MEMORIAL UNIVERSITY

Design and Control of a Solar Water Pumping System with Battery Storage and Backup Diesel Generation for a Remote Farm in Pakistan

Design, Optimization, and Control for Net-Zero Irrigation Infrastructure in Rural Pakistan

Presented by: Muhammad Umair Shabbir

Supervisor: M. Tariq Iqbal

Memorial University of Newfoundland, Faculty of Engineering | January 2026

MEMORIAL UNIVERSITY

Presentation Overview and Learning Objectives

1 Presentation Flow

- Introduction to Problem and Context
- System Design and Optimization Approaches
- Technical Implementation and Results

2 What You Will Learn

- Understanding challenges in remote agricultural irrigation
- Comparing three renewable energy system designs
- Evaluating economic and environmental benefits
- Learning advanced control strategies for solar systems
- Exploring implementation feasibility in Pakistan

Agricultural Energy Challenge in Pakistan

Current Energy Landscape

- Agriculture sector consumes 60% of freshwater resources
- Diesel-based irrigation dominates rural areas
- Fuel prices rising annually
- Limited grid connectivity in remote regions

Key Problem Statement

- Khushab District receives 5.5 kWh/m²/day solar potential
- Farmers face unreliable fuel supplies
- Operational costs burden small-scale farmers
- Environmental degradation from diesel emissions

Solar Resource Assessment at Kufri Site

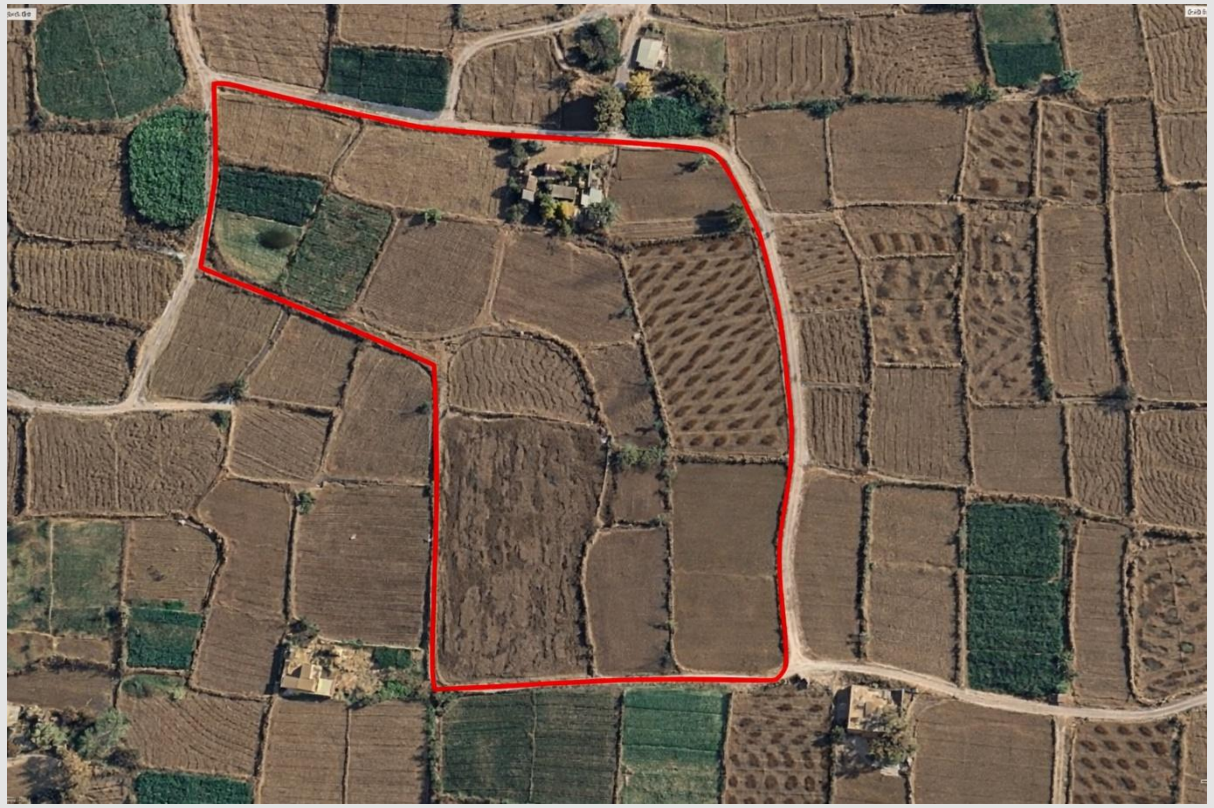


Figure 1: Kufri Site (Source Google Map)

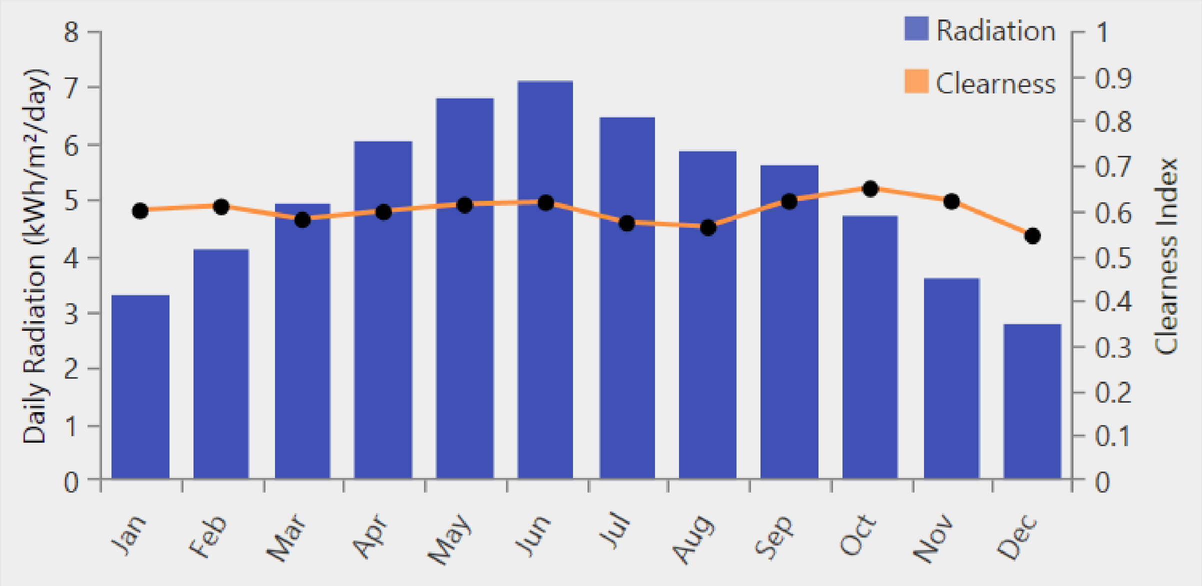


Figure 2: Kufri Site Irradiance (Source HOMER Pro)

Location Details

Kufri, Khushab, Pakistan (32°32.8'N, 72°5.5'E) in remote rural area with no grid connectivity.

Solar Irradiance Data

Average daily solar irradiance: 5.61 kWh/m²/day, Peak Sun Hours (PSH): ~6 hours/day. Monthly breakdown: Peak in May-June (~7.0 kWh/m²/day), minimum in December-January (~3.0-3.5 kWh/m²/day).

Climate Condition

Semi-arid climate with favorable solar conditions.

System Implication

This solar resource assessment validates the viability of solar water pumping systems and determines the optimal 6-hour pumping window from 10:00 AM to 4:00 PM when solar irradiance is at peak levels.

Project Site Profile: Kufri, Khushab, Pakistan

System Specifications

Farm Characteristics

- Farmland Area: 30,000 m^2
- Topography: Rural location
- Accessibility: Remote location

Irrigation Requirements

- Daily Water Demand: 137 m^3
- Total Dynamic Head: 47 meters
- Seasonal Variation: Yes

Resource Availability

- Solar GHI: 5.5 $kWh/m^2/day$
- Temperature Range: 0–42°C
- Grid Access: Limited

System Requirements and Design Constraints

Engineering Parameters

Technical Constraints

- Water delivery must meet daily demand consistently
- System must operate year-round
- Performance under variable solar irradiance
- Motor efficiency above 85%

Operational Constraints

- Remote location operation without operator
- Autonomous control systems needed
- Simplified maintenance procedures
- Weather resilience required

S	W
T	O

Economic Constraints

- Initial capital investment limited
- 20-year system lifespan target
- Maintenance accessibility critical
- Cost-competitiveness with diesel baseline

Environmental Constraints

- Zero net carbon emissions required
- Minimal environmental footprint
- Water conservation essential
- Sustainable resource management

Literature Review: Solar Water Pumping Landscape

State of Technology and Practice

1 Traditional

Diesel-only systems dominate, high fuel costs, consistent operation. Marked the baseline for water pumping technology with reliable but expensive energy solutions.

2 Early Solar

Small PV pilot projects, limited scalability, intermittency issues. Represented the first attempts at renewable energy integration with significant technical challenges.

3 Hybrid Approach

PV with backup generators, improved reliability, emerging solutions. Showed the transition phase where solar began complementing traditional systems.

