Digital Twin Simulation of Hybrid Solar-Grid System for Agricultural Cost Optimization

Shivendra Nath Tripathi

Abstract:

This project focuses on developing a digital twin of a farm's hybrid energy system, integrating a solar PV array with grid connectivity, using MATLAB Simulink. The primary objective is to optimize energy management and reduce operational costs for the farm operating on a limited budget. The digital twin will simulate dynamic farm loads and solar PV generation to test control strategies aimed at minimizing grid dependency and supporting predictive maintenance, ultimately demonstrating a pathway to significant cost savings [1].

Keywords: Digital Twin, MATLAB Simulink, Solar PV, Hybrid Energy, Agricultural Optimization, Predictive Maintenance.

1. Introduction:

Digital twin technology creates virtual replicas of physical systems, enabling real-time simulation, predictive maintenance, and operational optimization. In agriculture, where energy budgets are often constrained, a well-designed hybrid energy system combining grid support with solar power can yield significant cost savings and enhance energy efficiency. This project aims to leverage these technologies by developing a digital twin of a specific farm's hybrid solar-grid system. Using simulation tools, primarily MATLAB Simulink, this project will model the interaction between various farm loads and renewable energy sources. The core research question addressed is: "How can a digital twin be utilized to optimize the performance of a hybrid solar PV and grid connected energy system for cost effective operation of the farm?". The findings will provide a framework for decision-making to lower operating costs and improve energy sustainability in agricultural settings [1].

2. Problem Statement:

The agricultural farm in question operates under a limited budget and faces challenges in managing its variable energy demands effectively while striving to minimize reliance on grid power. The core problem is the need to design, test, and implement an optimized hybrid energy system (solar PV and grid-connected) that reduces operational costs and improves energy efficiency. Specifically, the challenges lie in [1]:

- Accurately representing the farm's complex and dynamic energy loads.
- Modelling the intermittent nature of solar power generation.
- Developing and testing control strategies that optimize energy distribution between solar generation, grid supply, and farm demand to achieve cost-effective operation.
- Without a robust simulation model, iteratively designing and testing such a system on the physical farm would be costly, time-consuming, and potentially disruptive. This

project directly addresses the research question: "How can a digital twin be utilized to optimize the performance of a hybrid solar PV and grid connected energy system for cost effective operation of the farm?".

3. Farm’s Needs, Standards, and Legislation:

3.1. Farm’s Needs

The primary user of the proposed hybrid solar-grid system is an agricultural farm with specific operational and financial requirements. The key needs for the farm include:

- Cost Reduction: A paramount need for substantial savings in farm operating costs, particularly electricity bills, given the farm's limited budget.
- Optimized Energy Management: Efficient utilization of both solar-generated power and grid electricity to meet demands.
- Reduced Grid Dependency: A desire to minimize reliance on the national grid, thereby lowering costs and potentially enhancing energy supply resilience.
- Reliable Power Supply: Consistent and dependable power for a diverse range of agricultural loads, including:
  - Three residential houses (single-phase, peak 2-3kW each).
  - Borehole pumps (1.25kW single-phase, 2kW 3-phase).
  - A 24/7 security fence (5kW, 3-phase).
  - A cold room for produce/feed (2.5kW, 3-phase, 10 h/day).
  - A maize cruncher (7.5kW, 3-phase, 6 h/day).
  - Five to six feed mixers (7.5kW each, 3-phase, 6 h/day).
  - Nightly security lights (500W total, single-phase).
  - Workshop electrical tools (1.5kW average, 3-phase, 8 h/day).
  - Four 48V 160Ah battery-powered golf carts.
- Support for Agricultural Operations: The system must reliably power operations related to maize and cattle farming, on-site animal feed production (for own use and sale), and cooled storage facilities.
- Predictive Maintenance Insights: An expectation that the digital twin can provide data to help forecast component degradation and prevent costly equipment failures.
- System Adaptability: The potential for the system design to be tuned or scaled for different agricultural environments.
- Backup Power Integration: The farm currently utilizes two generators (120kW and 15kW) for power outages, indicating a need for the new system to integrate with or enhance overall power resilience.

