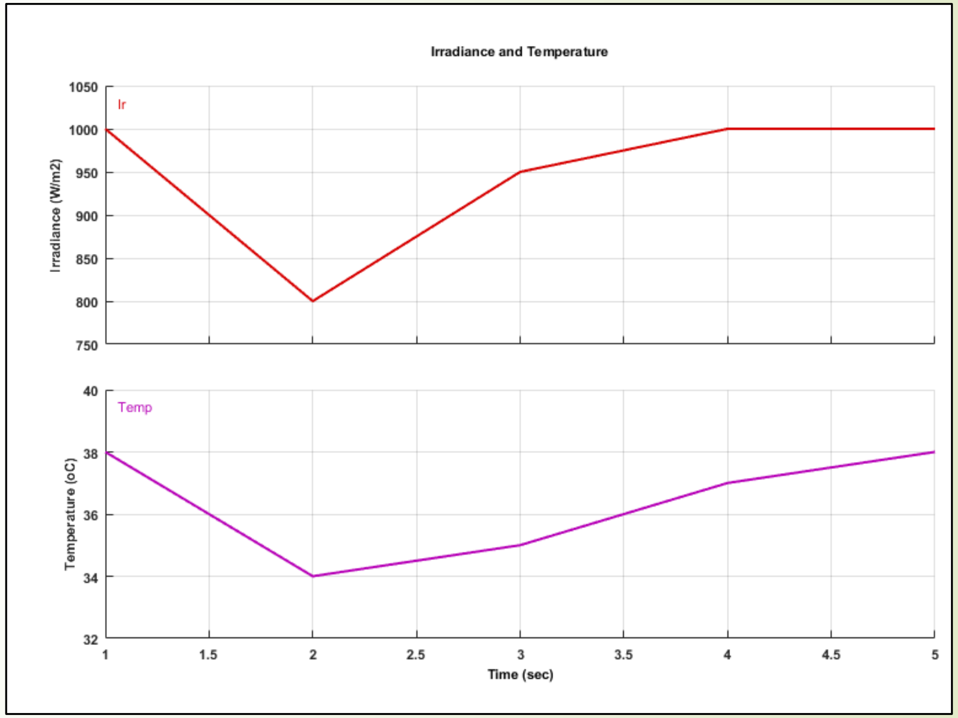
DYNAMIC MODELING AND SIMULATION IN SIMULINK

Irradiance and Temperature

Battery based system

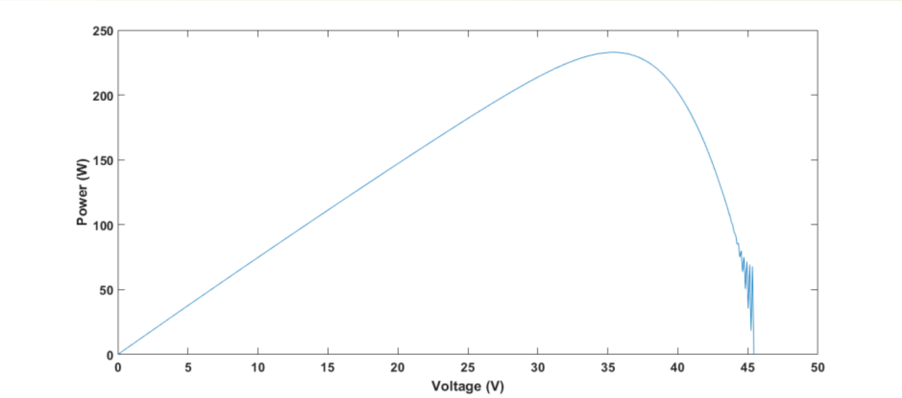


Battery less system

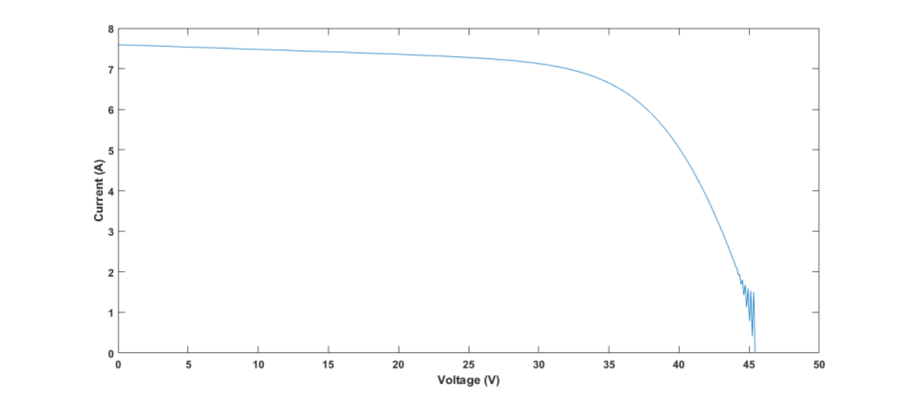


Solar PV array

PV model : Chint Solar (Zhejiang) CHSM6612P-310
Module capacity : 310 Wp
Shunt resistance = 85.7392 ohm
Series resistance = 0.44015 ohm
Diode saturation current = 1.8885e $^{(-09)}$ A
Light-generated current = 9.6521 A
Diode ideality factor = 1.1011
Number of cells connected in series in a module =72



Diode Power Curve



Diode V-I Curve

Motor Pump Set

Machine : asynchronous
Type : squirrel cage induction motor
Configuration : 20 HP, 460 V, 60 Hz
Nominal power : 1.492e^{04} VA
Mechanical power : 1.492e^{06} W
Nominal speed of the rotor : 1760 RPM
Mechanical torque input is 8 N.m.

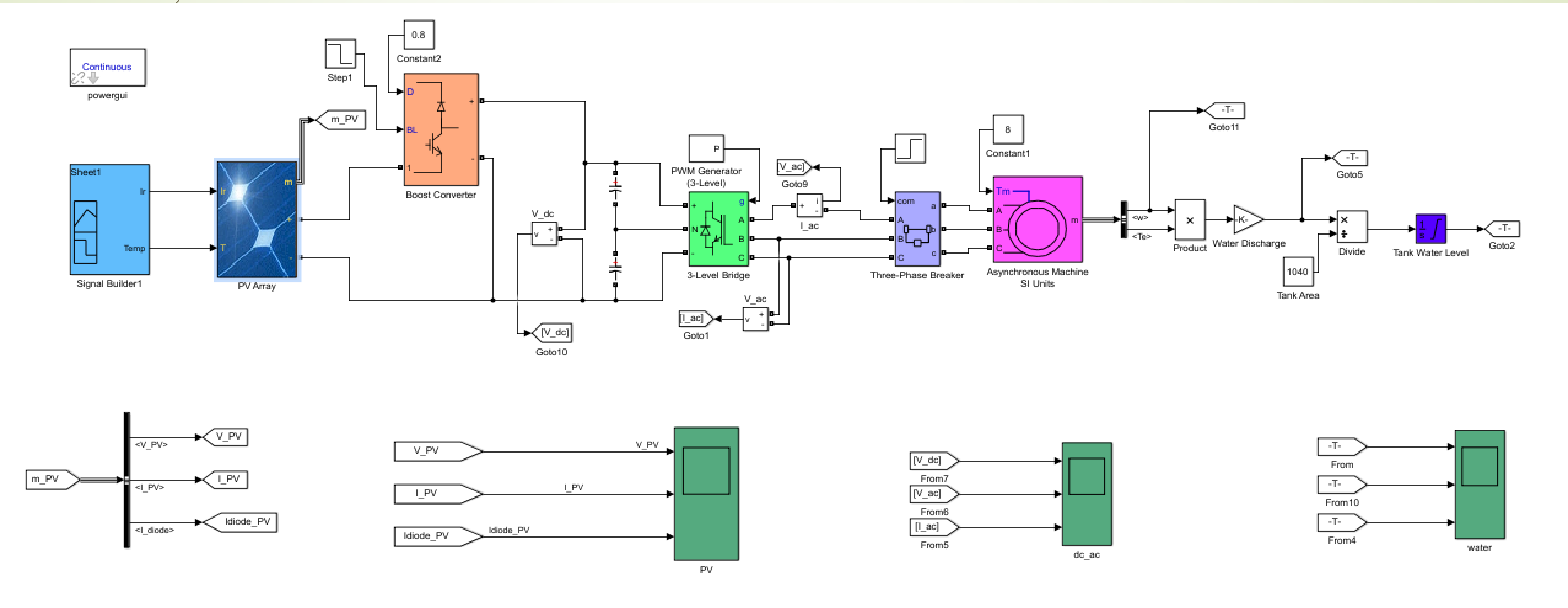
the water discharge rate, Q = $\mathbf{0.0000214(T_e \times w)}$.

Three-Phase Breaker

- Between inverter and asynchronous machine
- Used for protection purpose

DYNAMIC MODELING AND SIMULATION IN SIMULINK

Modelling of Battery-Less System



Modelling of Battery-Less System

Boost Converter

- Switching function model
- Directly controlled by duty cycle
- No PWM
- Duty cycle is 0.8
- Firing pulse are blocked

Inverter

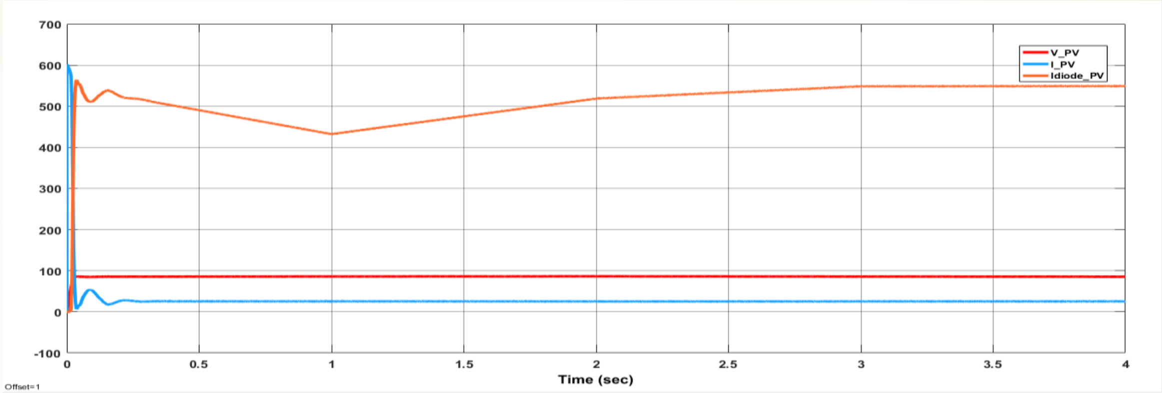
- 3 level bridge block
- 3 bridge arms
- 12 switching device along their antiparallel diodes
- 2 neutral clamping diodes
- IGBT/Diodes used