4 Battery Integration

Battery-backed systems, improved autonomy, cost declining. Demonstrated technological maturity with energy storage enabling more consistent solar operation.

5 Current State

Multi-solution approaches, optimization tools available, net-zero feasible. Represents the modern landscape where integrated smart systems achieve sustainable water pumping.

Research Objectives and Methodology

Comprehensive System Evaluation

Objective 1 (Design Optimization)

Design and optimize three distinct solar-based pumping configurations for Kufri farm using industry-standard tools (HOMER Pro and LORENTZ Compass).

Objective 2 (Dynamic Modeling)

Develop detailed MATLAB/Simulink models to evaluate real-time performance under varying solar conditions and load requirements.

Objective 3 (Economic-Environmental Assessment)

Compare system costs, environmental impact, and operational feasibility across all three configurations.

Methodology: Comparative techno-economic analysis using simulation tools and field-validated parameters.

Homer Pro Based Solar System: Architecture Overview

1

PV Array Block

8.75 kW Canadian Solar 345CS6U modules, mounted on ground structure (arranged in 2 parallel strings of 13 modules each), daily output 42.8 kWh

2

Battery Bank

24 Trojan SPRE 12-225 batteries (48V system), configured as 6 parallel strings of 4 batteries in series

3

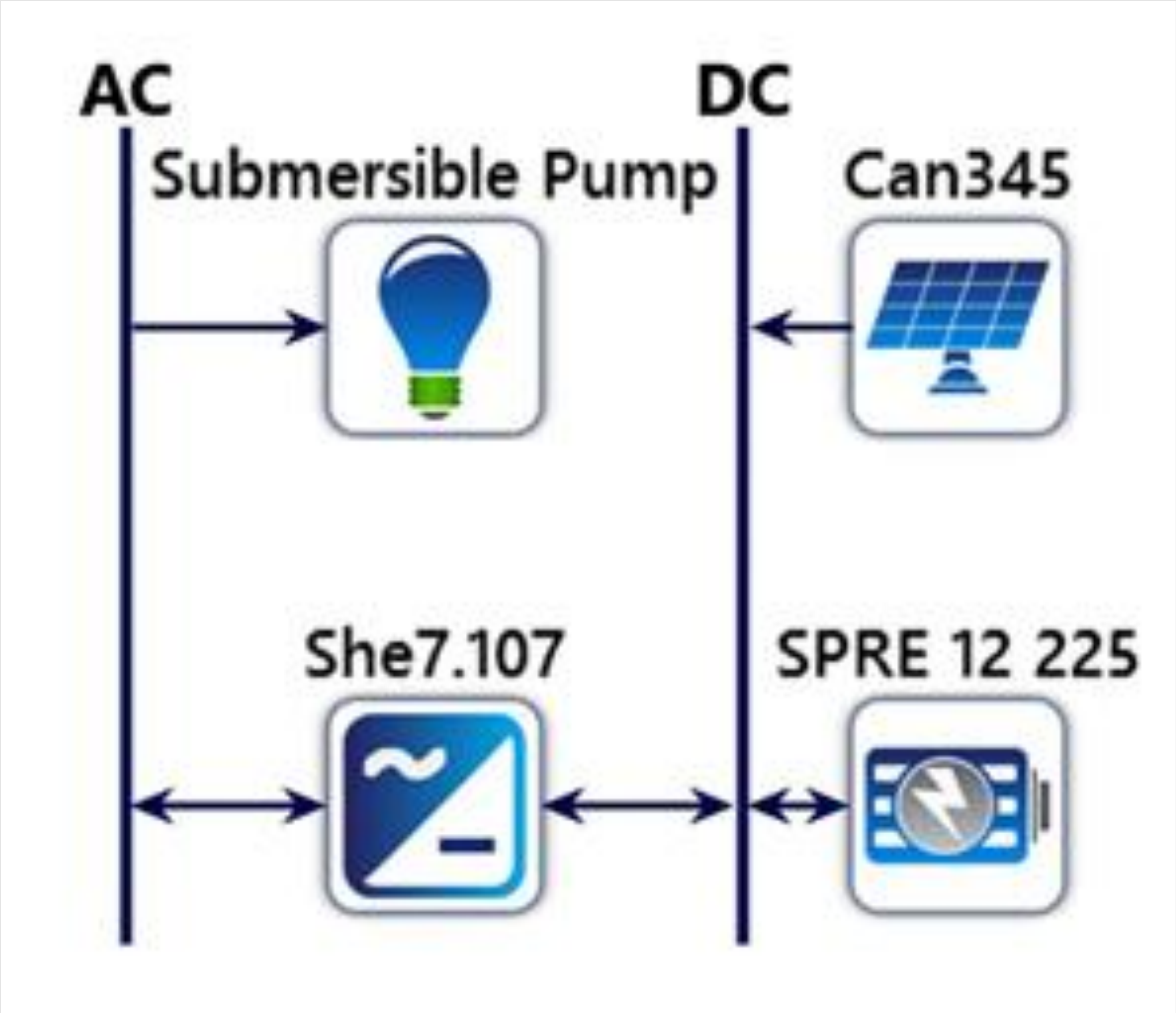
Pump System

7.5 HP induction motor, submersible design, rated for continuous operation

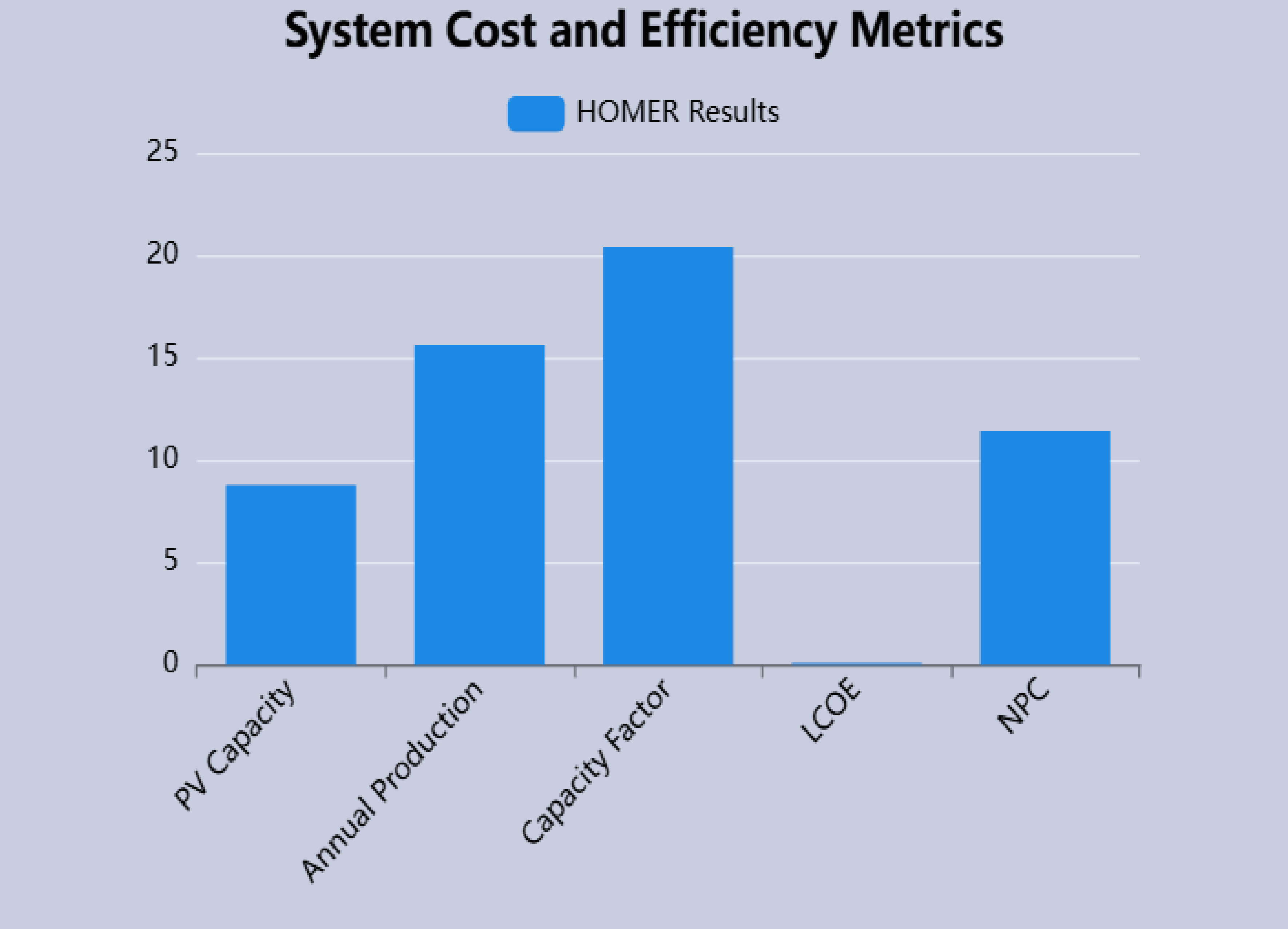
4

Inverter

7.11 kW Growatt 8000MTLP-US, 208V three-phase output, AC conversion



HOMER Pro Performance Results



Environmental Impact

Zero carbon emissions and 100% renewable operation achieved through optimal battery-based system design for continuous irrigation.