3.2. Standards of Practice and Legislation:

For a hybrid solar-grid system the farm needs to adherence to a comprehensive set of national and local standards and legislation is mandatory to ensure safety, compliance, and effective grid integration. The following key requirements apply:

- Core Electrical Installation Standards:
  - SANS 10142-1: This is the foundational South African standard for the safety of all low-voltage electrical installations, including those incorporating solar PV and hybrid systems. It covers wiring practices, earthing, overcurrent protection, and the

overall safety of the installation for both grid-connected and off-grid components [2, 3].
    - A Certificate of Compliance (CoC) issued by a registered electrician is mandatory for all electrical work, certifying conformity with SANS 10142-1[2, 4].
    - Occupational Health and Safety Act (OHS Act 85/1993): This act governs general workplace safety, which is applicable during the installation process of the solar energy system[5].
- Solar PV System Specific Standards:
    - SANS 10142-1 (and its relevant sub-sections like SANS 10142-1-2, if specifically cited for PV): Includes requirements specific to PV installations such as DC wiring, correct isolation procedures, and surge protection[2, 6].
    - Structural Compliance: For roof-mounted systems, load-bearing certification as per building regulations (like SANS 10409) is necessary to ensure structural integrity [7].
    - Shading Analysis: South African Photovoltaic Industry Association (SAPVIA) guidelines recommend proper shading analysis, often using sun-path diagrams, to optimize system performance [2].
- Grid Interconnection Requirements:
    - NRS 097-2-3: This standard is crucial as it defines the technical requirements for connecting embedded generation (EG), such as solar PV systems, to the public electricity distribution network. It covers aspects like voltage and frequency stability, mandatory anti-islanding protection (to prevent energizing a dead grid), power factor control, and limits on harmonic distortion for systems up to 1 MW[2, 8].
    - NERSA Grid Code: The National Energy Regulator of South Africa (NERSA) issues Grid Codes that provide comprehensive technical and procedural rules for the safe and reliable connection of renewable energy systems to the national grid [9].
    - Municipal and Local Approvals: Farms must obtain written approval from their local municipality or Eskom (if directly supplied) before installation. Requirements can vary significantly by region. For example, the City of Cape Town has specific procedures for Small-Scale Embedded Generation (SSEG) systems, including pre-approval and adherence to local technical standards like EEB 705 [6]. Eskom consent may also be needed if the system is near Eskom's high-voltage infrastructure[8].
- Broader Legal and Regulatory Framework:
    - Registration with NERSA: A significant recent development is the mandatory registration of all solar PV systems (both grid-tied and off-grid) with NERSA. The deadline for this registration is March 2026, with potential fines for non-compliance[8].
    - System Registration and Metering: Grid-connected hybrid systems must typically be registered with the local grid authority or municipality. Bidirectional meters are required if the system is to export surplus electricity to the grid, and specific net metering or feed-in tariff rules will apply, varying by municipality[7, 8].
    - National Energy Act (2008) & National Energy Regulator Act (2004): These acts form the overarching legal framework governing energy generation, distribution, licensing, and regulation in South Africa [10].
    - Environmental Authorisation: Large-scale projects may require environmental authorisation under the National Environmental Management Act (NEMA) [11]. For a

typical farm-scale system as described, this is less likely but depends on total generation capacity and footprint.

- Component Standards and Quality Assurance:
    - SABS-approved components: All electrical equipment used, including solar panels, inverters, and batteries, must comply with relevant SANS standards or equivalent recognized international standards (e.g., IEC, VDE, BS) to ensure safety and performance [2, 6, 8].
    - PV GreenCard: the PV GreenCard program by SAPVIA is a widely recognized quality assurance program for solar PV installations. Using SAPVIA-certified installers who issue a PV GreenCard provides assurance of compliance with key standards and best practices [12].

In summary, implementation of hybrid solar-grid system on a farm need to adherence to SANS 10142-1 for electrical safety, NRS 097-2-3 for grid connection, NERSA regulations including system registration, and all specific municipal by-laws and approval processes. Utilizing certified installers and SABS-approved components is crucial for a compliant, safe, and effective system.