*PWM: Pulse Width Modulation

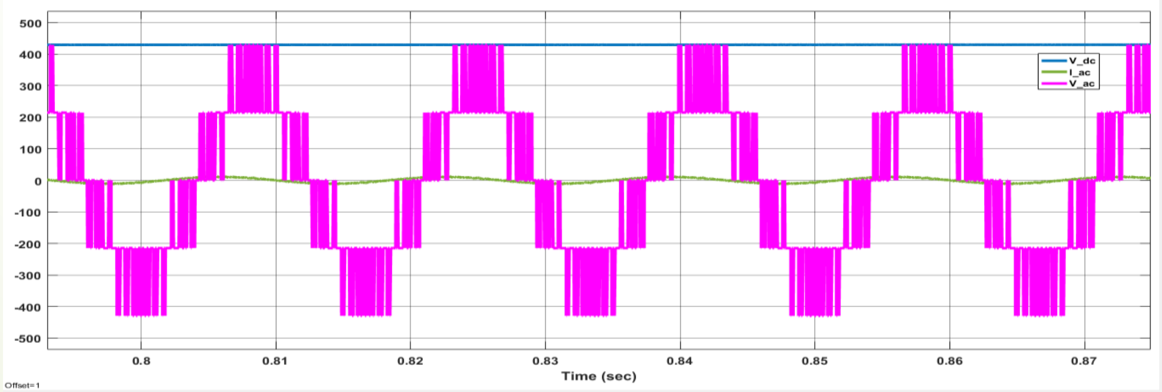
DYNAMIC MODELING AND SIMULATION IN SIMULINK

Simulation Result Analysis of Battery-Less System

PV Properties

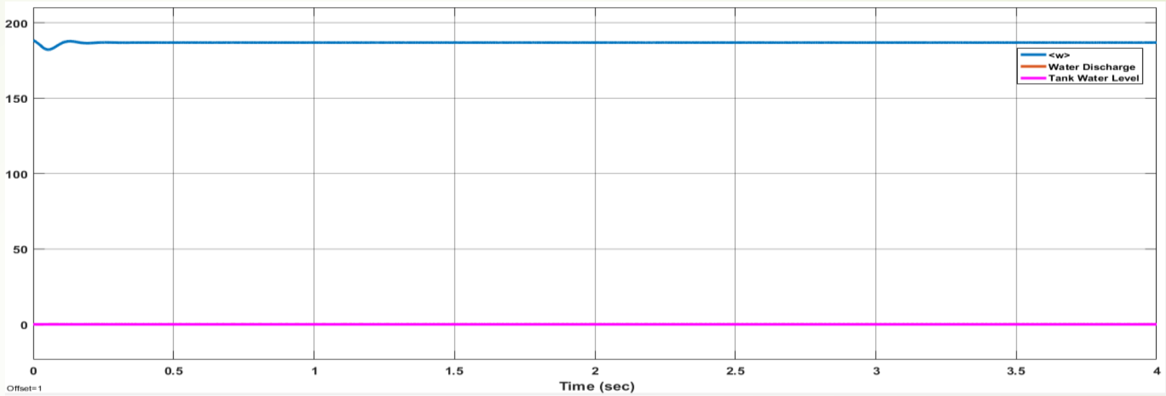


AC and DC Voltage and Current

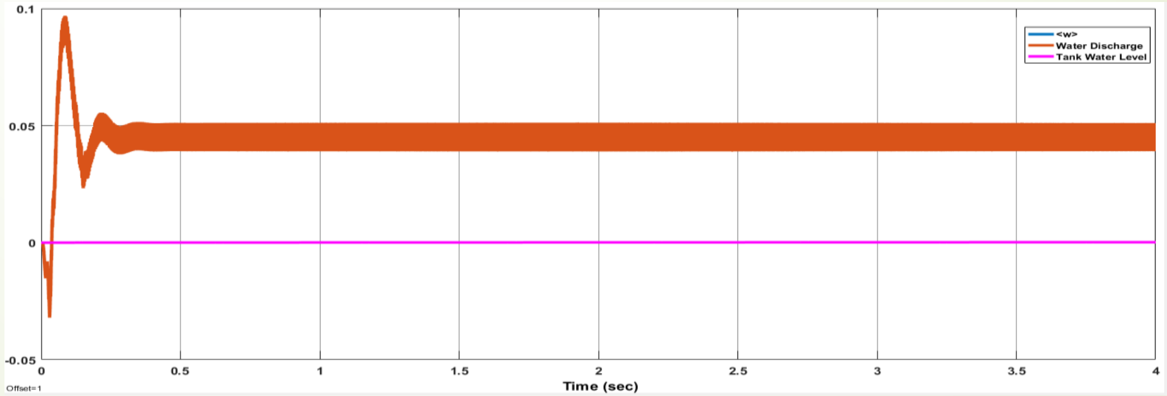


Simulation Result Analysis of Battery-Less System

Rotor Speed



Water Discharge and Tank Water Level



Simulation Result Analysis of Battery-Less System

Water discharge and tank water level

During five second of operation

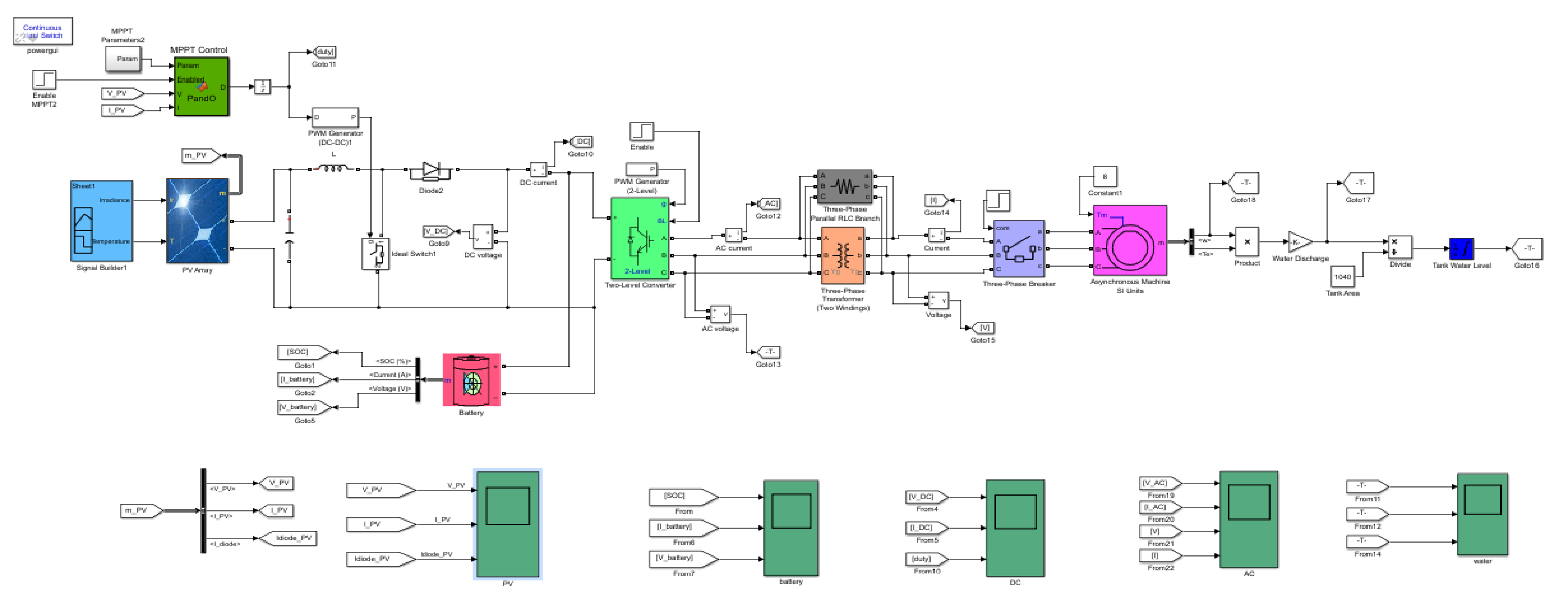
- water discharge rate : 0.045 m^3/s or 162 m^3/h
- Tank water level : 1.74e^{-4} m

After eight hours of operation

- water lifted: 1296 m^3
- Tank water level : 1 m

DYNAMIC MODELING AND SIMULATION IN SIMULINK

Modelling of Battery-Based System



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Modelling of Battery-Based System

MPPT Controller (P&O Method)

- MPPT control algorithm adjusts the duty ratio to find out the maximum power point
- Most popular because of its simplicity
- This method faces oscillation and power loss
- Unstable while atmospheric conditions changes rapidly

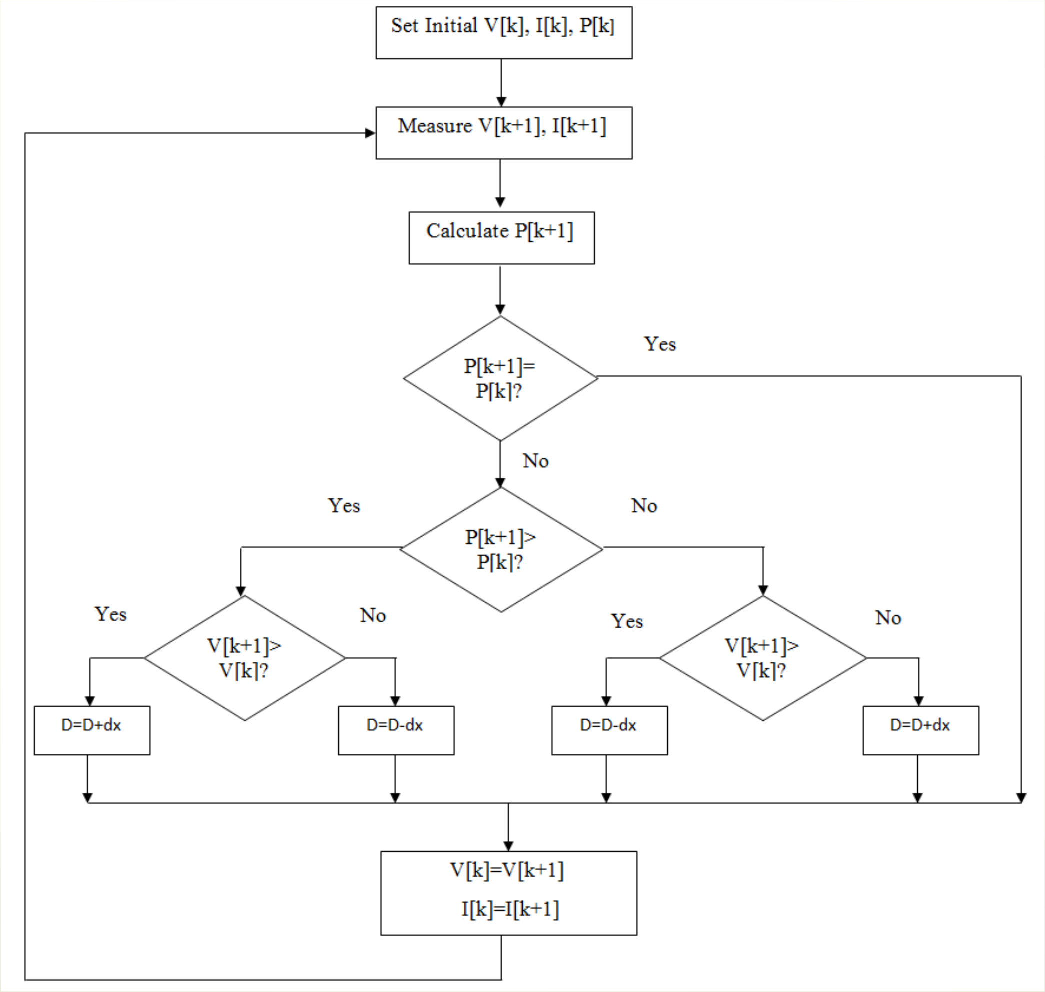
Parameters for Perturbation and Observation Method

Parameters	Values
Initial value for D output	0.5
Upper limit for D	0.6
Lower limit for D	0.45
Increment value used to increase or decrease	3e-4

*P&O Method: **Perturbation and Observation Method**

Modelling of Battery-Based System

Flow Chart of P&O Method



Modelling of Battery-Based System

Battery Storage

- Type : Lead Acid
- Capacity : 3000 Ah
- Nominal voltage : 48 V
- Initial state of charge : 60%

Inverter

- 2 level bridge block
- IGBT/Diodes used
- IGBT/Diodes pairs controlled by firing pulses produced by a PWM generator
- Converter controlled by vectorized gating signal
- Gating signal contains six firing pulses

Modelling of Battery-Based System

Transformer

- Type : three-phase step-up
- Primary voltage : 48 V
- Secondary voltage : 460 V
- Connection: Grounded Y – Grounded Y

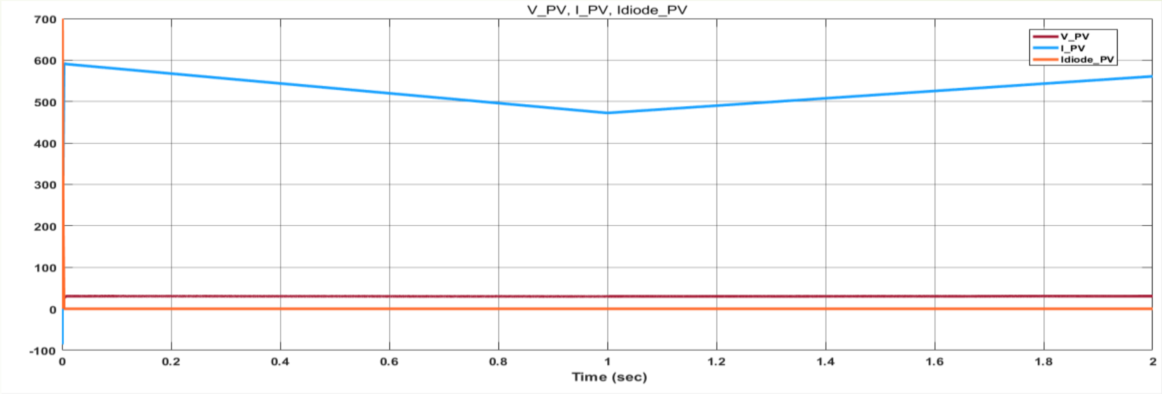
Transformer Parameter

Parameters		Values
Nominal power (VA)		15e3
Nominal frequency (Hz)		60
Primary winding parameters	Ph-Ph R.M.S. voltage (Vrms)	19.59
	winding resistance (Ohn)	0
	winding inductance (H)	0
Secondary Winding Parameters	Ph-Ph R.M.S. voltage (Vrms)	187.77
	winding resistance (Ohn)	500
	winding inductance (H)	500
Magnetization resistance (Ohm)		inf
Magnetization Inductance (H)		inf