Economic Efficiency

Net Present Cost of $11,438.85 with levelized cost of energy at $0.0740/kWh demonstrates cost-effective long-term operation.

MEMORIAL UNIVERSITY

HOMER Pro Optimization Results: Winning System

Techno-Economic Analysis and System Sizing

System Economics

Net Present Cost: $11,438.85

Levelized Cost of Energy: $0.074/kWh

Operating cost per year: $531.18

Payback period: 12 years

40% cheaper than diesel baseline

Energy Performance

Zero fuel consumption annually

100% renewable operation achieved

Zero carbon emissions

Grid-independent operation

Excess production available: 18% annually

Reliability Metrics

99.8% load serving capacity

Unmet load less than: 0.5 kWh/year

Annual shortage incidents minimized

Stable output maintained year-round

Alternative Approach: Water Tank Storage System by LORENTZ Compass

System Concept

Removes battery requirement entirely, PV array directly drives submersible pump, Gravity provide water pressure naturally, simple passive storage method

Water Tank Storage Approach

LORENTZ Compass utilizes water tank energy storage instead of batteries, storing energy directly as water volume for cost-effective and sustainable agricultural irrigation in remote areas.

Solar Array Configuration

8.8 kW system comprising 16 Longi LR5-72HPH-555M modules totaling 8,880 Wp for high-efficiency photovoltaic energy conversion.

Pump Specifications

LORENTZ PSk3-7 C-SJ17-9 submersible pump with 5.88 kW rating and integrated Data Module controller for automated water output management.

System Integration

Smart Start, Surge Protector, Float Switch, and PV Disconnect accessories ensure safe, efficient, and reliable autonomous pump operation.

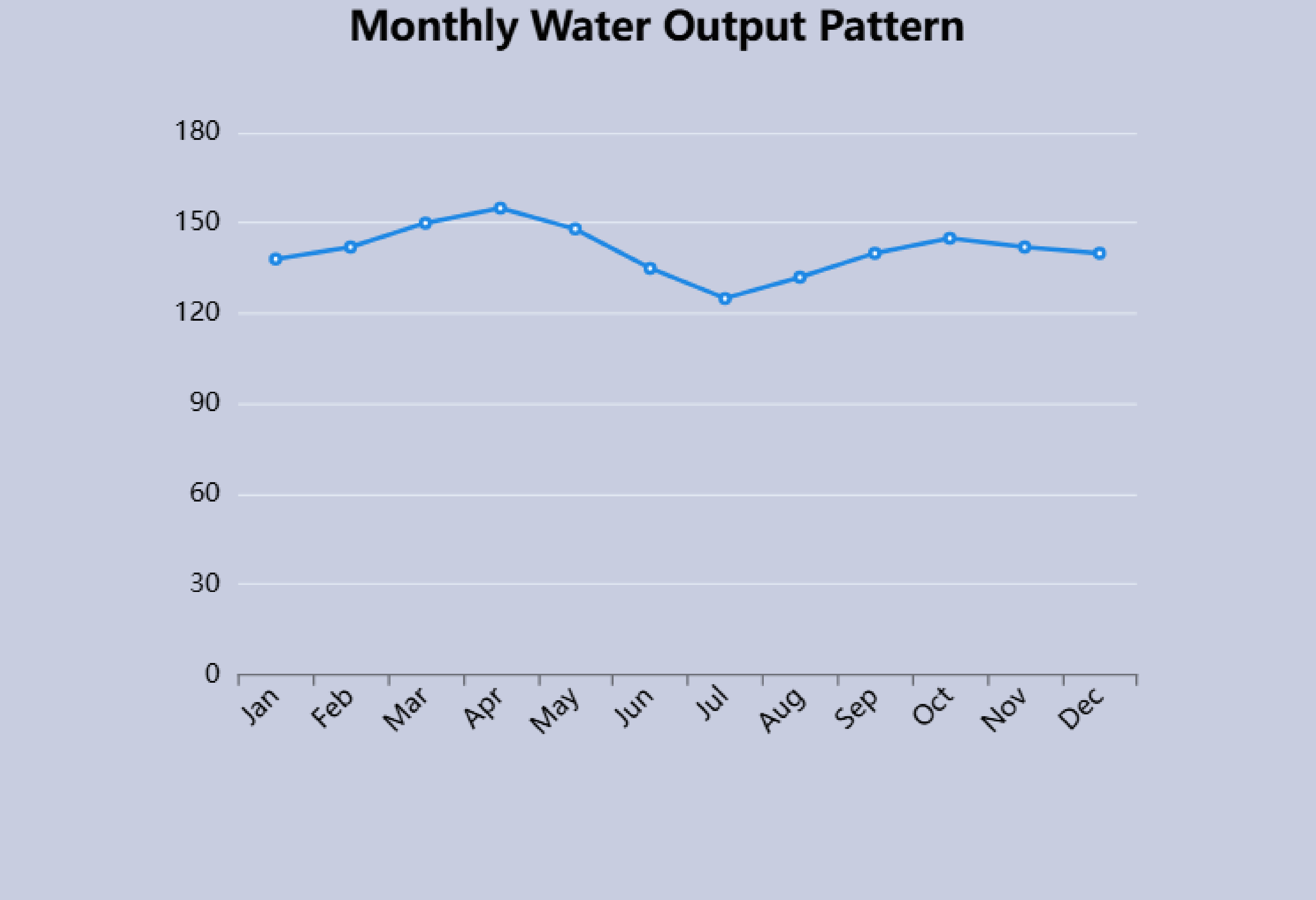
LORENTZ Monthly Water Output Analysis

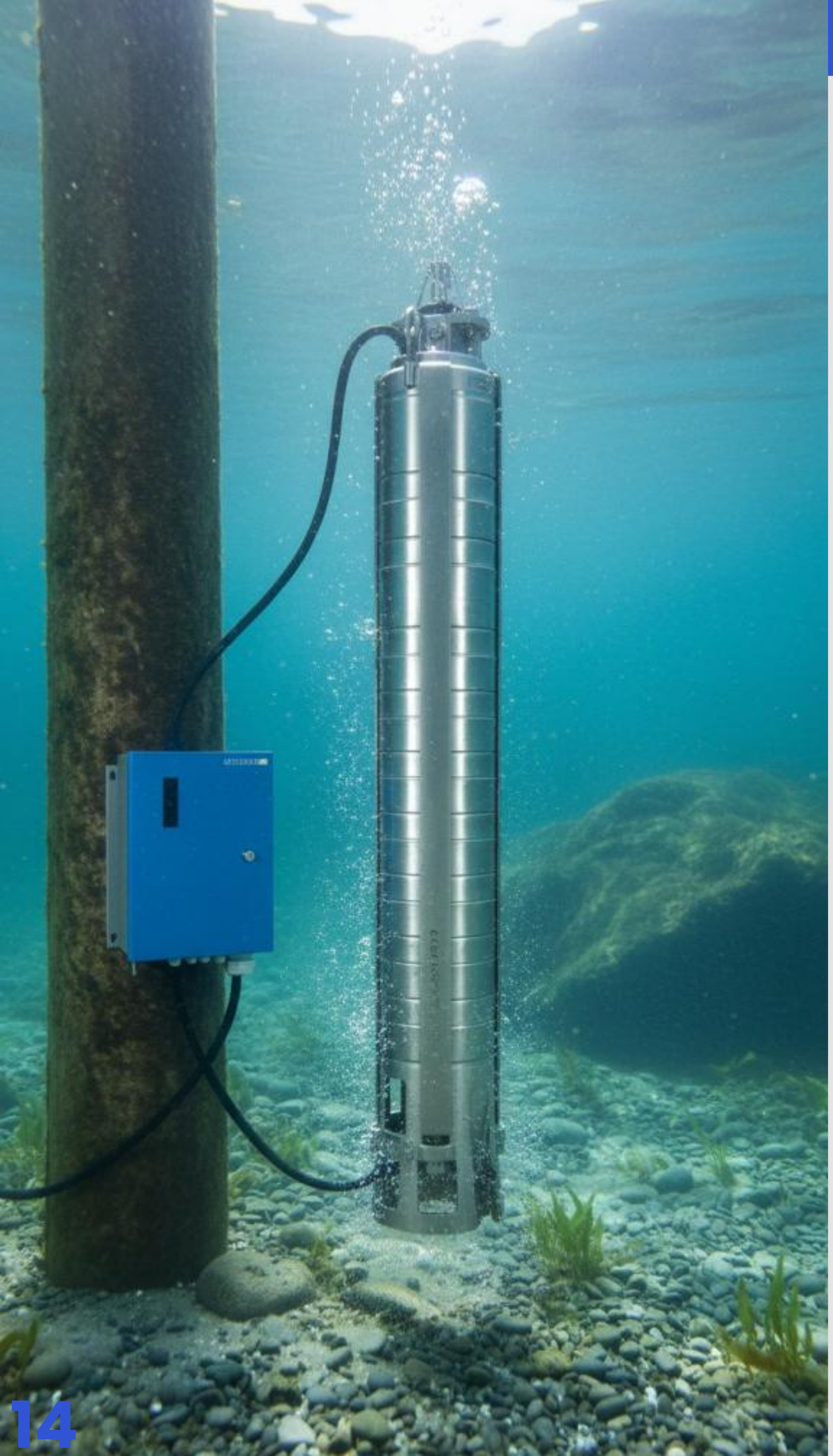
Seasonal Performance Insights

LORENTZ Compass simulation demonstrates consistent year-round water delivery with seasonal variations reflecting solar irradiance and temperature patterns in Kufri, Khushab. Peak output occurs in April at approximately 155 m³/day, while July registers 125 m³/day, both exceeding the daily requirement of 137-140 m³.