4. Preliminary Research and Literature Review:

The development of a digital twin for agricultural cost optimization is grounded in substantial preliminary research. This review covers the foundational concepts of Digital Twins (DTs), their specific applications and challenges in smart agriculture, and the groundwork for modelling the farm's hybrid energy system.

4.1. Digital Twin Technology: Concepts, Values, and Applications:

The concept of a Digital Twin, a virtual representation of a physical asset or system synchronized with its real-world counterpart, has gained significant traction across various industries. Rasheed et al. (2020) define a DT as "a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making" [1, 13]. This encompasses creating a virtual model, using it for predictive analysis, and integrating these insights back into operational processes. Key values derived from DTs include real-time remote monitoring, enhanced efficiency and safety, predictive maintenance, scenario and risk assessment, and improved decision support[13].

The author in [14] provide a comprehensive overview of DTs in smart farming, emphasizing their role in creating a virtual replica of a farm that includes crop cultivation, soil composition, and weather conditions by amalgamating data from diverse sources like sensors, UAVs, and satellite imagery. This enables farmers to make well-informed, timely decisions regarding irrigation, fertilization, and pest management, ultimately enhancing farm productivity and sustainability [14]. They note that while DTs are revolutionizing agriculture, many current implementations are often simulation models proposed for future practical use, indicating an "evolving concept lacking substantial support from implemented case studies" for fully realized DTs [14].

4.2. Digital Twins in Smart Farming: Specifics and Typologies:

The author in this paper [15] focus specifically on DTs in smart farming, defining them as a "digital equivalent of a real-life object of which it mirrors its behaviour and states over its lifetime in a virtual space" [1, 15]. Their work introduces a crucial typology of Digital Twins relevant to agriculture, categorizing them based on their lifecycle stage and capabilities: Imaginary (for design), Monitoring (current state), Predictive (future state), Prescriptive (recommending actions), Autonomous (self-controlling), and Recollection (historical data) DTs[15]. This typology helps in understanding that most current agricultural applications implicitly use basic monitoring DTs, with more advanced predictive and prescriptive capabilities still emerging [15].

The literature concurs that DTs can significantly enhance operational efficiency and reduce maintenance costs in agriculture. These studies support the premise of this project: that a digital twin can serve as a powerful tool for optimizing energy use and reducing costs in an agricultural energy system [1].

4.3. Enabling Technologies, Challenges, and Simulation Tools:

The successful implementation of DTs relies on a confluence of enabling technologies, including IoT sensors for data acquisition, robust communication networks (Ethernet, LoRa, Wi-Fi, cellular), AI and Machine Learning (ML) for data analysis and prediction, and cloud computing for data storage and processing [13, 14]. Also this paper [14] highlight how DTs allow farmers to simulate and enhance farming methods in a virtual setting before real-world application.

Key challenges identified across the literature include ensuring data quality, managing large volumes of data, data privacy and security, achieving model accuracy and scalability, maintaining real-time synchronization between the physical and digital asset, and the complexity of integrating diverse data sources [13, 14]. Specifically for agriculture, paper [15] point out the challenges posed by highly dynamic biological systems, the complexity of diverse living organisms, and the dynamic nature of farm networks involving multiple stakeholders [15].

The choice of MATLAB Simulink for this project, as mentioned in the project proposal is supported by literature such [16], which showcases its efficacy for simulating complex renewable energy scenarios and its relevance in Industry 4.0 contexts involving DTs [1]. The project documents further detail the use of MATLAB's "DecoupledPVArrayGrid" [17] model for the PV system, indicating a practical application of established simulation tools.

4.4. Foundational Research for System Component Modelling:

To ensure the digital twin accurately reflects the farm's physical hybrid energy system, preliminary research was also conducted to identify and characterize key components and data sources:

- Solar Panels: An investigation into commercially available 500W solar panels in South Africa was performed, considering cost, efficiency, and warranties. Brands like JA Solar were identified, with a specific JA Solar 500W mono-perc panel [18] model noted for use in the Simulink simulation.