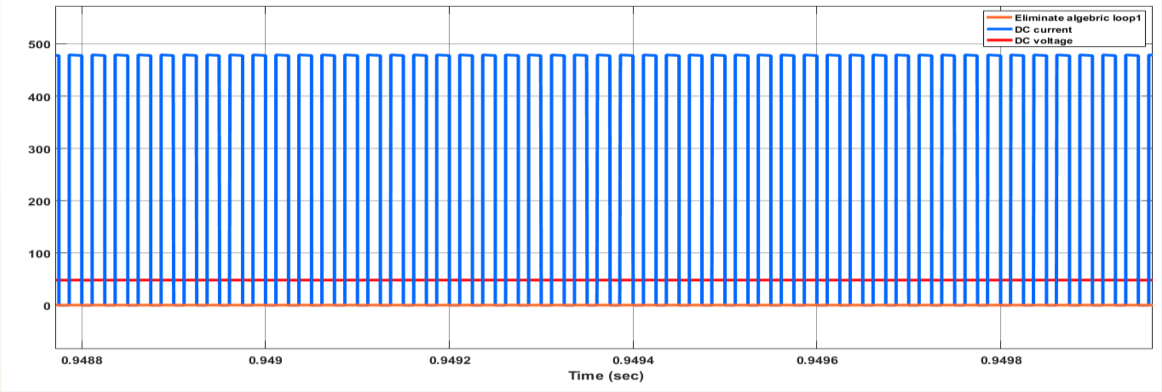
DYNAMIC MODELING AND SIMULATION IN SIMULINK

Simulation Result Analysis of Battery-Based System

PV Properties

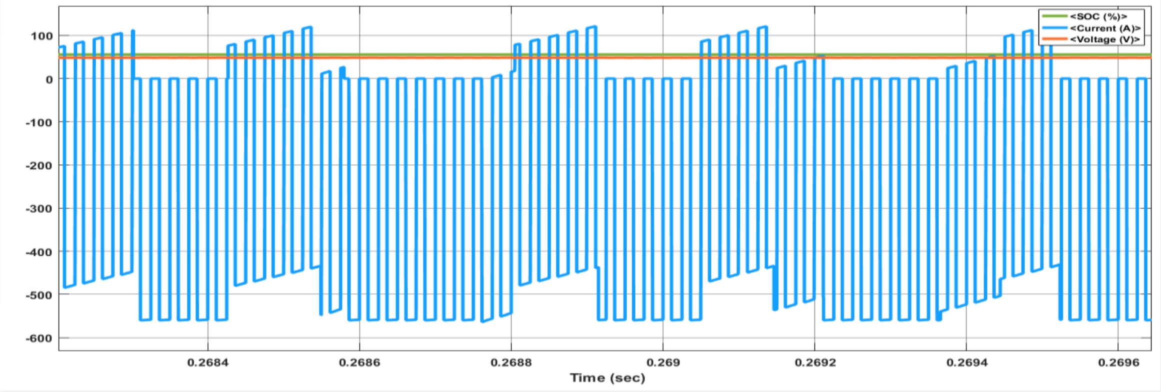


DC Voltage and Current

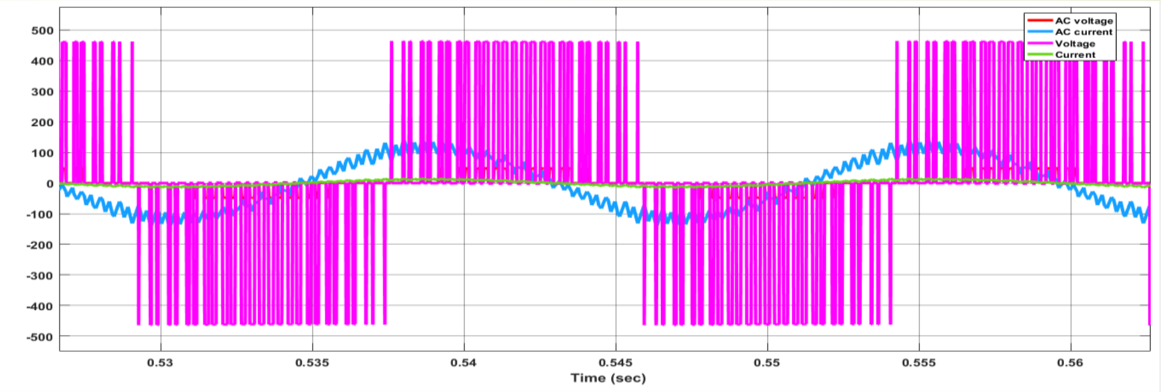


Simulation Result Analysis of Battery-Based System

Battery Storage

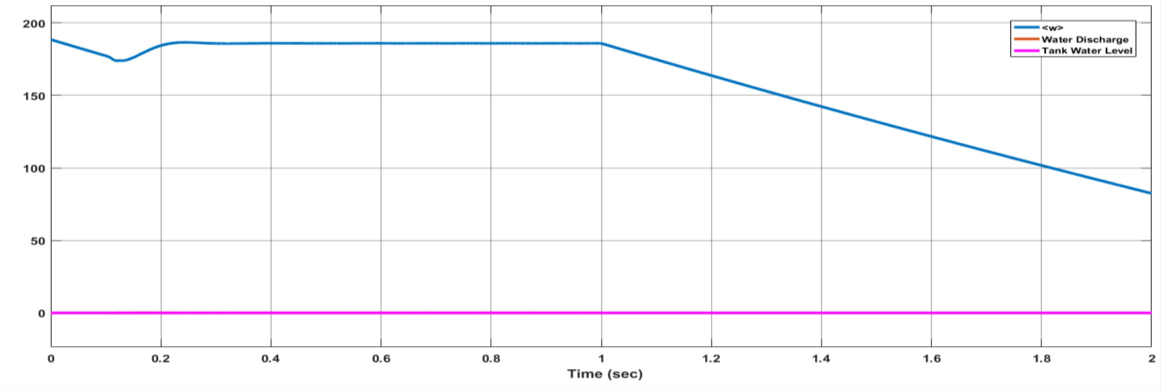


Transformer Inputs and Outputs

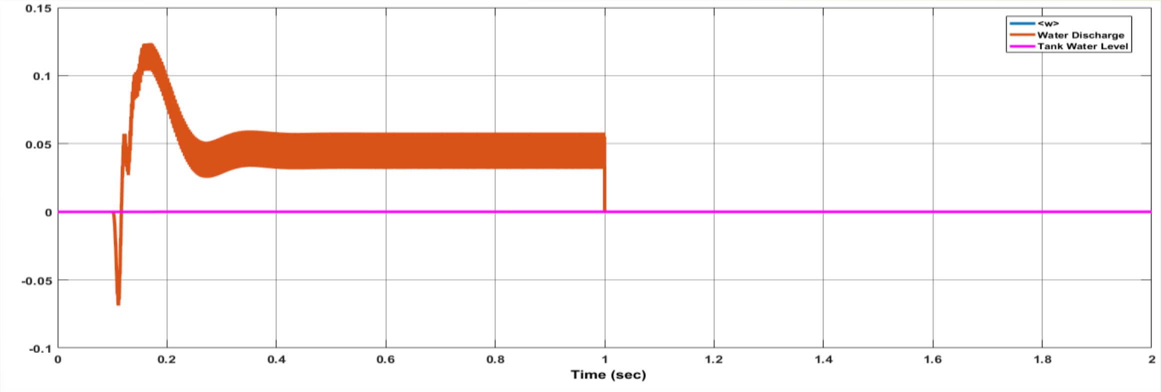


Simulation Result Analysis of Battery-Based System

Rotor Speed



Water Discharge and Tank Water Level



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Simulation Result Analysis of Battery-Based System

Water discharge and tank water level

During five second of operation

- water discharge rate : 0.05 m^3/s or 180 m^3/h
- Tank water level : 4.24 e^{-4} m

After eight hours of operation

- water lifted: 634.4 m^3
- Tank water level : 0.61 m

Excess energy stored as **electrical** form in **battery storage**

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Modelling of Proposed System

- Combined storage system
- Configuration almost same as battery based system except the energy storage

Battery storage : 1400 Ah
Water tank Storage : 660 m^3

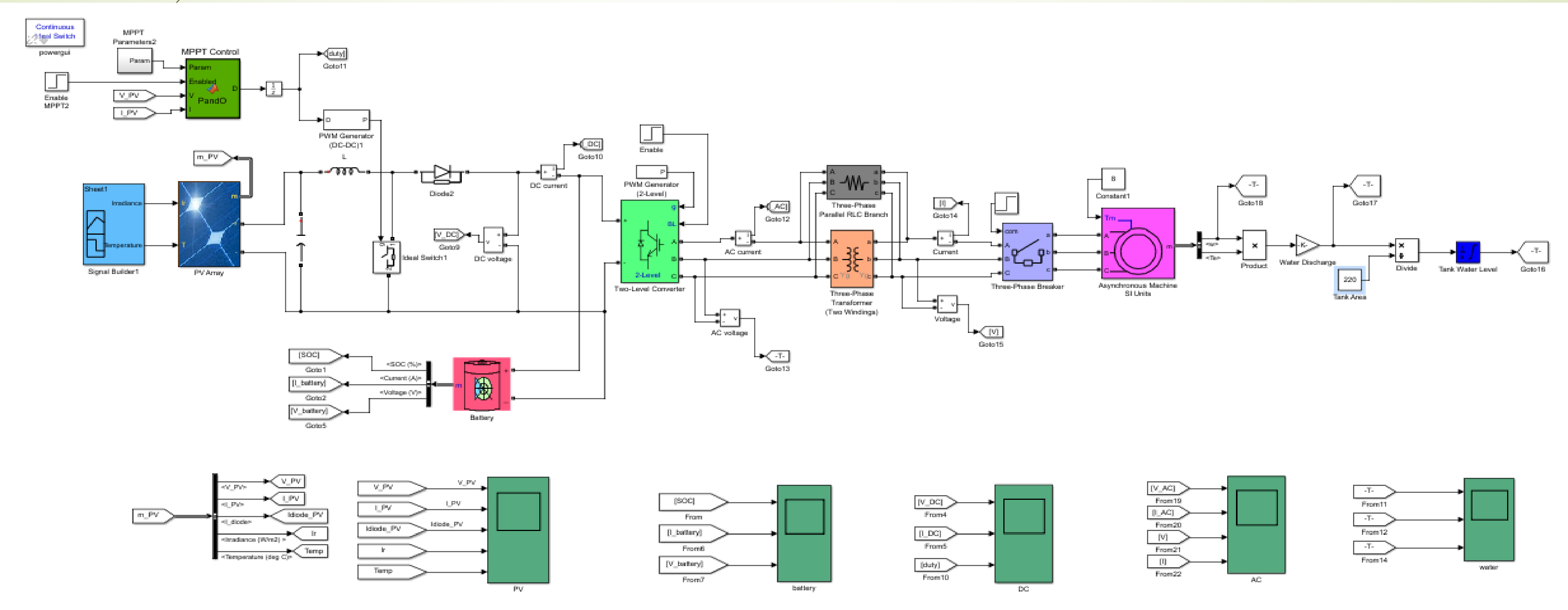
Advantages:

- User has both energy storage in electrical form and stored water in a water tank for later use
- If any fault occurs in the system, the user can handle the emergency with back-up stored water