137

Daily Water Requirement m³





LORENTZ Compass Simulation: Water Tank Design

Pump Selection and Performance Validation

Pump Selection

LORENTZ PSk3-7 C-SJ17-9 submersible pump selected, rated power 5.88 kW, head capacity 47 meters (meets site TDH exactly), maximum flow 5.2 m^3/hour, brushless motor design for reliability.

Controller Technology

Integrated PSk3 controller with MPPT function, dynamic voltage and current optimization, data module for performance monitoring, surge protector and float switch included, automated system control without operator.

Year-Round Validation

LORENTZ simulation confirms consistent 137-140 m^3 daily delivery throughout all 12 months, winter performance maintained even in low-light periods, tank refill cycles optimized for efficient solar utilization.

MEMORIAL UNIVERSITY

Comparative Analysis - HOMER Pro vs LORENTZ Compass

HOMER Pro Characteristics

- Battery-Based Storage Approach
- System Components (PV + Inverter + Battery)
- Complexity Higher (multiple components)
- Cost Higher (battery investment ~$3,000)
- Maintenance Required (battery upkeep)
- Best For Systems needing uninterrupted 24/7 power
- Levelized Cost $0.0740/kWh

LORENTZ Compass Characteristics

- Water Tank Storage Approach
- System Components (PV + Controller + Pump)
- Complexity Lower (simplified design)
- Cost Lower (water tank)
- Maintenance Minimal (pump maintenance)
- Best For Agricultural irrigation with daily operation
- Simplified Technology Integration

Comparison Note: Both systems deliver required 137-140 m³ daily water output using similar PV capacity (~8.75-8.8 kW).

Environmental Impact: Net-Zero Achievement

Sustainability and Carbon Footprint Analysis

Carbon Emissions

Baseline diesel system 2,680 kg CO2/year

Proposed solar system 0 kg CO2/year

Annual emissions avoided equivalent to planting 450 trees

20-year carbon offset 53,600 kg

Resource Sustainability

Zero fossil fuel consumption

Renewable energy source with 25+ year panel lifespan

Water pumping maintained year-round without environmental strain

Supporting agricultural productivity sustainably

Social Benefits

Improved air quality in rural area

Reduced noise pollution versus generator operation

Energy independence for farming community

Model for regional sustainable agriculture

MEMORIAL UNIVERSITY

Dynamic Modeling in MATLAB/Simulink

System Goals

Design and simulate a solar-powered water pumping system for irrigation in Kufri, Khushab, Pakistan, optimizing performance under real-world conditions.

Dynamic Simulation

Examine short-term fluctuations and component interactions in solar pumping systems using MATLAB/Simulink.

Performance Validation

Confirm HOMER-optimized configuration is practically achievable and sustainable for rural irrigation.

Real-World Conditions

Model variable solar input, PV response, motor operation, and hydraulic loads for accurate assessment.

System Design Specifications

MEMORIAL UNIVERSITY

8.75	48	7.11	7.5
PV Array (kW)	Battery Voltage (V)	Inverter (kW)	Pump HP

Photovoltaic Array

Canadian Solar Inc. CS6U-345M modules configured with two in series and thirteen parallel strings for optimal power generation.

- Maximum Power: 345.186 W per module
- Voc: 46.4 V, Isc: 9.56 A
- Vmp: 38.1 V, Imp: 9.06 A

Energy Storage

Lead-acid battery bank providing energy backup and DC bus stabilization for continuous system operation.

- Rated Voltage: 48 V DC
- Capacity: 1350 Ah
- Maintains stable DC bus voltage

Power Conversion

Integrated DC-AC inverter with step-up transformer for efficient power delivery to three-phase induction motor pump.

- Inverter Output: Three-phase AC
- Transformer Ratio: 33.94 V to 380 V RMS
- Frequency: 50 Hz

Dynamic Modeling in MATLAB/Simulink: System Architecture

Comprehensive Real-Time Performance Simulation

1

Module 1 (PV Array Model)

Photovoltaic characteristics modeled using single-diode equation, irradiance and temperature inputs vary dynamically, output current and voltage produced matching real-world response.

2

Module 2 (MPPT Controller)

Perturb-and-observe algorithm implemented for maximum power tracking, voltage reference updated every 1 second, efficiency tracking above 95% throughout operating range.

3

Module 3 (DC-DC Buck Converter)

Input voltage 48-96V from battery bank, output regulated to 380V DC for inverter input, efficiency 96%, current ripple controlled below 10%.

4

Module 4 (Three-Phase Inverter)

7.11 kW capacity, sine-wave PWM control strategy, output 208V 60Hz three-phase, total harmonic distortion below 5%.

5

Module 5 (Step-Up Transformer)

380V DC input through inverter, step-up to 480V three-phase, isolation and EMI filtering provided.

6

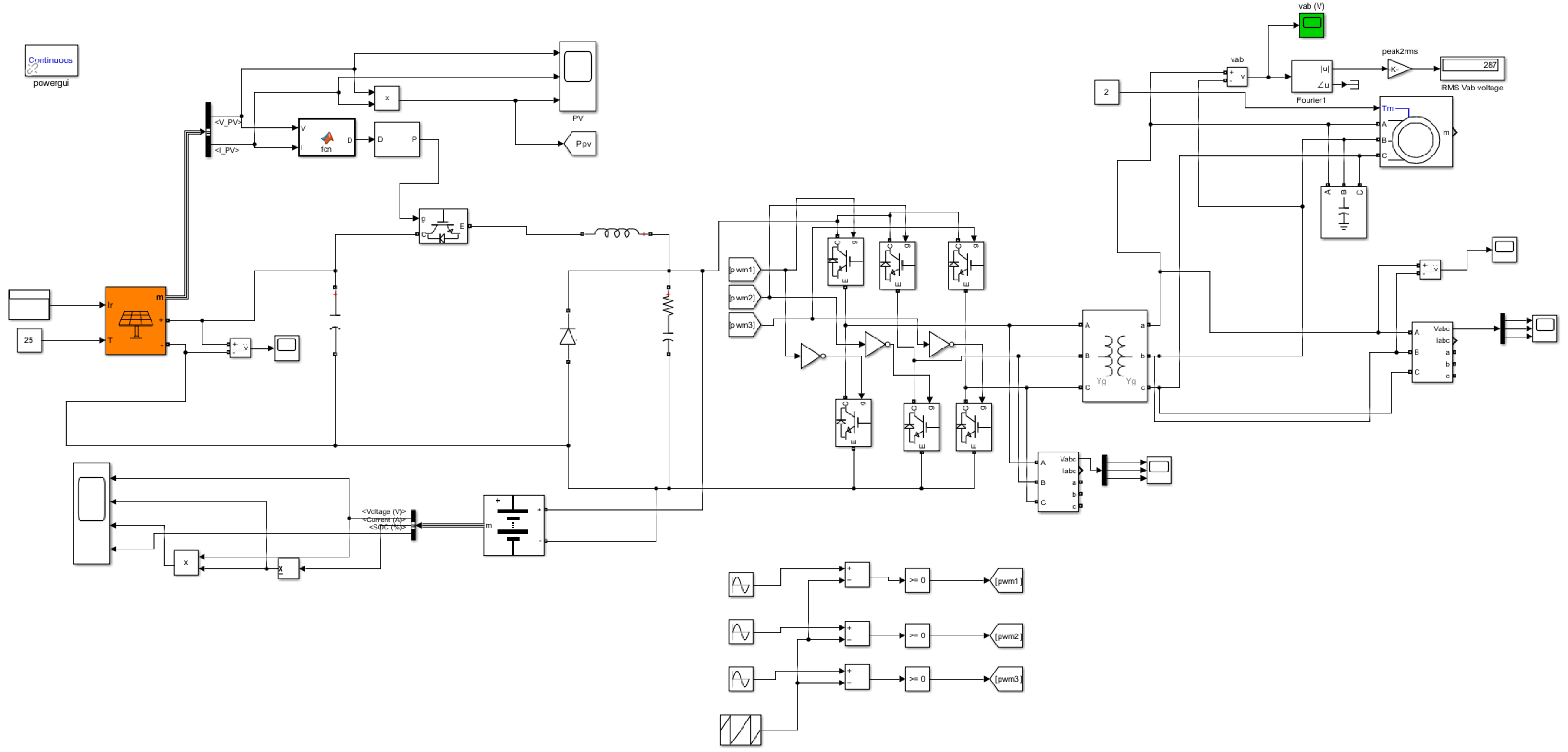
Module 6 (Pump and Motor)

7.5 HP induction motor modeled with mechanical dynamics, submersible pump load model, output water flow as function of motor speed.