- Inverters: Research into 60kW and 25kW three-phase grid-tie and hybrid inverters suitable for the South African context was undertaken, evaluating options from manufacturers like Sunsynk [19], Sol-Ark, Growatt, and Deye. The potential for battery integration through hybrid inverters was also considered.
- Irradiance Data: Solar irradiance data, a critical input for PV simulation, is sourced from the NASA Prediction of Worldwide Energy Resources (POWER) website [20].
- Farm Load Data: Real-world farm power consumption data, essential for load modelling, was measured using a Dranetz Energy Power Platform (EP1) [21] over a one-week period (30 April 2025 9h30 to 8 May 2025 11h00). This data, after processing, forms the basis for creating realistic dynamic load profiles in the simulation.

This body of research collectively confirms the viability and timeliness of developing a digital twin for agricultural energy optimization. It highlights the transformative potential of DTs, acknowledges the associated challenges, and provides a solid foundation of tools, component knowledge, and data sources for the proposed project.

5. Proposed Solution: System Design and Mythology:

This section details the systematic approach undertaken to design and develop the digital twin simulation for the farm's hybrid solar-grid system. The methodology involved iterative testing, data acquisition and processing, detailed system modelling in MATLAB Simulink, simulation under various scenarios, and finally, an economic analysis.

5.1. Overview of Approach

The core solution involved an iterative development process. Initial tests were conducted to determine the farm's power requirements and the potential scale of the solar PV system. This was followed by detailed data acquisition, meticulous data preprocessing, and the construction of a digital twin in MATLAB Simulink. The model was progressively enhanced, starting with grid-only loads, then integrating a PV system, and finally incorporating battery storage and backup generators to reflect the farm's complete energy infrastructure.

5.2. Data Acquisition and Preprocessing

Accurate data is fundamental to a reliable digital twin. The following steps were taken to gather and prepare the necessary data:

5.2.1. Farm Load Data Measurement

The farm's electrical loads were measured using a Dranetz EP1 device [21] from 30 April 2025 (9h00) to 8 May 2025 (11h30).

- **Data Scope**: The dataset comprised approximately 2324 rows and 10 columns, including Date and Time, Voltage for each phase, Current for each phase, impedance for each phase, and kW rating at each timestamp.
- **Measurement Method**: The two-wattmeter method was employed.
- **Data Correction**: An initial issue was identified where one voltage phase reading was incorrect due to a connection error (yellow channel not connected to the overall system

but to a breaker of individual loads). This was rectified by performing linear interpolation for that phase, averaging the voltage of the correctly measured phases. The current for that phase was measured correctly.

- **Missing Data Handling**: The original measured data did not consistently provide current and voltage values at every 10-minute interval (e.g., for the first 5 minutes, voltage and current were recorded, but not for the next 5 minutes). To address this, linear interpolation based on adjacent recorded rows was performed using a Python algorithm.