Proposed system may give the most feasible solution

DYNAMIC MODELING AND SIMULATION IN SIMULINK

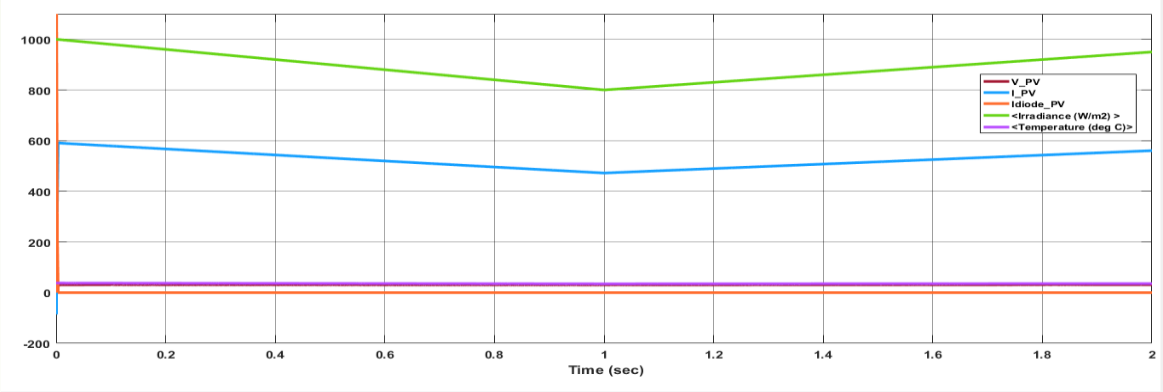
Modelling of Proposed System



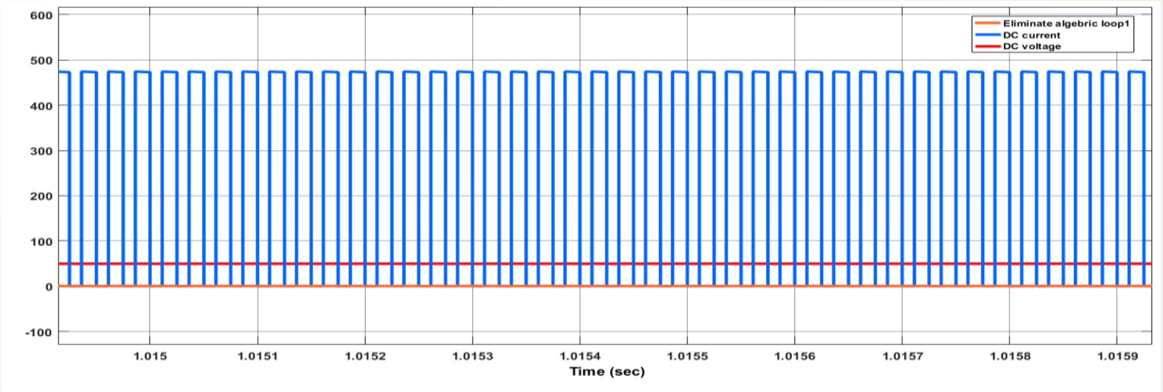
DYNAMIC MODELING AND SIMULATION IN SIMULINK

Simulation Result Analysis of Proposed System

PV Properties



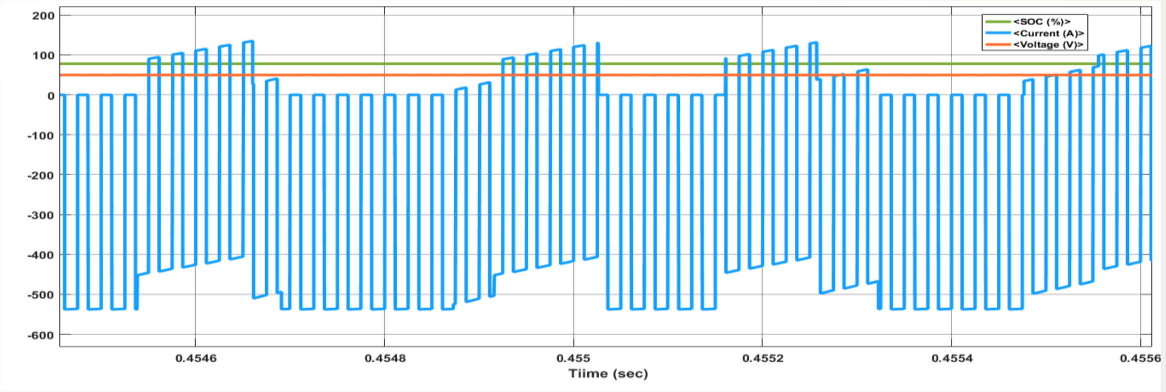
DC Voltage and Current



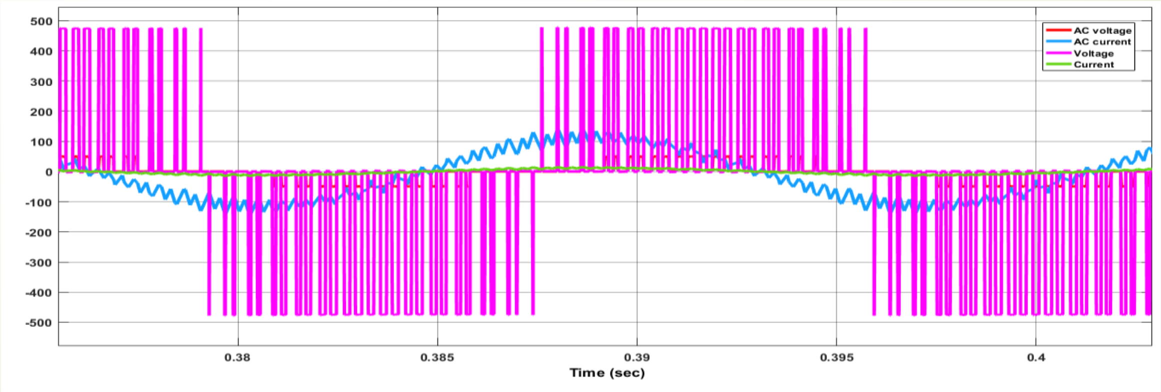
DYNAMIC MODELING AND SIMULATION IN SIMULINK

Simulation Result Analysis of Proposed System

Battery Storage



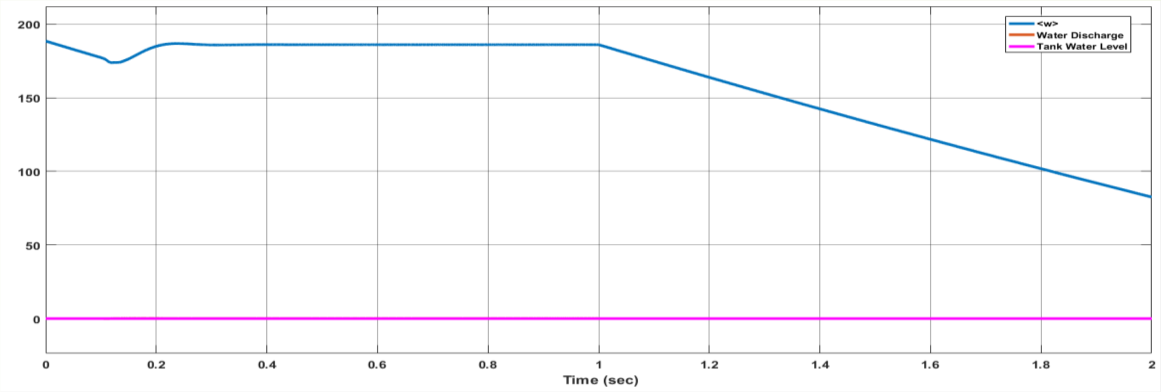
Transformer Inputs and outputs



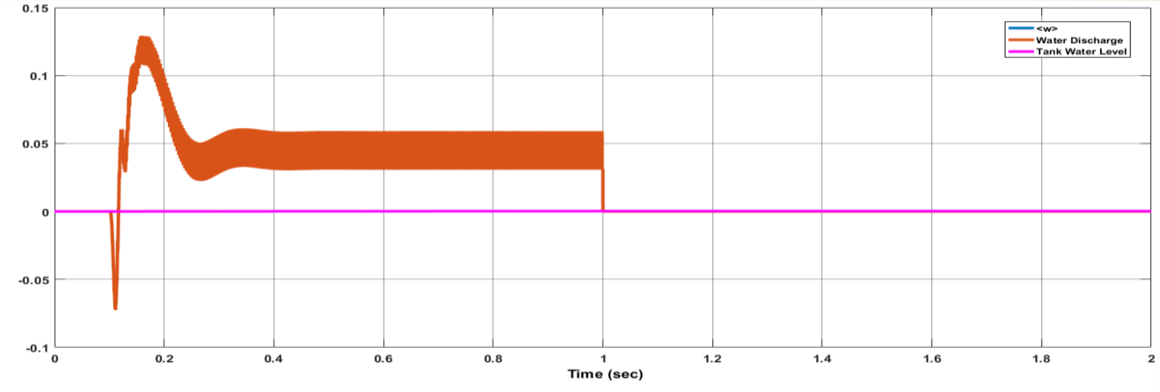
DYNAMIC MODELING AND SIMULATION IN SIMULINK

Simulation Result Analysis of Proposed System

Rotor Speed



Water Discharge and Tank Water Level



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Simulation Result Analysis of Proposed System

Water discharge and tank water level

During five second of operation

- water discharge rate : 0.05 m^3/s or 180 m^3/h
- Tank water level : 2.00826 e^{-4} m

After eight hours of operation

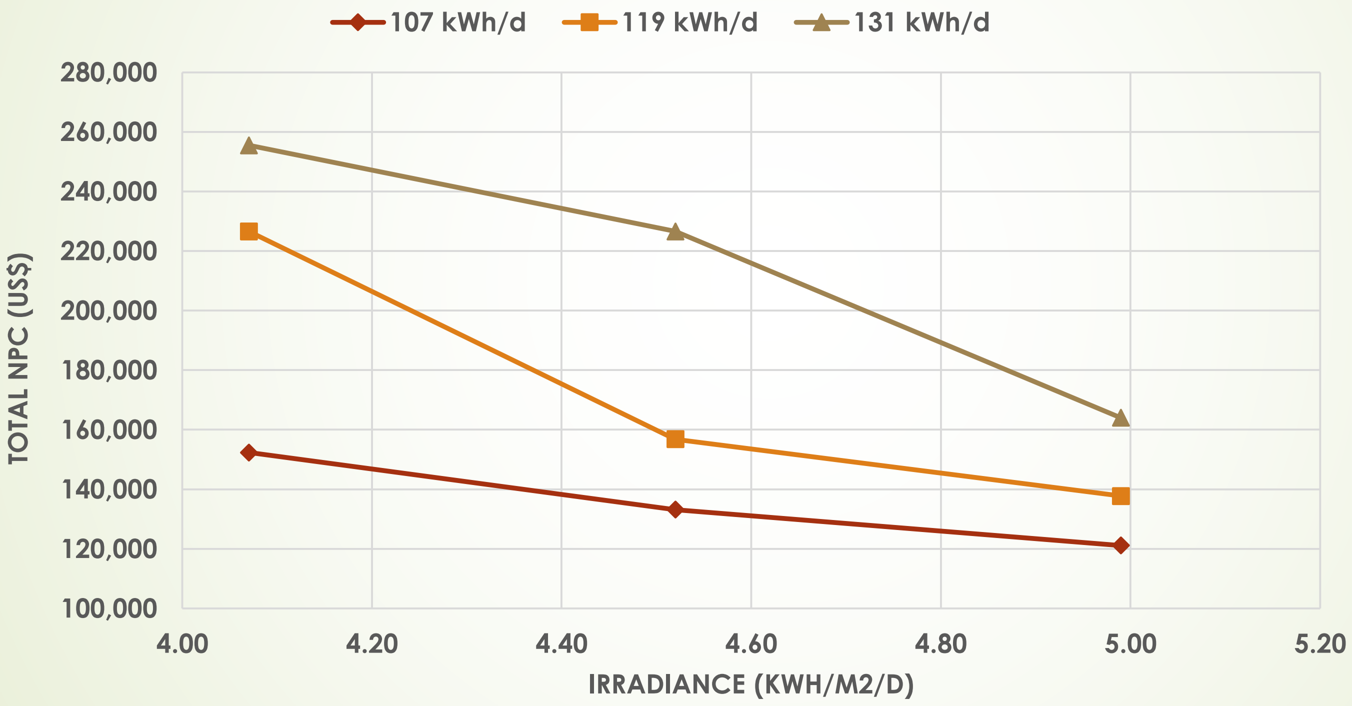
- water lifted: 635.8 m^3
- Tank water level : 2.89 m

Tank is **full** at the end of the day
Excess energy stored as **electrical form** in battery storage