Dynamic Modeling in MATLAB/Simulink: System Architecture

MEMORIAL UNIVERSITY

Complete model of solar water pump



MPPT Control and Buck Converter Operation

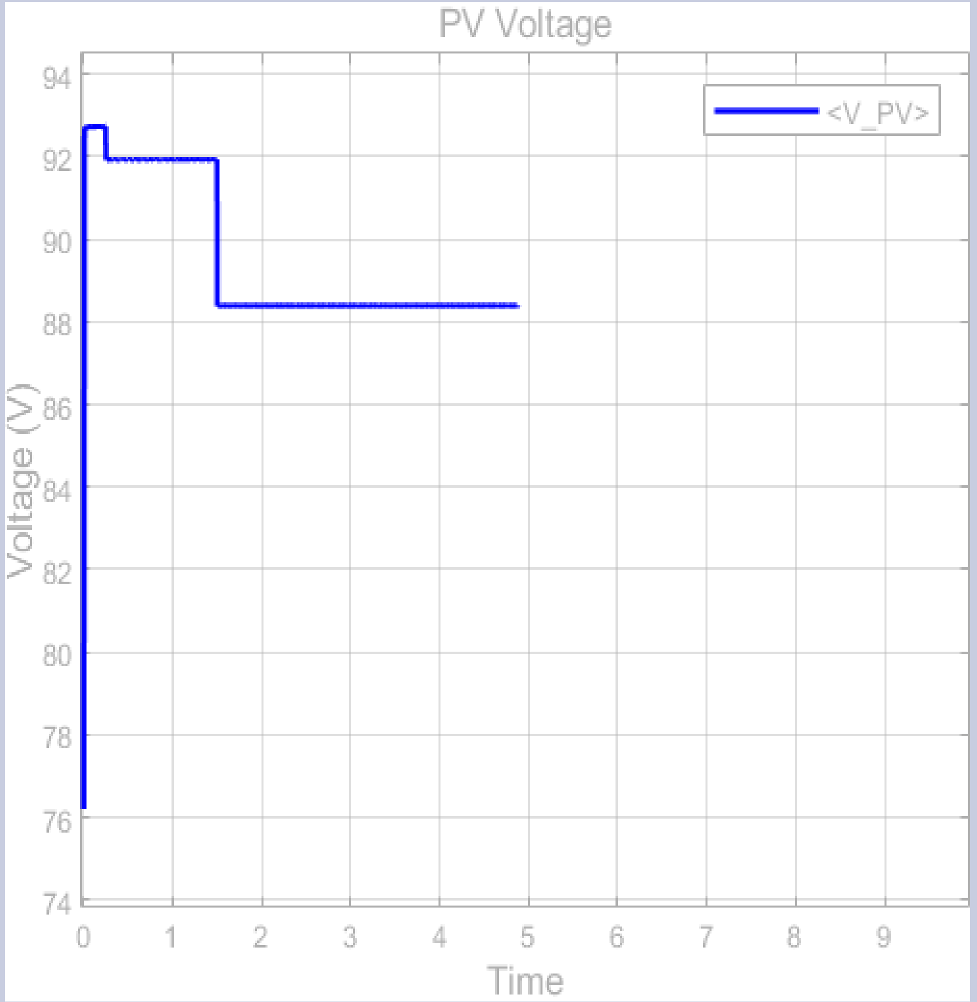


Figure 3: PV voltage (Source MATLAB)

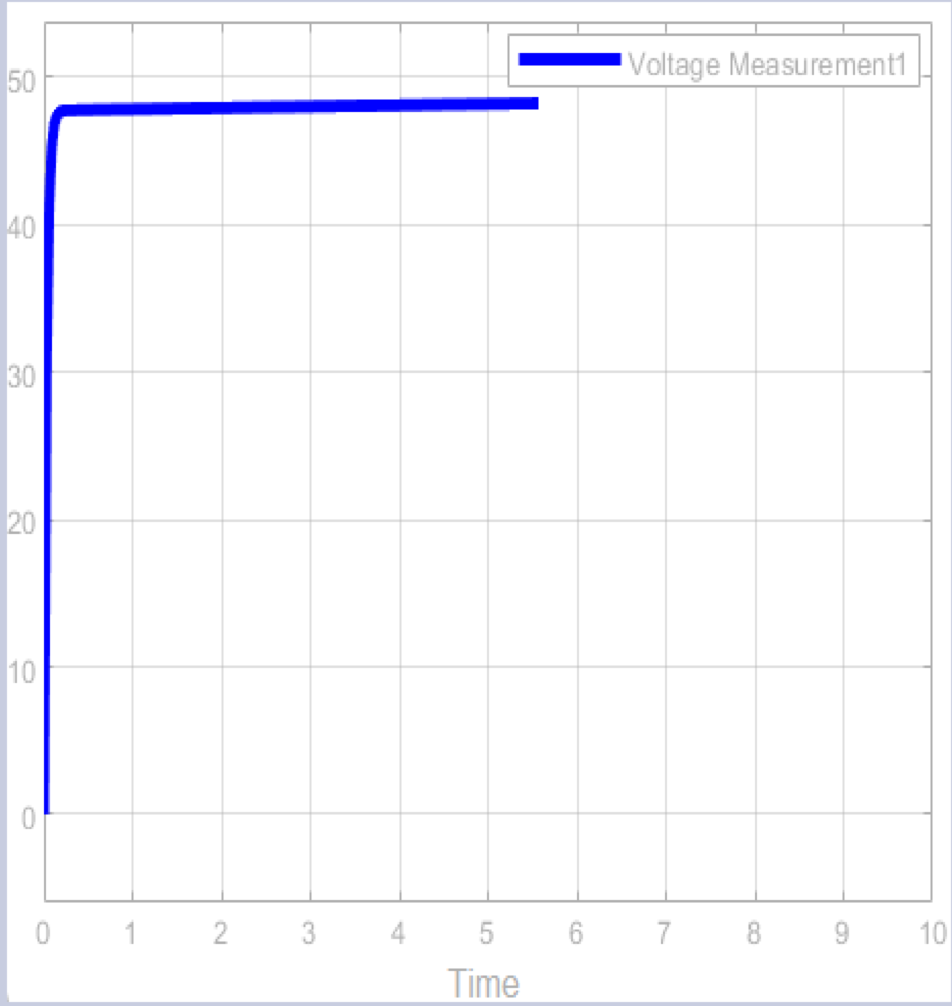


Figure 4: Buck Converter voltage (Source MATLAB)

PV & MPPT

Fast-tracking MPPT algorithm adjusts panel voltage based on instantaneous conductance relative to maximum power point voltage, enabling rapid response to irradiance changes.

Buck Converter Regulation

DC-DC converter steps down PV output and regulates voltage to stable 48V DC link through IGBT switch duty cycle control for downstream component protection.