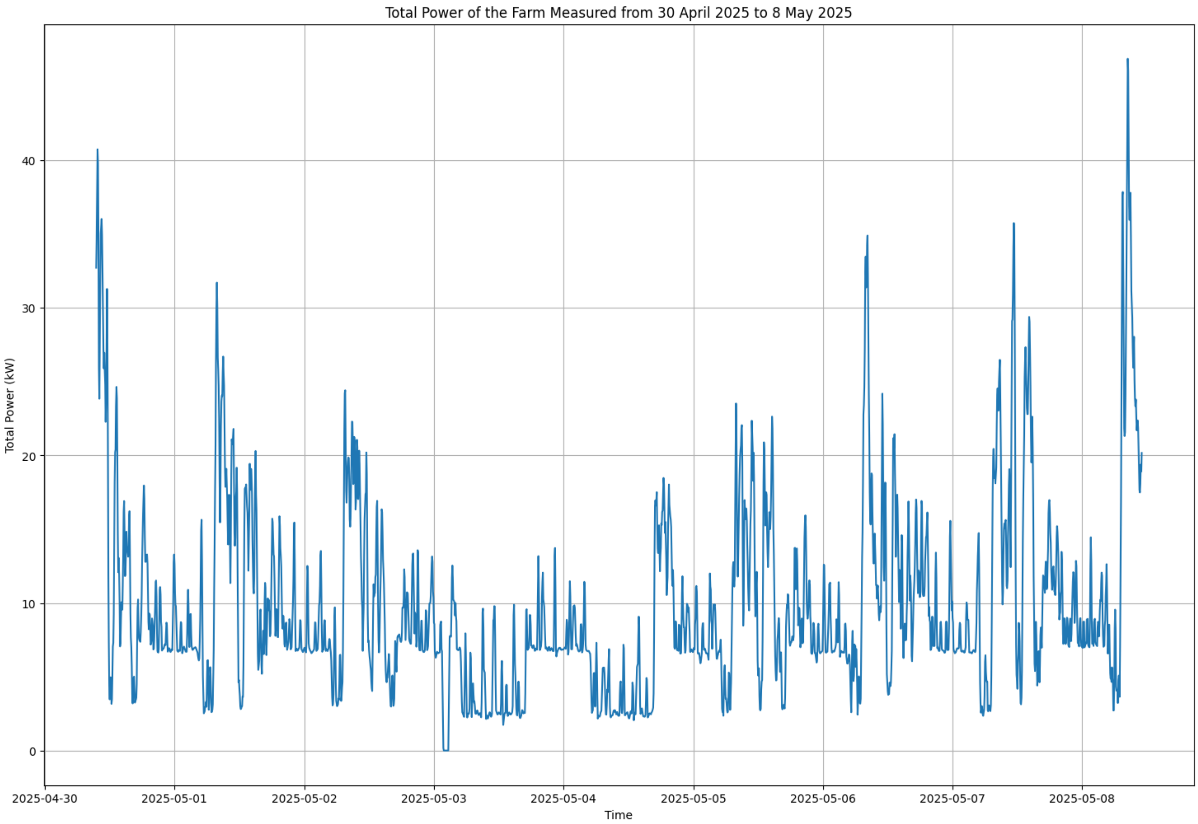

Figure 1: Load graph from Dranetz EP1 measurement after initial processing

5.2.2. Initial Load Analysis and Sizing Considerations

Analysis of the measured data revealed:

- The maximum power demand of the farm was approximately 50kW to 60kW.
- On days with lower power consumption (e.g., when heavy loads like the maize cruncher and feed mixers were not operational), the demand was around 15kW to 30kW.
- This initial analysis suggested that a minimum PV system size of around 20kW to 25kW could potentially cover loads on lighter days. A 60kW PV system was also conceptually tested to understand its behaviour under peak load conditions.

5.2.3. Solar Irradiance Data

Solar irradiance data, essential for modelling the PV system, was obtained from the NASA Prediction of Worldwide Energy Resources (POWER) website [20].

- **Data Period**: Data from 30 April 2024 to 8 May 2024 was used, as 2025 data was not yet available on the site.
- **Data Type**: "All Sky Surface Shortwave Downward Direct Normal Irradiance" was used, provided as hourly data.

5.2.4. Data Processing with Python

Python was extensively used for various data manipulation tasks [22]:

- **Load Profile Matching Algorithm**: An algorithm, designed with the assistance of Google Gemini 2.5 Pro, was developed to match or approximate the measured power data (from CSV) with the farm's load specifications and estimated operating times. This automated the estimation of actual operating schedules for each load, which were then used to build the digital twin in Simulink. This script also performed power profile optimization using scipy.optimize.minimize (L-BFGS-B method) to best fit measured power while minimizing errors and penalizing daily usage constraint violations. Results were exported to CSV and MATLAB .mat formats .
- **kWh and Cost Calculation**: A Python code was developed to calculate the daily and monthly electricity energy consumption (kWh) from the time-series power data using the trapezoidal integration method. It also calculated the cost based on a tiered City Power tariff, processing each calendar day and filling missing time intervals with zero power.
- **Data Point Reduction for Initial Simulations**: To manage computational load during initial simulations, the data (originally 2324 rows with multiple power columns) were condensed. For some test runs, one day with the highest power consumption (7 May 2025, 11h05 to 8 May 2025, 11h00) and one day with the lowest (3 May 2025 to 4 May 2025) were selected. This resulted in 288 data points per day (5-minute intervals). This was further reduced to 24 points per day (hourly peaks) for certain rapid test simulations, though this introduced a Mean Absolute Percentage Error (MAPE) around 50.12%.
- **Irradiance Data Upsampling**: The hourly irradiance data was upsampled from 24 points to 288 points per day using cubic interpolation in Python to match the 5-minute resolution of the load data for final simulations.