SENSITIVITY AND EFFECTIVENESS ANALYSIS

Sensitivity Analysis

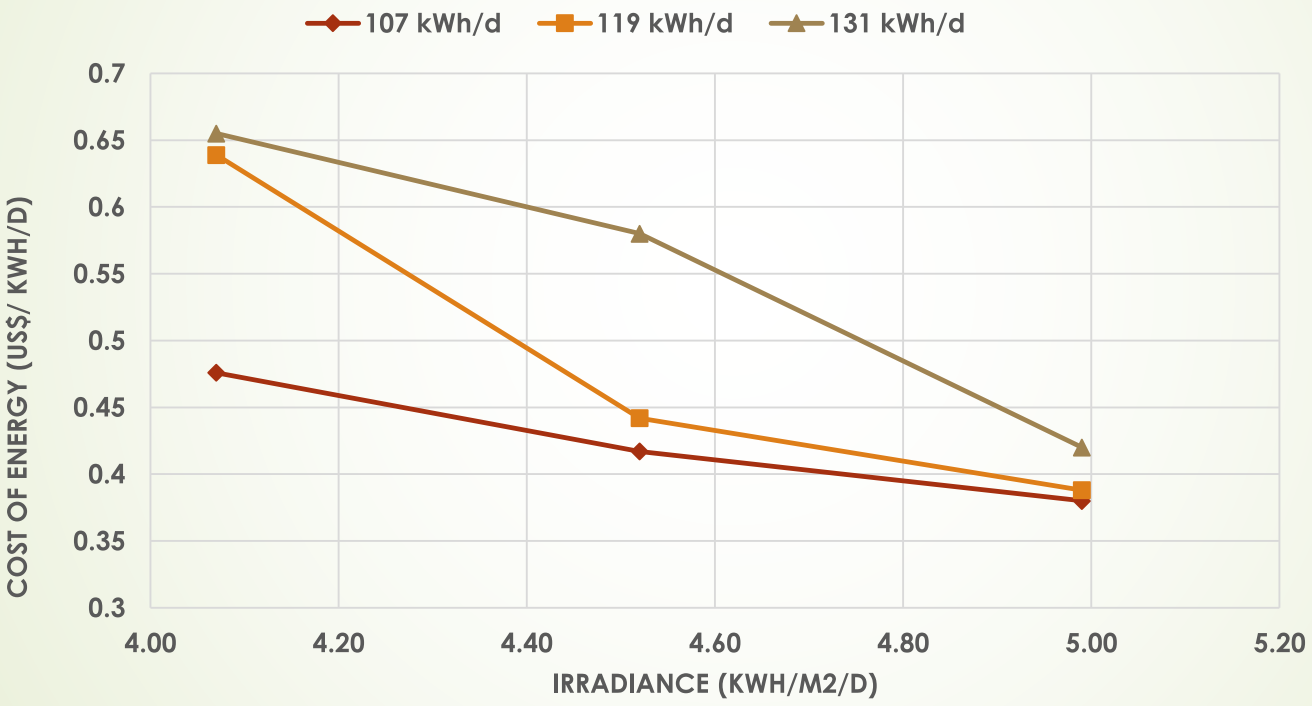
Sensitivity Analysis based on NPC



SENSITIVITY AND EFFECTIVENESS ANALYSIS

Sensitivity Analysis

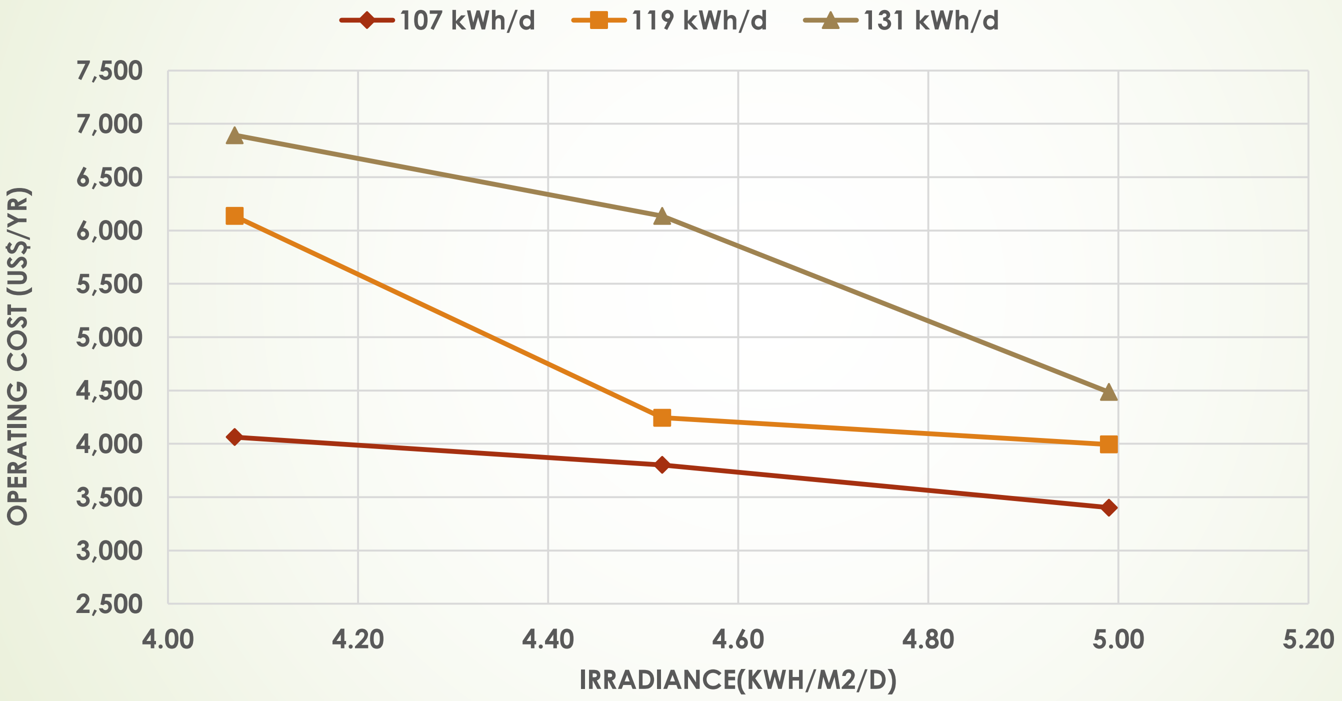
Sensitivity Analysis based on COE



SENSITIVITY AND EFFECTIVENESS ANALYSIS

Sensitivity Analysis

Sensitivity Analysis based on Operating Cost

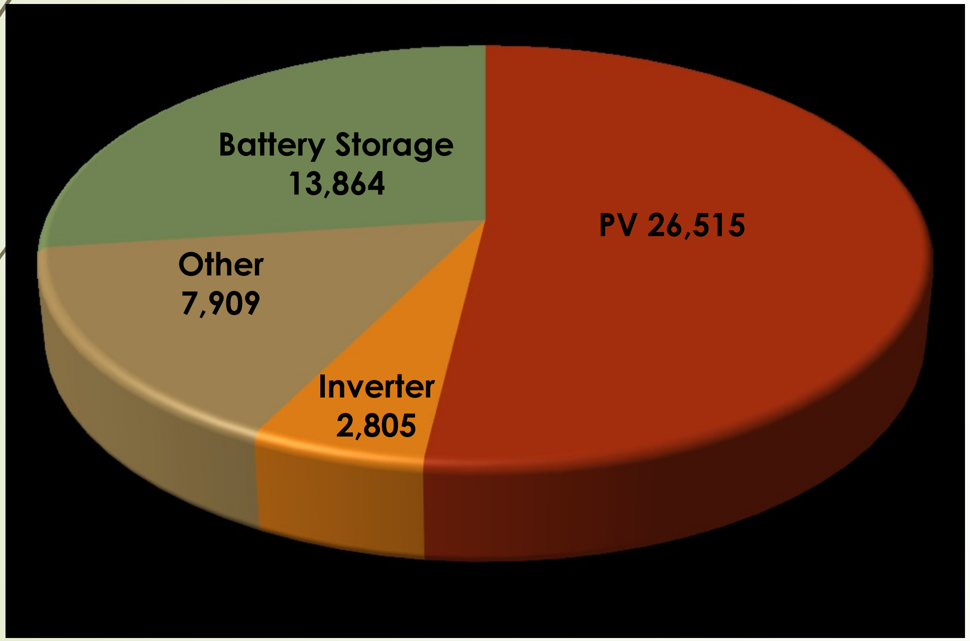


SENSITIVITY AND EFFECTIVENESS ANALYSIS

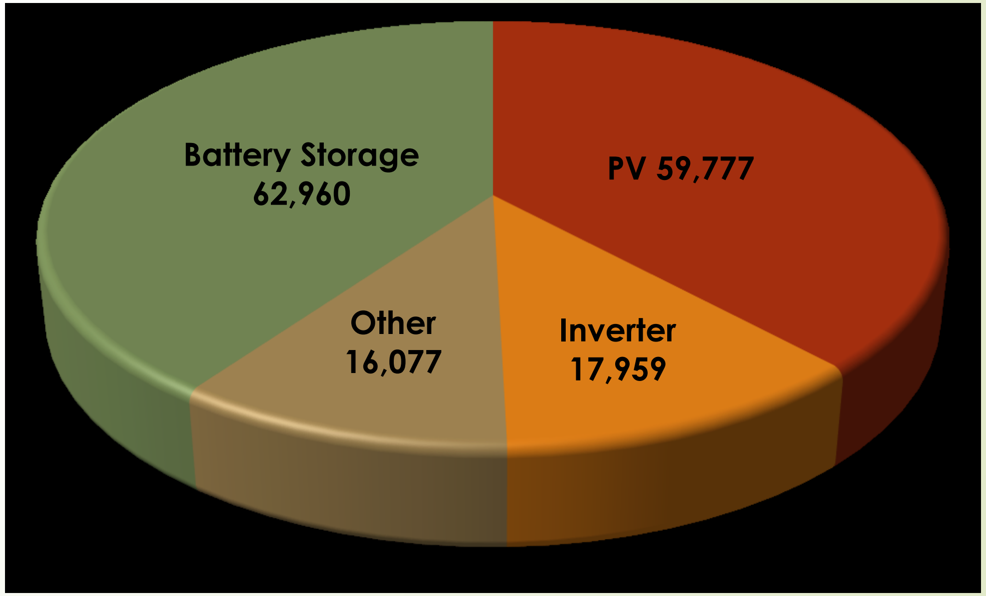
Effectiveness Analysis

Cost Breakdown of Battery Based System

FOR ONE 1 OF PERIOD (US$)



FOR 25 YEARS OF PERIOD (US$)



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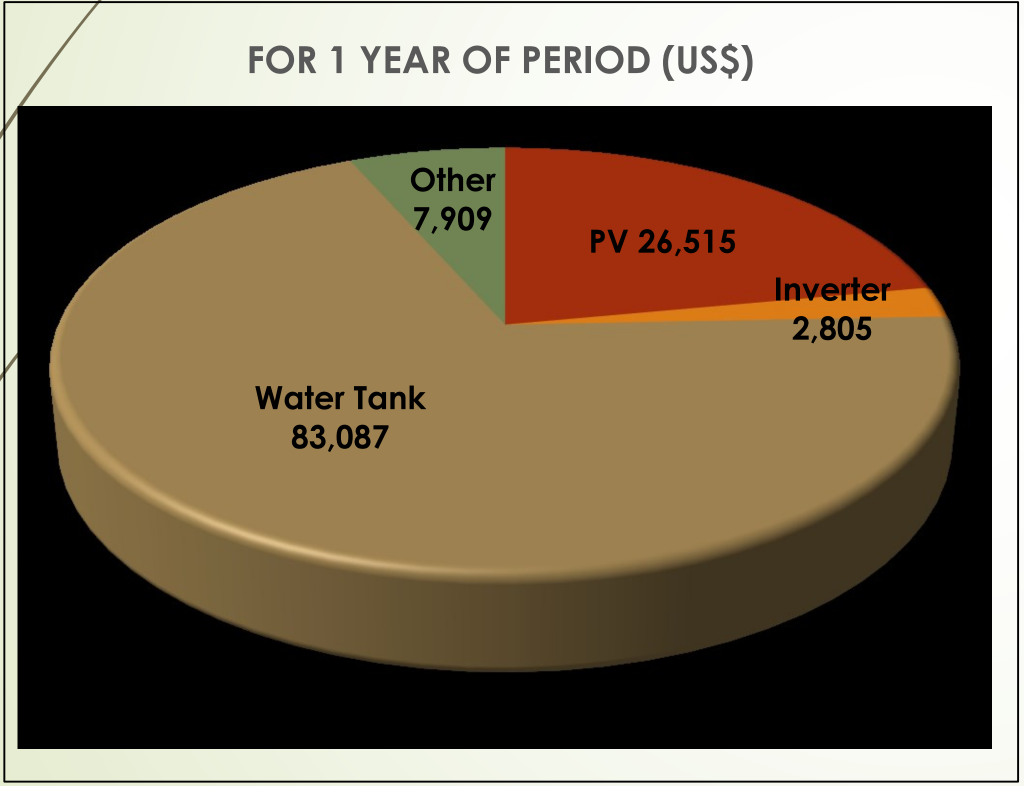
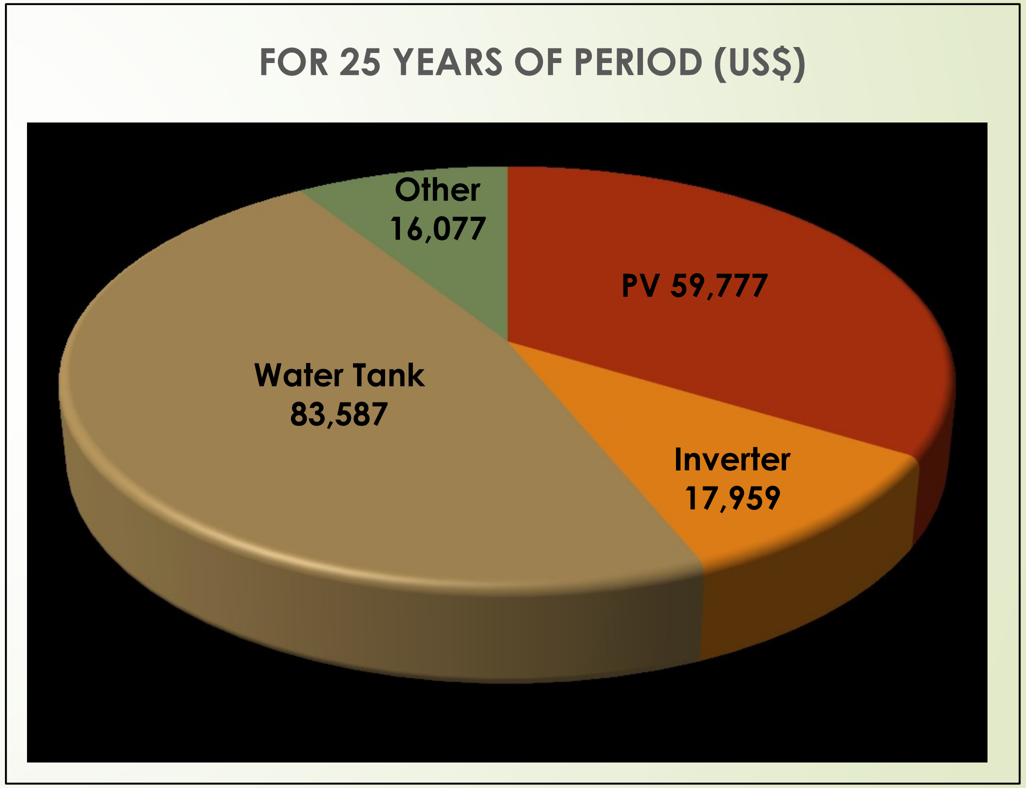
SENSITIVITY AND EFFECTIVENESS ANALYSIS