DC-AC Inverter and Transformer Analysis

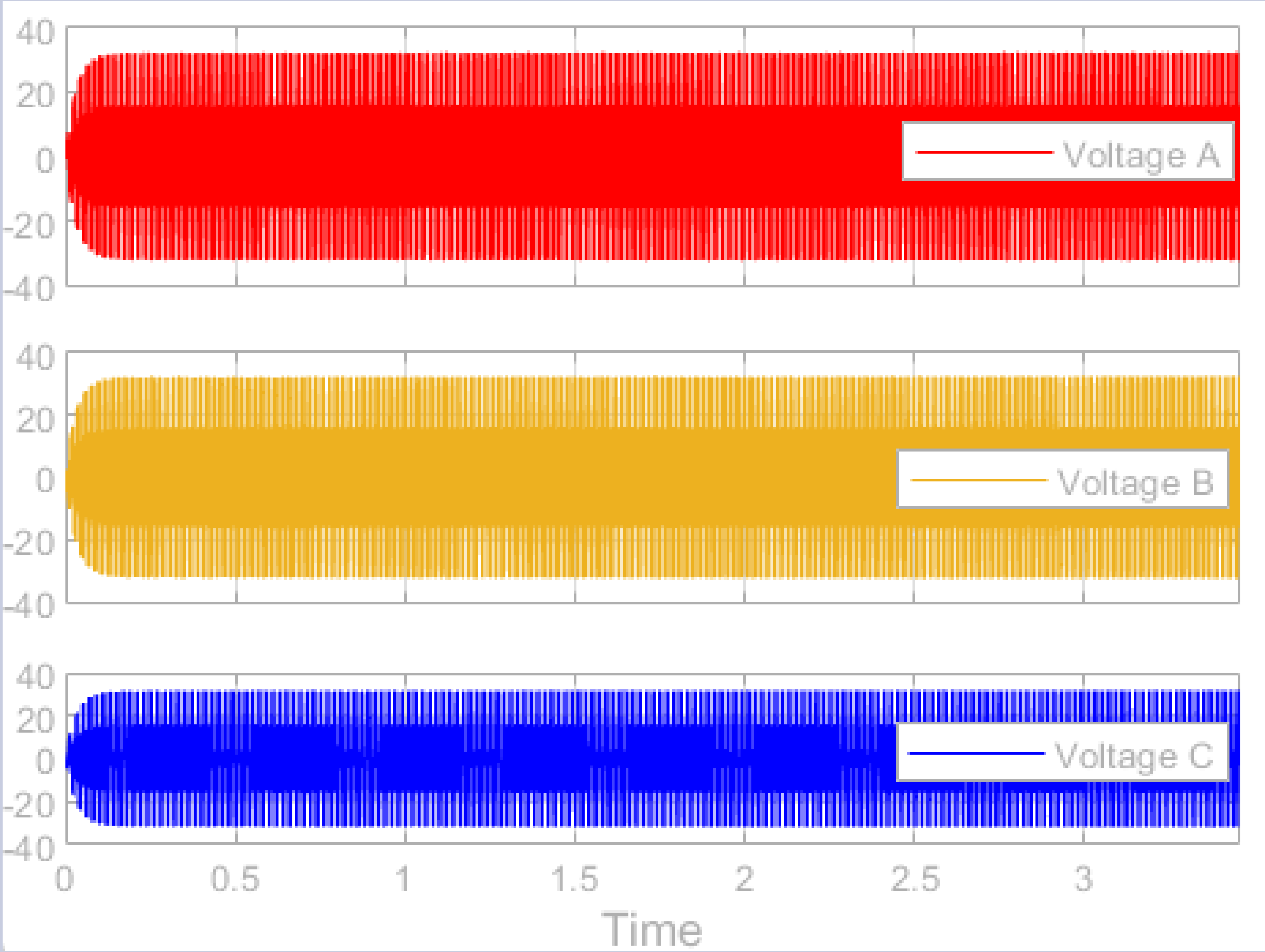


Figure 5: Three-Phase AC Inverter output (Source MATLAB)

Three-Phase Inverter

Sinusoidal PWM controlled six IGBT switches convert 48V DC supply into balanced three-phase AC output with 120° phase shift between waveforms for efficient motor operation.

Step-Up Transformer

Two-winding transformer with Yg-Yg grounded connection steps up inverter output from 33.94V to 380V RMS at 50 Hz, providing adequate voltage for three-phase induction pump.

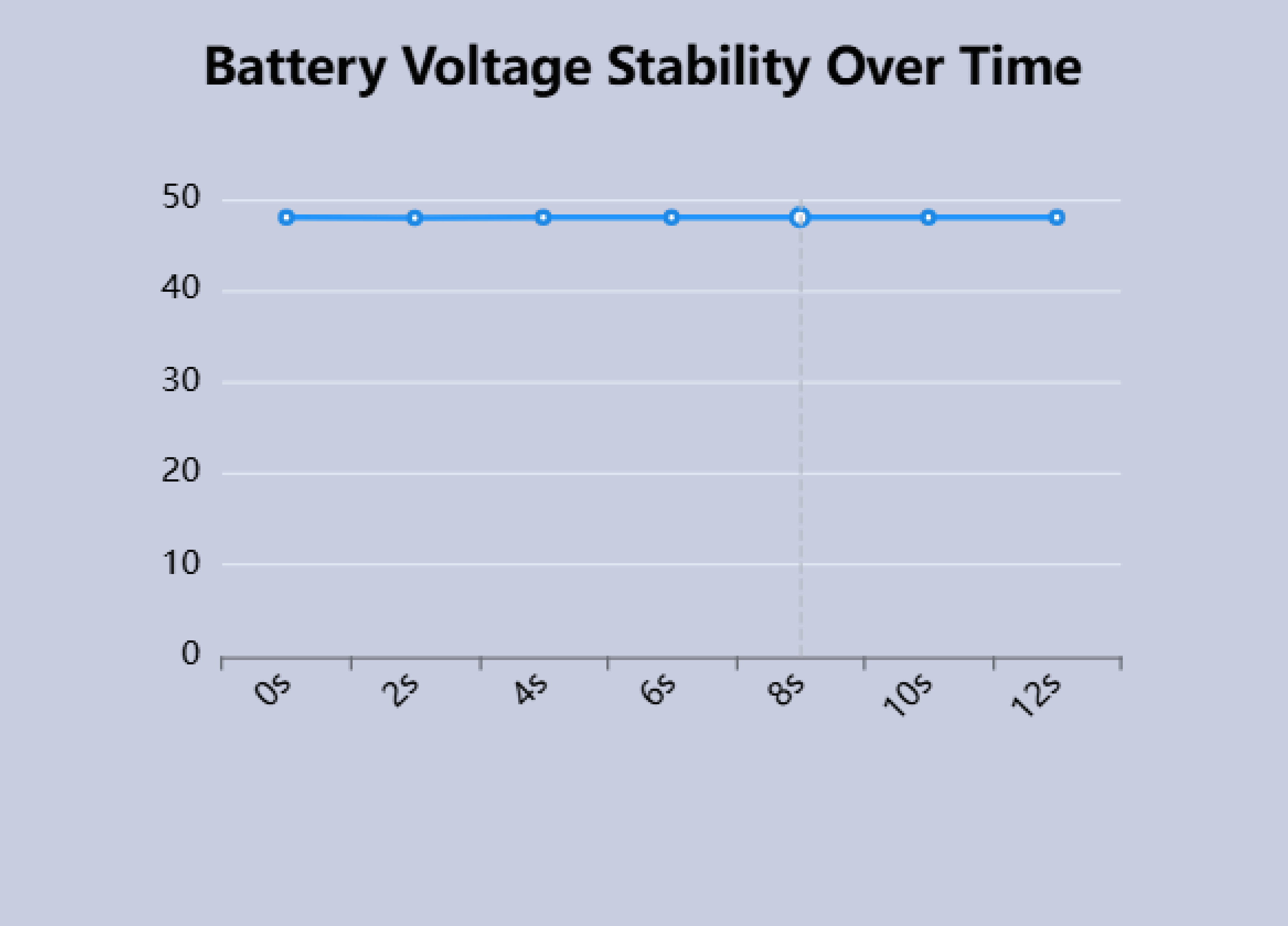
Battery Bank Performance and DC Bus Stability

Energy Storage System

The lead-acid battery bank maintains DC bus voltage stability and provides backup power during solar generation shortfalls. Rated at 48V with 1350 Ah capacity, it enables continuous irrigation operation regardless of solar irradiance variations.

48

Battery Voltage (V)



MEMORIAL UNIVERSITY

Key Findings and Technical Insights

MATLAB/Simulink Validation

The complete dynamic model successfully demonstrates feasibility of HOMER-optimized solar pumping system configuration, confirming both theoretical design and practical implementation viability.

Component Integration

Seamless integration of MPPT, buck converter, inverter, and transformer ensures efficient power flow from PV array to motor pump with minimal losses.

Performance Validation

Consistent 137-140 m^3/day irrigation output demonstrates reliable system performance under Standard Test Conditions with strong irradiance tolerance.

System Reliability

Battery backup ensures continuous operation during fluctuating solar conditions. Stable voltage and balanced three-phase output guarantee motor pump durability.

Hybrid Solar-Diesel System Optimization using HOMER Pro and MATLAB Simulation

MEMORIAL UNIVERSITY

Reduce Fuel Cost

Diesel-only systems are expensive to operate and maintain.

Guarantee Water Delivery

Leverage renewable solar energy to ensure consistent water supply.

Minimize Maintenance

Hybrid system reduces diesel dependency and maintenance requirements.

Environmental Impact

Reduce emissions and carbon footprint with cleaner energy solutions.

Protections and Safety Systems

DC/AC Isolators

Provides complete electrical disconnection safety during maintenance or emergencies

Surge Protection Device (SPD)

Protects system components from voltage spikes and transient surges

Earthing System

Ensures safety grounding to prevent electric shock hazards

Tank-Full Interlock

Automatically prevents fuel overflow during refueling operations

Dry-Run Interlock

Protects pumps from damage by preventing operation without fluid

MEMORIAL UNIVERSITY

HOMER Pro Modeling Framework

Step 1

Import Data (hourly GHI, ambient temperature)

Step 2

Define Components (PV, converter, pump, genset)

Step 3

Set Load Profile (deferrable water demand 140 m³/day)