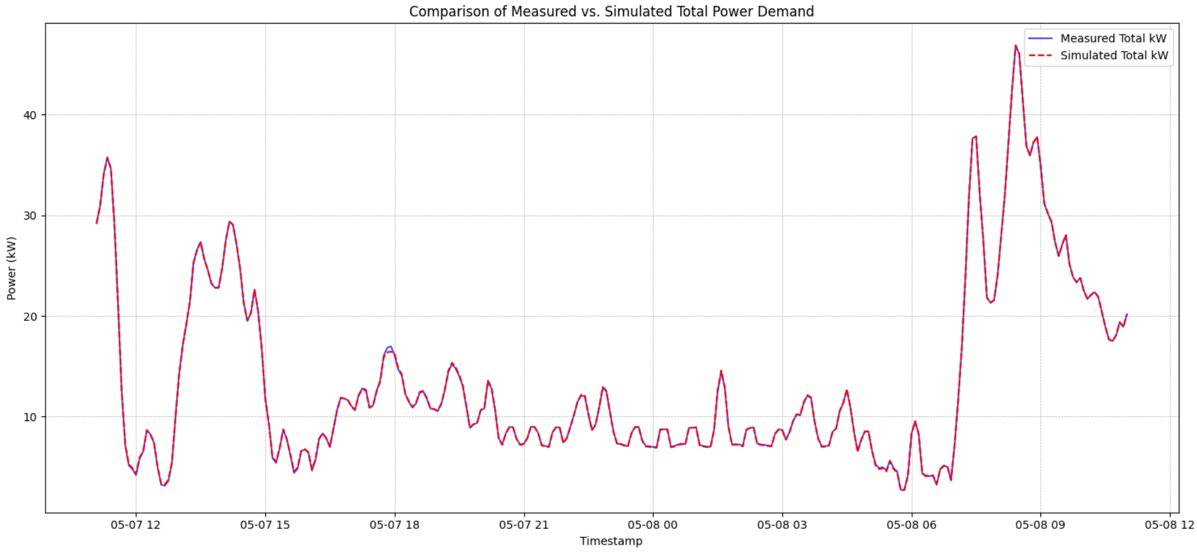

Figure 2: Python code output graph of load matching

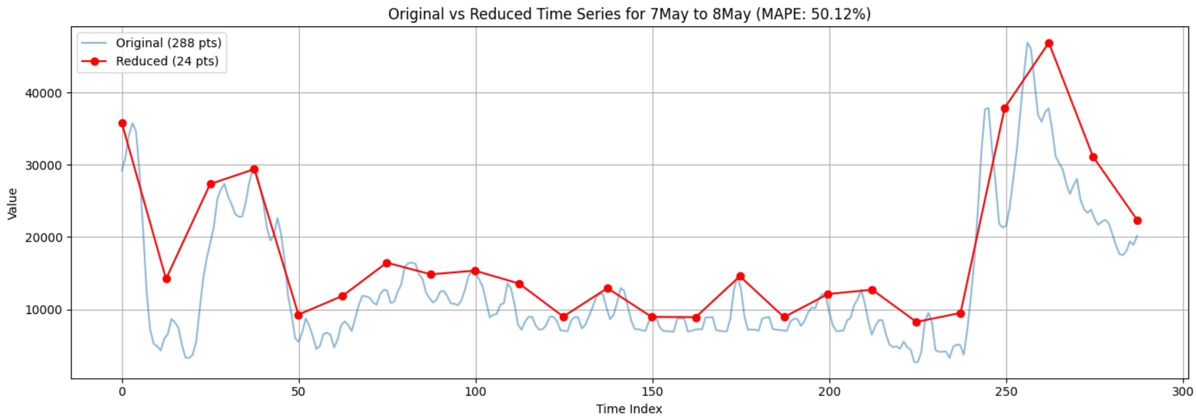

Figure 3: Graph showing point reduction from 288 to 24 with error percentage

5.3. Digital Twin Development in MATLAB Simulink

The digital twin of the farm's energy system was constructed and simulated using MATLAB Simulink.