Effectiveness Analysis

Cost Breakdown of Battery Less System

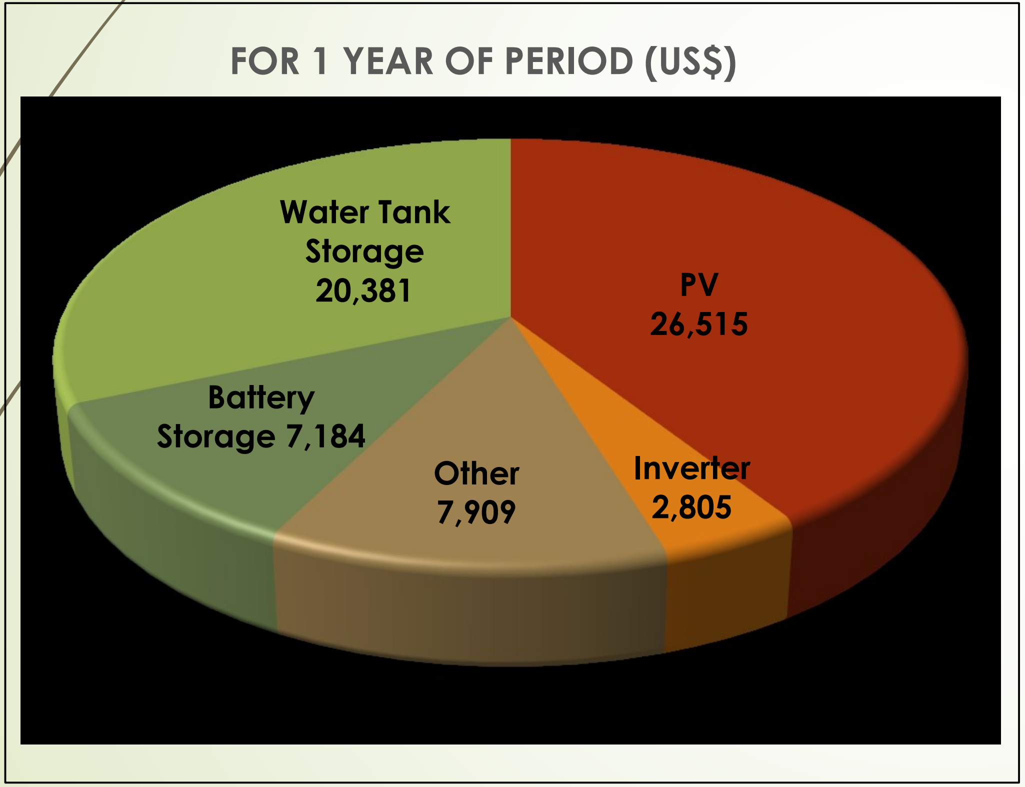


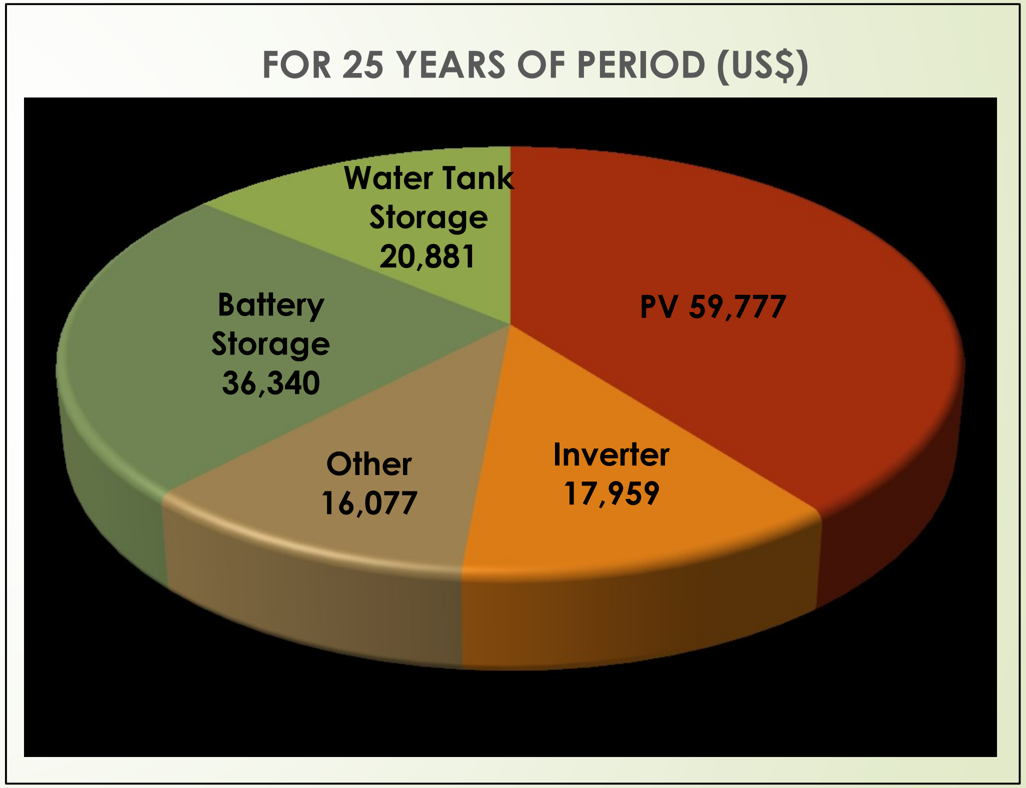


SENSITIVITY AND EFFECTIVENESS ANALYSIS

Effectiveness Analysis

Cost Breakdown of Proposed System





SENSITIVITY AND EFFECTIVENESS ANALYSIS

Conventional Diesel Engine System

Economic Cost Breakdown

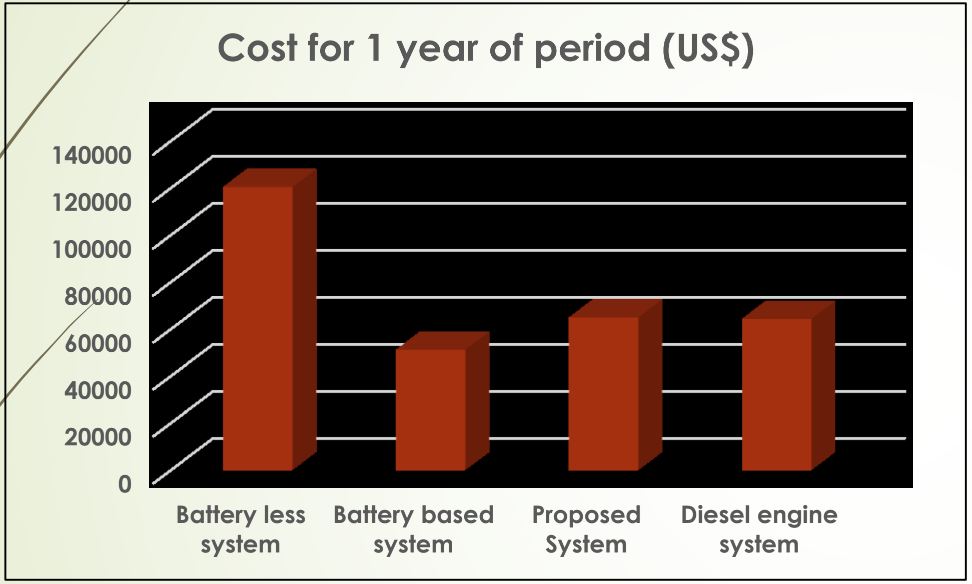
Component	Capital (US$)	Replacement (US$)	O&M (US$)	Fuel ($)	Salvage (US$)	Total ($)
Generator	25,000	58,204	94,377	204,759	-506	381,833
Other	7,000	0	6,464	0	0	13,464
System	32,000	58,204	100,841	204,759	-506	395,298

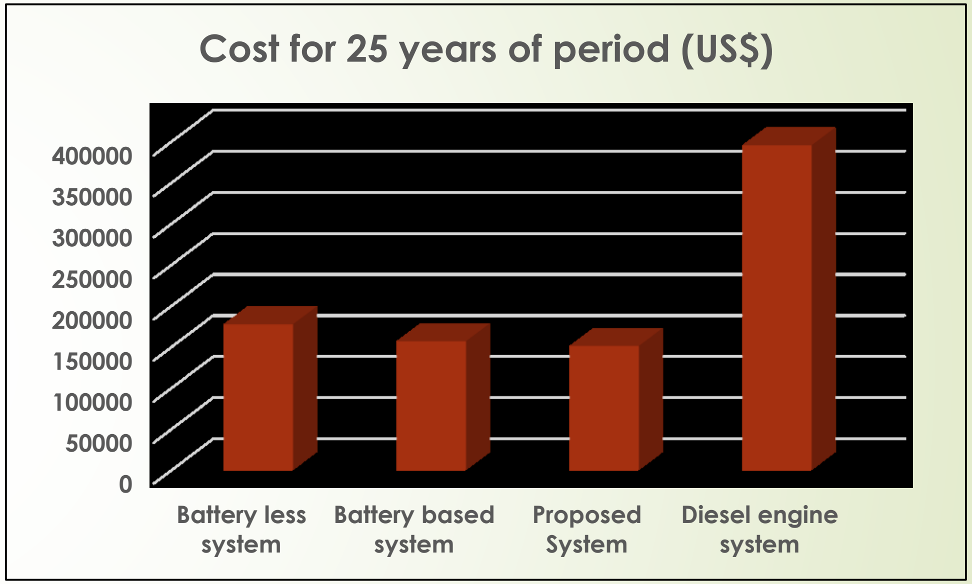
Emission

Pollutant	Emission (kg/yr)
Carbon dioxide	104,267
Carbon monoxide	257
Unburned hydrocarbons	28.5
Particulate matter	19.4
Sulfur dioxide	209
Nitrogen oxides	2,297

SENSITIVITY AND EFFECTIVENESS ANALYSIS

Comparison Between Alternatives





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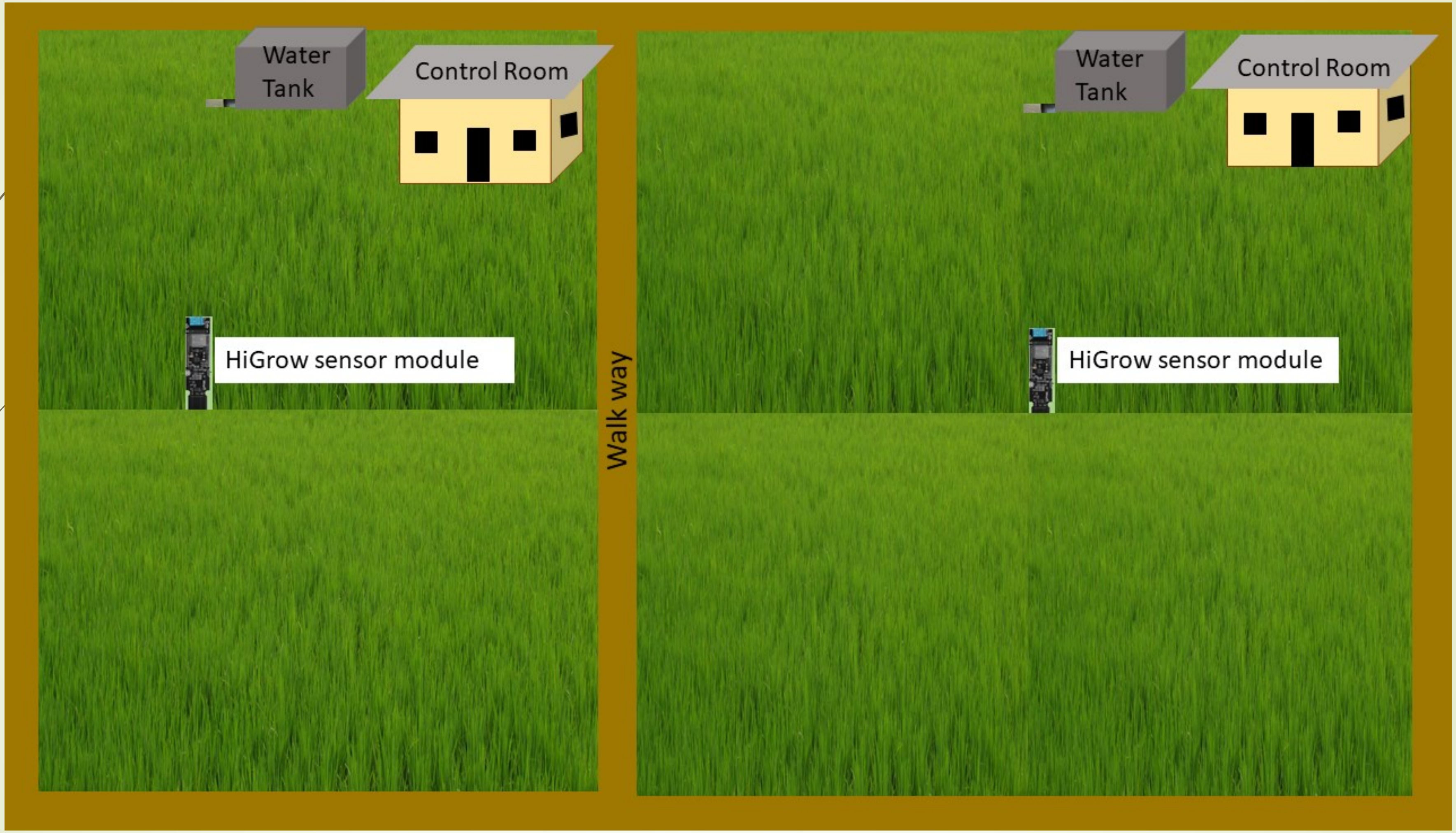
DESIGN OF INSTRUMENTATION AND CONTROL SYSTEM

- Automatic irrigation system can reduce the water wastage
- HiGrow sensor module is an effective solution
- HiGrow sensor module and water level sensors detects the field conditions and sends the information to the microcontroller
- Microcontroller decides when to operate the motor
- User gets the information and able to control the system through webserver
- There is also option for manual operation

DESIGN OF INSTRUMENTATION AND CONTROL SYSTEM



ESP32 : introduced by Espressif System

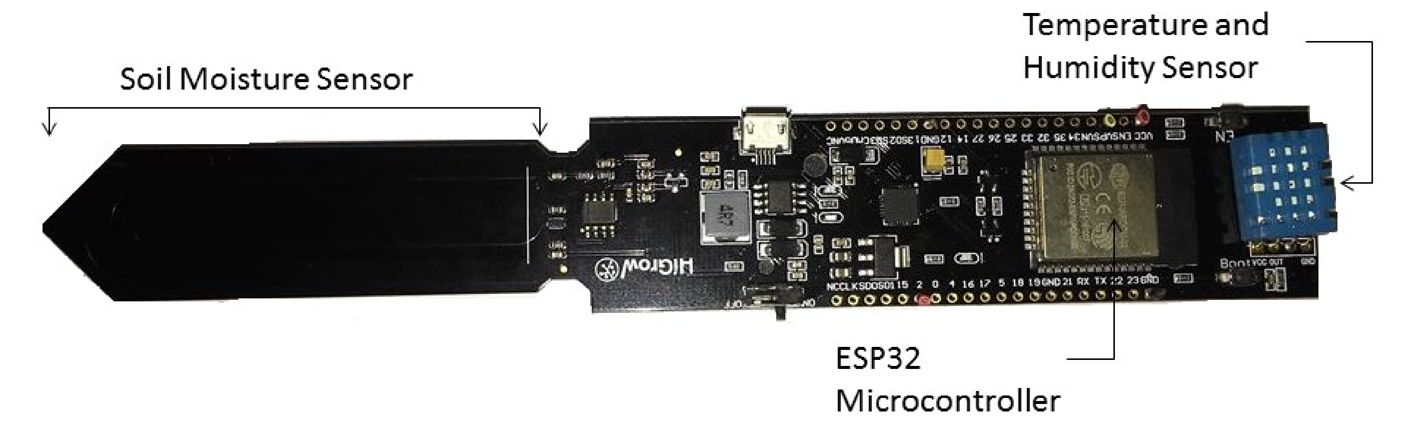
Features:

- Low cost
- Low power system on a chip microcontroller with integrated WiFi
- Dual mode Bluetooth capabilities
- Power saving features
- Compatible with mobile devices and IOT application
- Wide operating temperature range
- Can act as a complete standalone system
- Can be operated as a slave device to a host microcontroller

*IOT: Internet Of Things

DESIGN OF INSTRUMENTATION AND CONTROL SYSTEM

Higrow sensor module : Senses the field condition

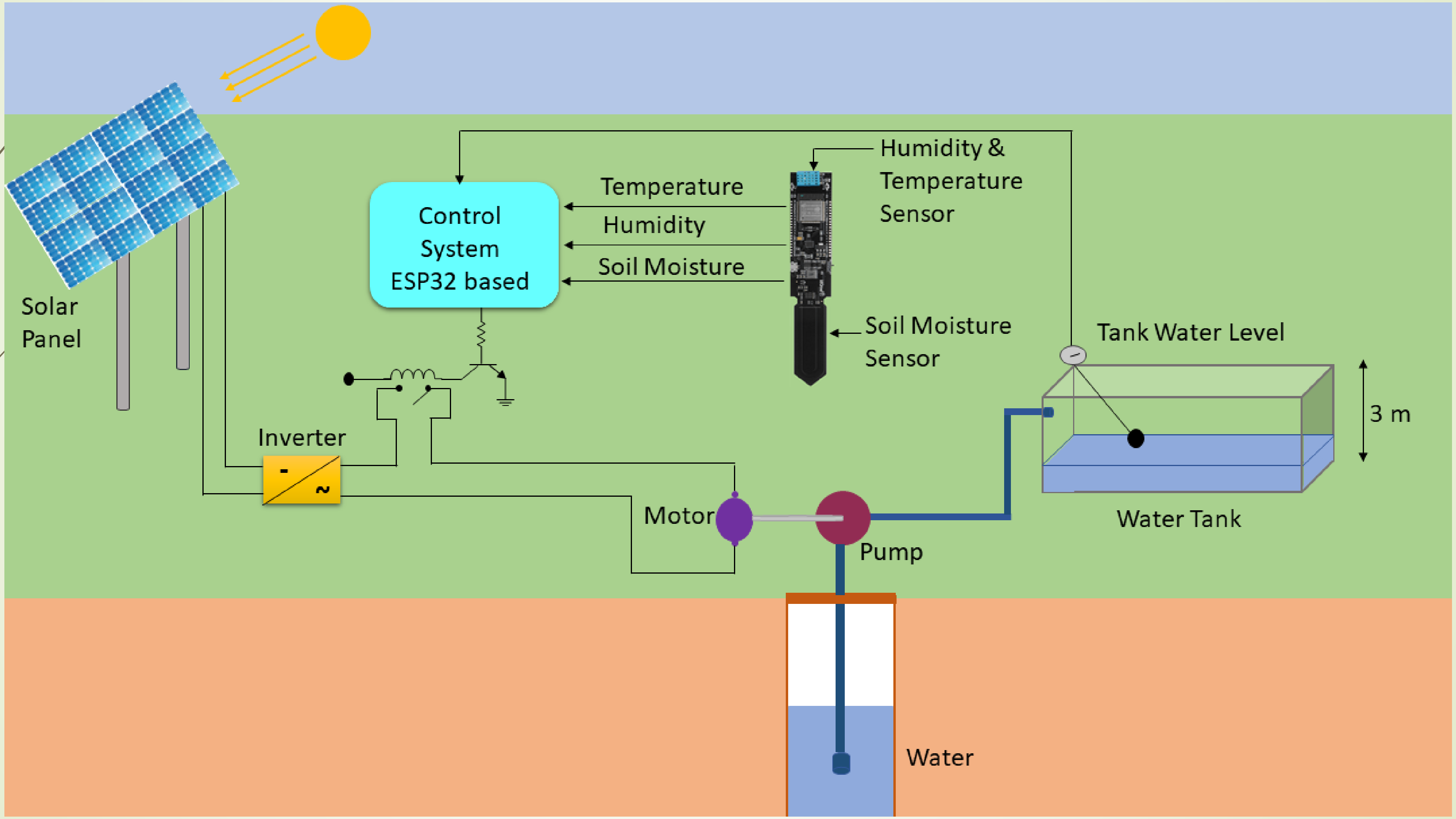


Features:

- Communicates with cloud application to upload sensor data
- Can be connected to the webserver
- Senses temperature and humidity through DHT11 sensor module
- Capacitive type soil moisture sensor detects the water content in the soil
- Run by a LG 3000mAh battery up to 17 hours

DESIGN OF INSTRUMENTATION AND CONTROL SYSTEM

Proposed Control System



Working Principle of proposed control System

❑ ESP32 Microcontroller:

- Gets data from sensor units
- Takes decisions
- Sends output signal to the relay to control the motor-pump

❑ Webserver:

- HiGrow sensor module connects to a webserver
- Client can be connected to the webserver through HTTP
- Returns a web page to the client
- Two HTML buttons control the motor operation

*HTTP : Hyper Text Transfer Protocol
*HTML : Hyper Text Markup Language

Working Principle of proposed control System

❑ Water level Sensor :

- Floating type water level sensor
- Potentiometer reading changes as the water level changes
- Connected to ESP32 and send information about tank water level

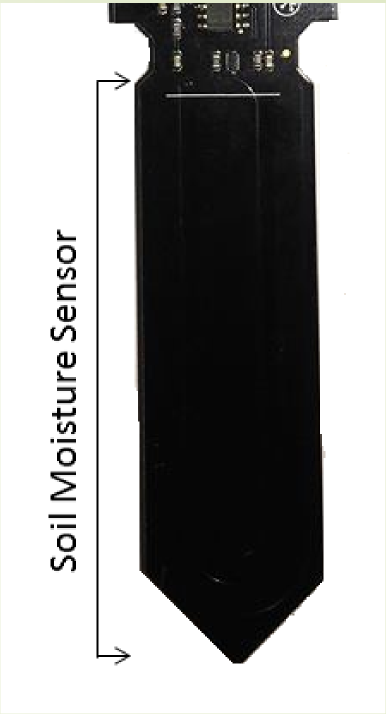
❑ Humidity and Temperature Sensor :

- ESP32 is connected to DHT11 to read the temperature and humidity
- Results are routed to pin 22

Working Principle of proposed control System

❑ Soil Moisture Sensor :

- Capacitor is electrically connected with two small resisters
- As the water touches the sensor, the dialectic constant changes
- As a result the timer runs at different frequency
- The output RC oscillator of the timer generates a stable analog voltage
- This voltage detects the moisture content and routes to pin 32



Working Principle of proposed control System

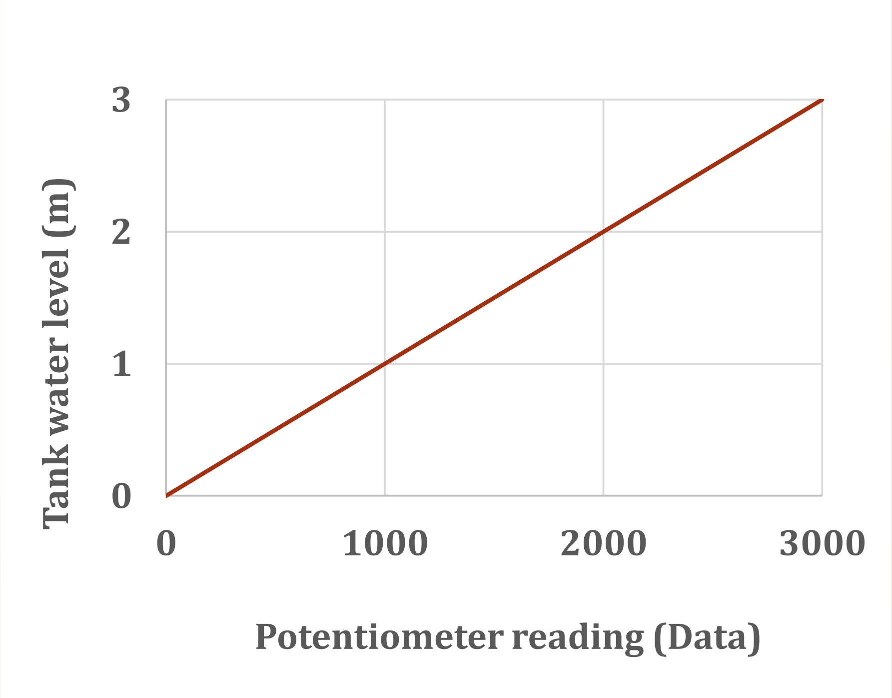
❑ Control Program:

- ESP32 control code refereed as sketch
- The sketch is written in Arduino 1.8.5 environment
- The sketch is uploaded in ESP32 using Arduino software
- A built-in LED; connected to pin 13; represents the motor status
- Field condition and tank water level are being checked continuously
- If the conditions satisfy, the microcontroller takes necessary step

Working Principle of proposed control System

Deciding Tank Water Level

- A 10K potentiometer represents the water level sensor
- Potentiometer reading mapped into tank water level
- Lower limit of the tank : 0 m
- Upper limit of the tank : 3 m
- Lower limit of the potentiometer : 0 ohm
- Upper limit of the potentiometer : 3000 ohm



Working Principle of proposed control System

Deciding Moisture Content limit

- Soil moisture sensor produces output voltage
- An experiment was done for
  - 300 gm engineered soil which had 36.2% moisture content initially
  - Water added to the soil up to 549.6% to make it slurry
  - Output voltage are recorded accordingly

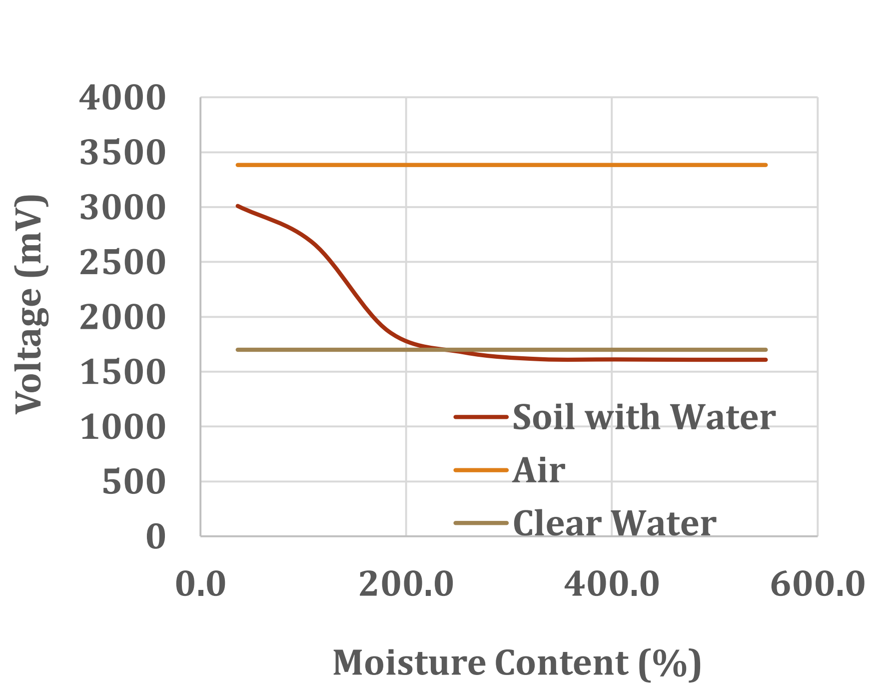
Moisture content of the soil, $\theta = (W_w / W_s) \times 100\%$

where, θ = moisture content,
W_w = mass of the water (g)
W_s = mass of the soil (g)