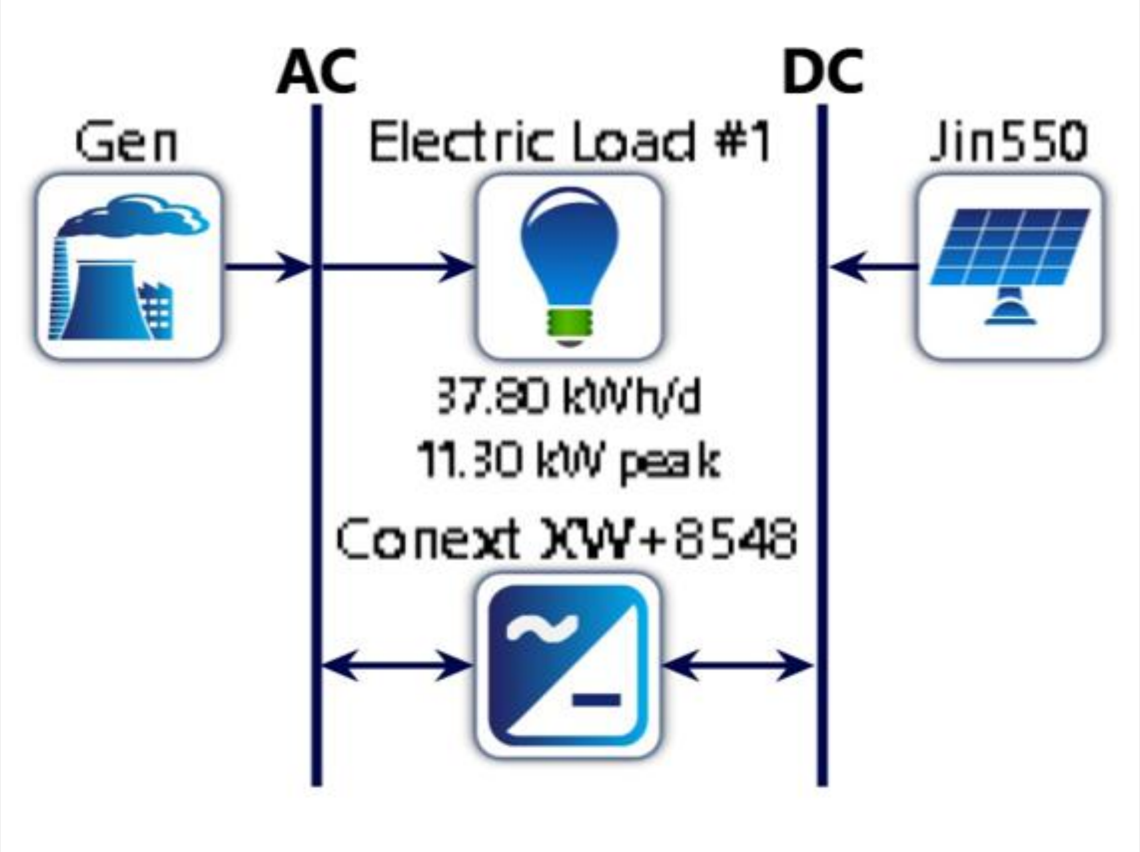
Step 4

Configure Control Strategy (solar-priority dispatch)

Step 5

Economic Analysis (LCOE, NPC, sensitivity analysis)

System Architecture and Components



PV Array (8.97 kW)

26 Canadian Solar modules at 345W each

Submersible Pump (7.5 HP / 5.6 kW)

Lifts water to storage tank

Hybrid Inverter with VFD/MPPT

Converts DC to AC and manages power flow

Diesel Genset (10-12 kVA)

Backup power for low irradiance periods

HOMER Pro Results

Simulation Results

System Architecture: Schneider Conext XW+8548 (13.0 kW)
JKM550-570N-72HL4 (9.34 kW) HOMER Load Following
Autosize Genset (12.0 kW)

Scaled Average (37.80 kWh/d)
Scaled Average (5.61 kWh/m²/day)

Total NPC:	Rs19,705,150.00
Levelized COE:	Rs110.48
Operating Cost:	Rs1,433,632.00

Emissions

Cost Summary | Cash Flow | Compare Economics | Electrical | Fuel Summary | Autosize Genset | Renewable Penetration | JKM550-570N-72HL4 | Schneider Conext XW+8548

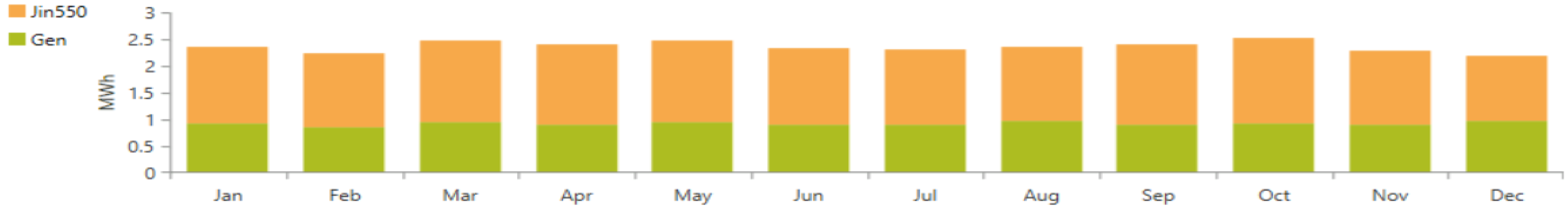
Production	kWh/yr	%
JKM550-570N-72HL4	17,241	60.8
Autosize Genset	11,116	39.2
Total	28,358	100

Consumption	kWh/yr	%
AC Primary Load	13,797	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	13,797	100

Quantity	kWh/yr	%
Excess Electricity	14,416	50.8
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	19.4	%
Max. Renew. Penetration	444	%

Monthly Electric Production



MATLAB Simulation Overview

Purpose

Validate HOMER Pro design through detailed transient and steady-state simulations

Toolbox

Simulink-based modeling for component behavior

Scope

Pump performance curves, inverter dynamics, genset response

Validation

Compare simulated vs measured system performance

Hybrid PV-Diesel System: Architecture and Rationale

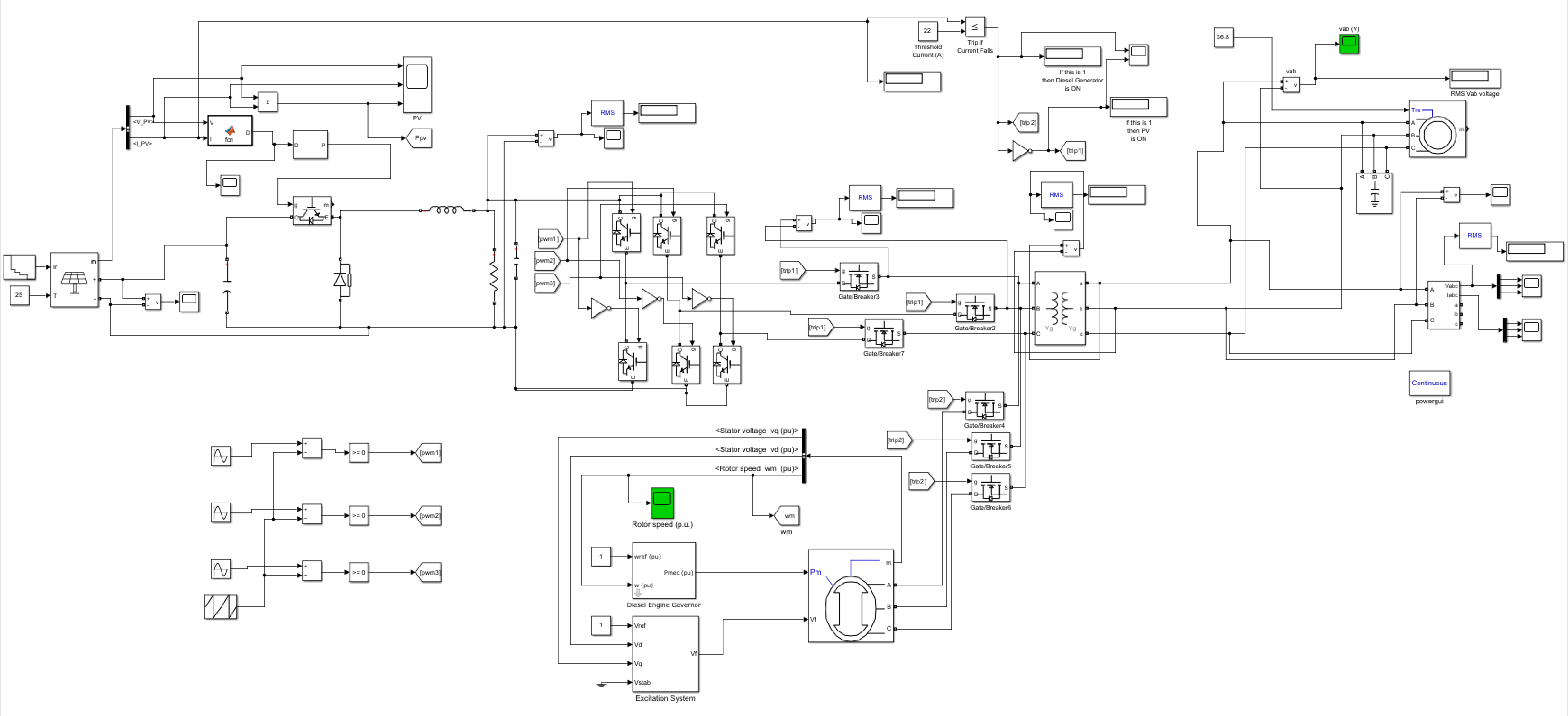
Backup Power for Guaranteed Delivery

1. **PV Array** — 9.34 kW photovoltaic array capacity, produces variable output based on solar irradiance, priority power source during daylight hours, excess capacity beyond pump requirements available.
2. **Supervisory Controller** — Current-based control logic monitors PV output in real-time, compares available solar power against pump demand, makes switching decisions automatically without operator intervention.
3. **Diesel Generator** — 12 kW backup generator unit, activated when PV output insufficient, provides guaranteed power delivery during consecutive cloudy days, operates in complementary mode with solar system.
4. **Pump and Motor** — Single 7.5 HP motor receives power from either PV or diesel source through seamless switchover, maintains constant speed and water delivery regardless of power source.