Working Principle of proposed control System

Deciding Moisture Content limit

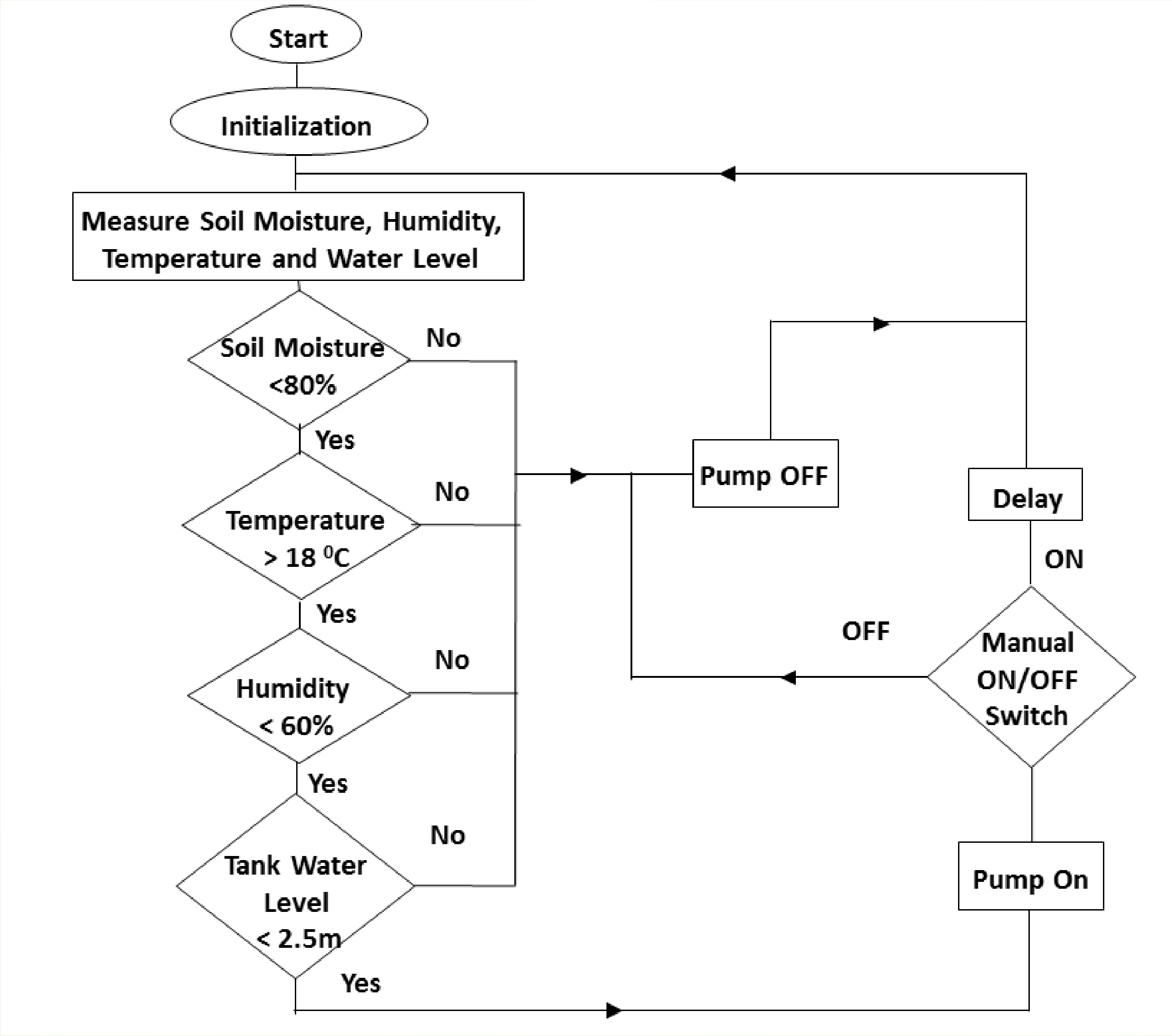
- Output voltage in the air : 3383 mV
- Output voltage in the clear water : 1700 mV
- Lower limit of output voltage in soil : 1572 mV
- Upper limit of output voltage in soil : 3025 mV
- Lower limit of moisture content in soil : 36.2%
- Upper limit of moisture content in soil : 549.6%



After adding more than 200% water, the output voltage of the slurry becomes same as clear water

DESIGN OF INSTRUMENTATION AND CONTROL SYSTEM

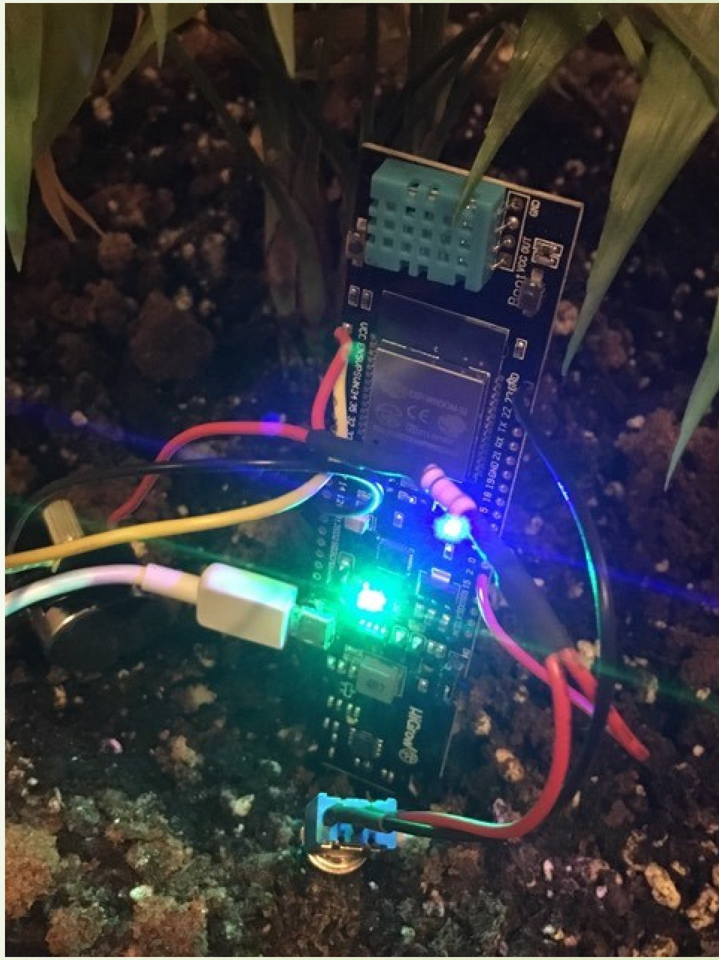
Flow Chart of The Proposed Control System



Experimental Results

Testing

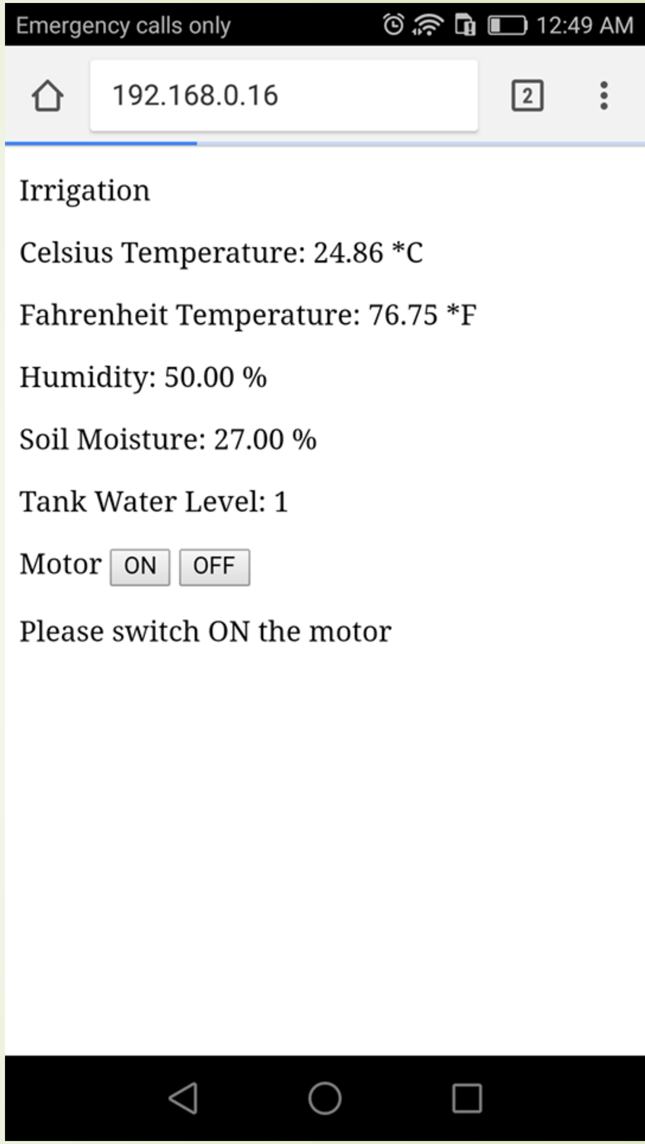
- Programmed HiGrow sensor module inserted into dry soil.
- Powered from a USB port which was connected to a laptop
- The IP address was printed on serial monitor of Arduino software
- IP address navigates to the webserver through any browser
- Status of dry soil was checked
- Some water was added to the soil
- Status of wet soil was checked



Experimental Results

Webserver Page When Soil is Dry

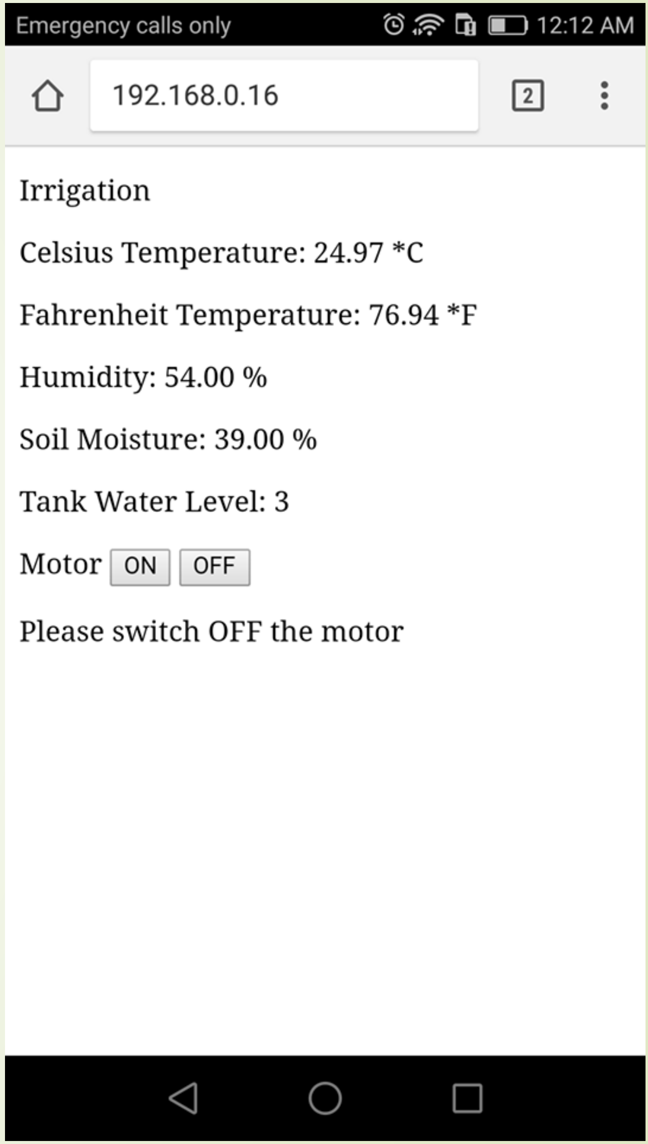
- Webserver page shows the temperature, humidity, soil moisture content and tank water level before adding water
- User can control the motor operation by pressing the HTML buttons
- Webserver page is requesting the user to run the motor
- If the user is unavailable, the motor will start running automatically after some delay (5 min)



Experimental Results

Webserver Page When Soil is Wet

- Webserver page shows the temperature, humidity, soil moisture content and tank water level after adding water
- User can control the motor operation by pressing the HTML buttons
- Webserver page is requesting the user to stop the motor
- If the user is unavailable, the motor will stop running automatically after some delay (5 min)



CONCUSIONS

- The immensely low cost automated solar irrigation pumping system is affordable for the marginal farmers in developing countries
- The system is time saving and ensures lowest water wastage
- Homer optimization provides a feasible solution for battery based solar PV system for the selected site
- Manual calculation for water tank equivalent to battery storage was done for battery less system
- Dynamic modelling in Simulink was done for : (i) battery-less system, (ii) battery-based system and (iii) proposed system

CONCUSIONS

- Dynamic modeling provides the dynamic behaviors of the system components
- Dynamic modeling also provides the water discharge rate and the tank water level at the end of the day
- For the longer operational period, the diesel operated engine is the costliest solution and the combined storage system is the most economical solution
- For lowest load demand, Costs (NPC, COE and operational cost) and irradiance have a negative relationship

CONCUSIONS

- The HiGrow sensor module is extremely cheaper than other PLC devices or commercial controller for water pumping system
- The capacitive soil moisture sensor is advantageous over resistive sensors
- It is highly recommended to test the soil moisture limits and boundary conditions for temperature and humidity before installation of the system
- The proposed control system is more convenient as the user can control the whole operation far from the field

RECOMMENDATIONS FOR FUTURE WORK

- Control strategy for larger field area with multiple scattered sensor is recommended
- Better user interface in local language and with more features
- Longer duration dynamic simulation

LIST OF PUBLICATIONS

- Shatadru Biswas, M. Tariq Iqbal, “Sizing and dynamic modeling of solar water pumping system for irrigation in Bangladesh” 2016 Newfoundland Electrical and Computer Engineering Conference, St. John’s, Canada, NL, 2016
- Shatadru Biswas, M. Tariq Iqbal, “Dynamic modeling of solar water pumping system with energy storage” 2017 Newfoundland Electrical and Computer Engineering Conference, St. John’s, Canada, NL, 2017
- Shatadru Biswas, M. Tariq Iqbal, “Dynamic modeling of solar water pumping system with energy storage” Hindawi Journal of Solar Energy. Volume 2018, Article ID 8471715, 2018
- Shatadru Biswas, M. Tariq Iqbal, “ Solar water pumping system control using a low cost ESP32 microcontroller”, 31 Canadian Conference on Electrical and Computer Engineering, Quebec City, Quebec, Canada, 2018

Thank You

Any Question?