Dynamic Modeling in MATLAB/Simulink: System Architecture

MEMORIAL UNIVERSITY

Complete model of the hybrid PV–diesel water pumping system



Solar PV Array Modeling in MATLAB

Step 1: PV Model Parameters

Extract datasheet specs (Voc, Isc, Pmax), temperature coefficients

Key equations: $V_{oc} = V_{oc\_STC} + \beta V(T - T_{STC})$

Step 2: I-V and P-V Curves

Generate characteristic curves for varying irradiance (0-1000 W/m^2) and temperature (-10 to 50°C)

Variables: $I_{ph} = I_{sc} \times G/G_{STC}$

Step 3: MPPT Algorithm

Simulate perturb-and-observe method for maximum power tracking

Algorithm: $\Delta P/\Delta V > 0 \rightarrow$ increase V; else decrease V

Step 4: Array Configuration

Model 26 modules in series-parallel configuration

$V_{array} = N_s \times V_{module}$

Control Strategy

Solar-Priority Mode

- Pump runs directly from PV
- Prioritizing solar input
- Automatic switchover when PV current less than 22A threshold
- Continuous power monitoring

Diesel Genset Trigger

- Genset starts when PV current drops below threshold (22 A)
- Automatic shutdown when PV current exceeds 22 A

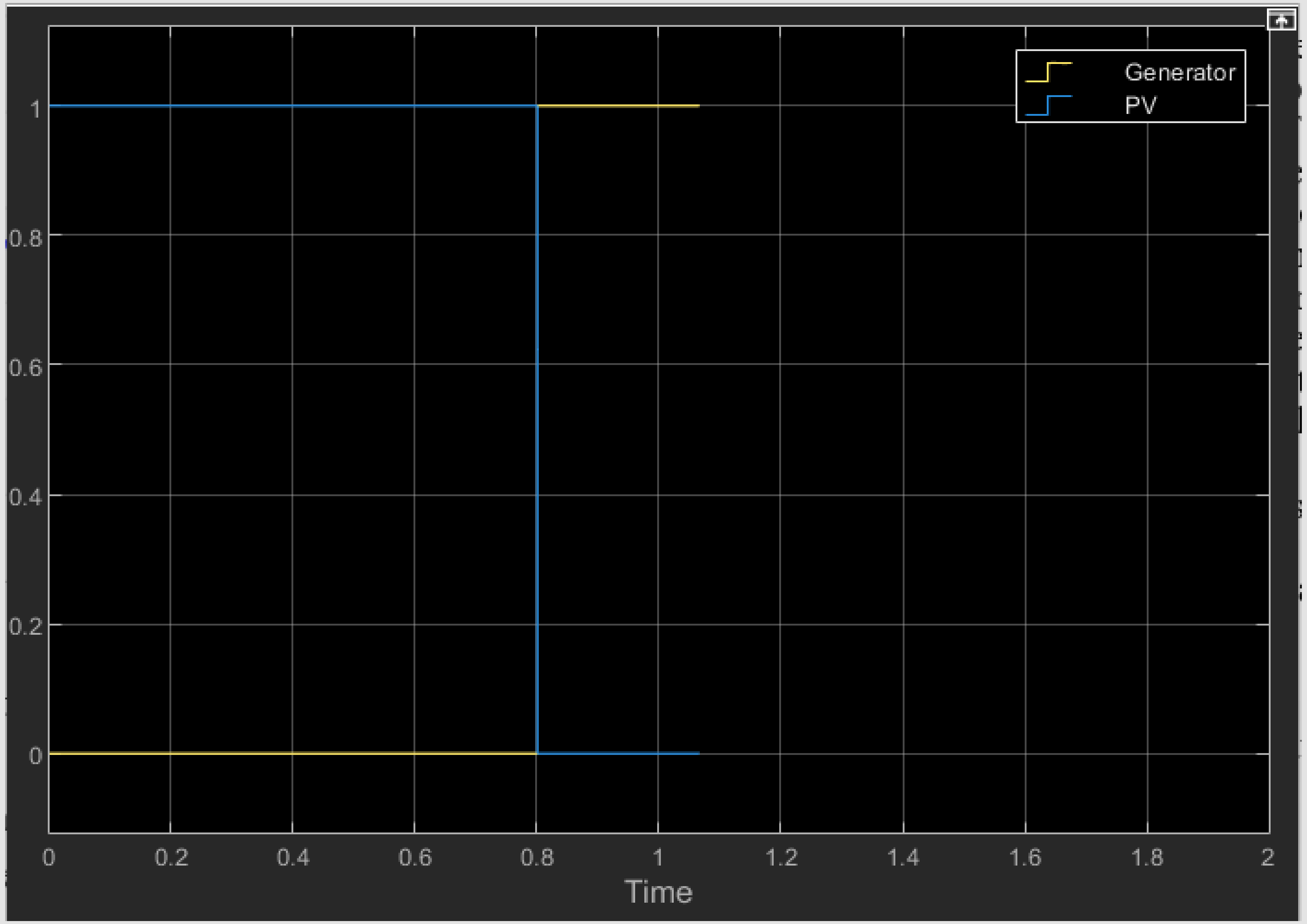


Figure 6: Switching PV and Generator (Source MATLAB)

Simulation Results and Conclusions

Economic Benefits

Estimated cost savings 60-70% vs diesel-only

Operational Reliability

95%+ water availability with minimal unmet hours

Environmental Gain

Reduces diesel consumption by 70-80%, saves ~200+ tons CO_2e over 20 years

Implementation

Design validated, ready for field deployment with VFD soft-start and interlock commissioning

Final Recommendations: Scaling and future enhancements include expanding system capacity, integrating smart monitoring technologies, and optimizing maintenance protocols for long-term sustainability.

Conclusion: Three System Solutions

MEMORIAL UNIVERSITY

Comparative Overview of All Approaches

Battery-Based System Viability

Successfully optimized using HOMER Pro to achieve 100% renewable operation without fossil fuels, levelized cost of energy 0.074 dollars per kilowatt-hour represents 82% reduction versus diesel baseline of 0.40 dollars per kilowatt-hour, economic payback achieved in 12 years within system lifespan, suitable for applications requiring nighttime pumping capability.

Water Tank Alternative Feasibility

LORENTZ simulation validates year-round water delivery of 137-140 cubic meters daily without electrical storage systems, system simplicity enables 25+ year operational lifespan, eliminates expensive battery replacement cycles at 10-year intervals, passive storage reduces maintenance and operational complexity requirements.

Hybrid PV-Diesel Robustness

Current-based supervisory control successfully prioritizes solar operation while guaranteeing power availability, 80% fuel consumption reduction compared to conventional diesel-only systems, provides farmer with reliable irrigation regardless of weather patterns or seasonal variations.

Practical Implementation

Socio-Economic Viability and Regional Applicability

Technical Feasibility

Solar resource in Khushab district proven at 5.5 kilowatt-hours per square meter per day sufficient for all three system designs, component availability through local distributors and regional suppliers well established, technical expertise available from engineering firms and contractors in major cities.

Economic Feasibility

Farmer financing through agricultural development banks available at 5 to 7 percent annual interest rates, solar system generates positive cash flow after 8 to 12 years depending on configuration, government subsidies for renewable energy agriculture programs available in Pakistan through Ministry of Climate Change.

Operational Feasibility

System designs require minimal daily operator intervention with full automation, quarterly maintenance activities performable by semi-skilled technician after training, local spares supply chain developing through solar installation contractors and networks active throughout region.

Future Research Directions

Emerging Opportunities and Unresolved Questions

Advanced Control Strategies

Develop artificial intelligence-based control algorithms optimizing daily water tank refill timing according to weather forecasts, machine learning predictive models anticipating weather patterns 48 hours ahead, algorithms adapting autonomously to seasonal solar variation without manual reprogramming.

Energy Storage Innovation

Investigate emerging battery technologies with improved cycling lifespan, explore compressed air energy storage as alternative to water pumping for energy conservation, examine thermal storage using heated fluid for potential agricultural greenhouse heating applications.

System Integration

Integrate multiple farm water demands including greenhouse irrigation and livestock watering in unified system design, combine solar pumping with aquaculture systems for integrated resource utilization and revenue diversification, explore agrivoltaic designs combining crop production with solar array installation.

Socio-Economic Study

Conduct longitudinal study of farmer income improvement after system implementation, analyze impact on groundwater depletion rates over 10-year monitoring period, evaluate community-wide adoption potential across multiple villages in region.

Climate Adaptation

Model system performance under climate change scenarios with altered precipitation patterns, investigate resilience during extended drought periods lasting multiple months, design scalable solutions adaptable to different agro-climatic zones across Pakistan.

Publications:

- Shabbir, Muhammad & Iqbal, Mohammad. (2025). Solar Water Pumping System Designed with HOMER and LORENTZ for Kufri, Khushab, Pakistan. European Journal of Electrical Engineering and Computer Science. 9. 77-83.10.24018/ejece.2025.9.5.756.

- "Dynamic Modeling and Simulation of a Solar-Powered Water Pumping System for Irrigation in Kufri, Pakistan", EJECE, vol. 9, no. 6, pp. 1–6, Nov. 2025, doi: 10.24018/ejece.2025.9.6.759.

- Design and Dynamic Analysis of a PV–Diesel Hybrid Water Pumping System for Kufri, Khushab, Pakistan Using HOMER and Simulink (Submitted for Publication December 2025 and Under Review).

Thank You for Your Attention

Questions and Discussion Welcome