5.3.1. Initial Grid-Only Load Simulation

The first phase involved modelling only the farm loads powered by the grid to test normal operating conditions.

- **Power Source**: A three-phase source block set to 380V at 50 Hz, with an assumed power capacity of 1MW.
- **Load Blocks**:
  - **Three-Phase Loads**: A Three-Phase Dynamic Load block was used, with load profiles approximated by the Python algorithm and uploaded via a Lookup Table with Linear Point-Slope Interpolation.

  - **Single-Phase Loads**: Since no direct model was available in the Simulink toolbox, a MATLAB example model named "Single Phase Dynamic Load Block" [23] was utilized.
  - **Load Voltages**: Three-phase loads were powered by 380V AC, and single-phase loads by 230V AC.
- **Computational Load Management**: Initial simulations with 10 different loads, each with 288 daily data points, were computationally heavy (20-30 minutes run time). To reduce this, three-phase loads were combined, and two of the three house loads (sharing a 15kW backup generator) were grouped, significantly reducing run time.

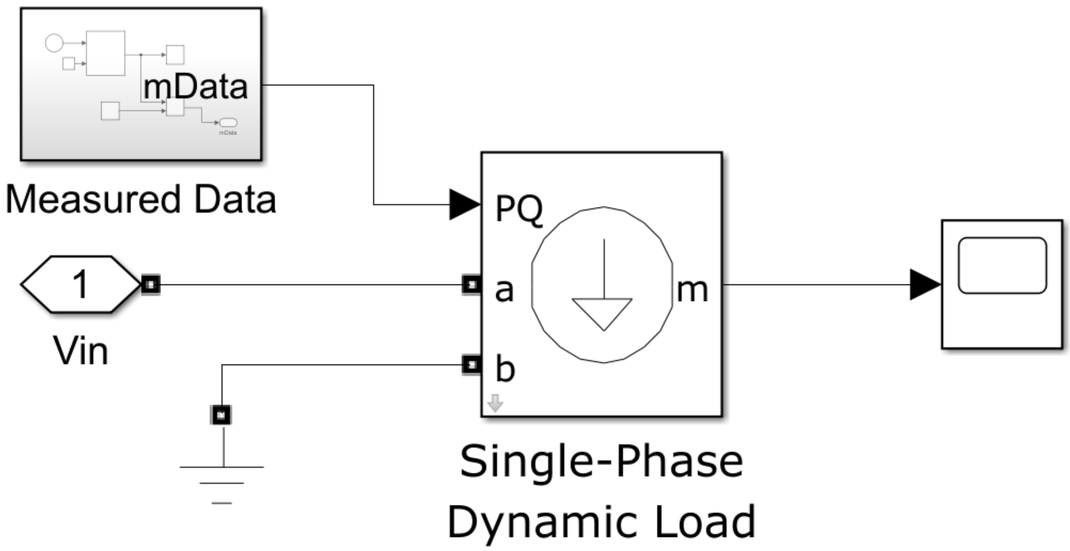

Figure 4: Single Phase representation in Simulink

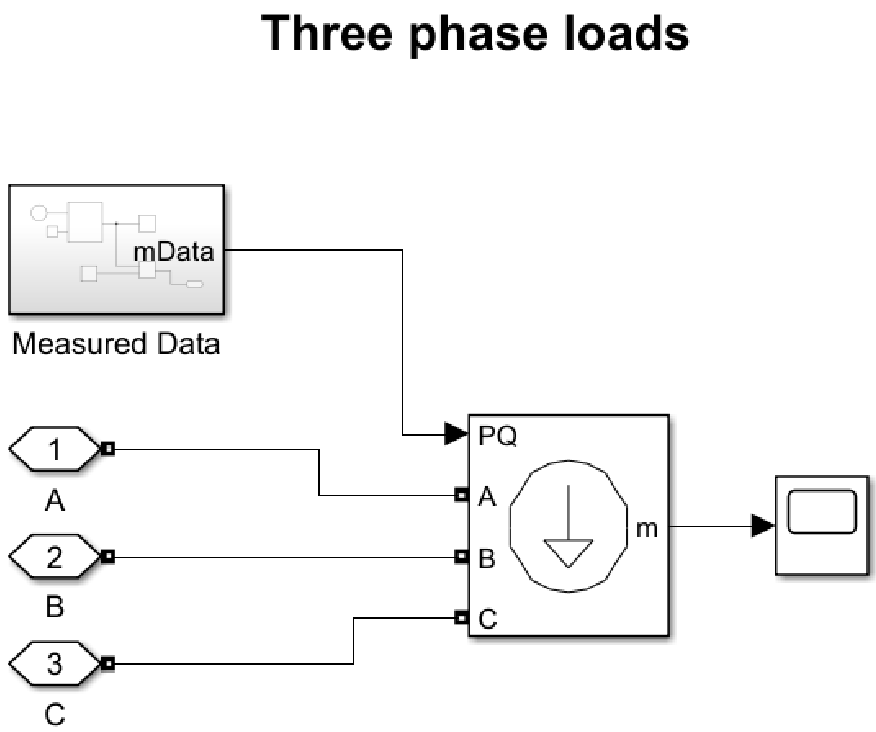

Figure 5: Three Phase Load representation in Simulink

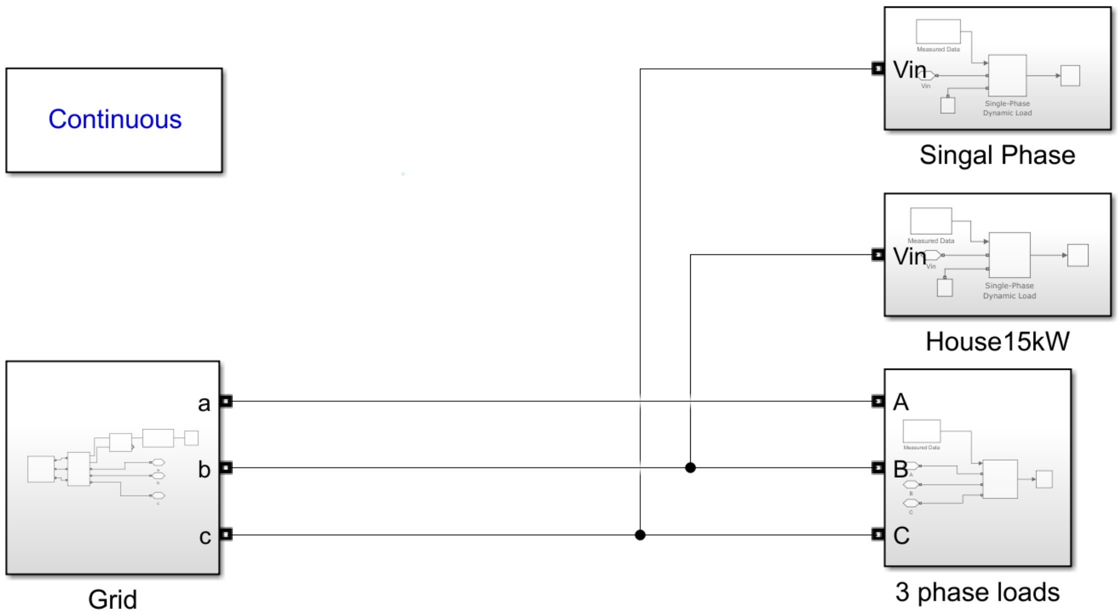

Figure 6: All the loads connected to the Grid

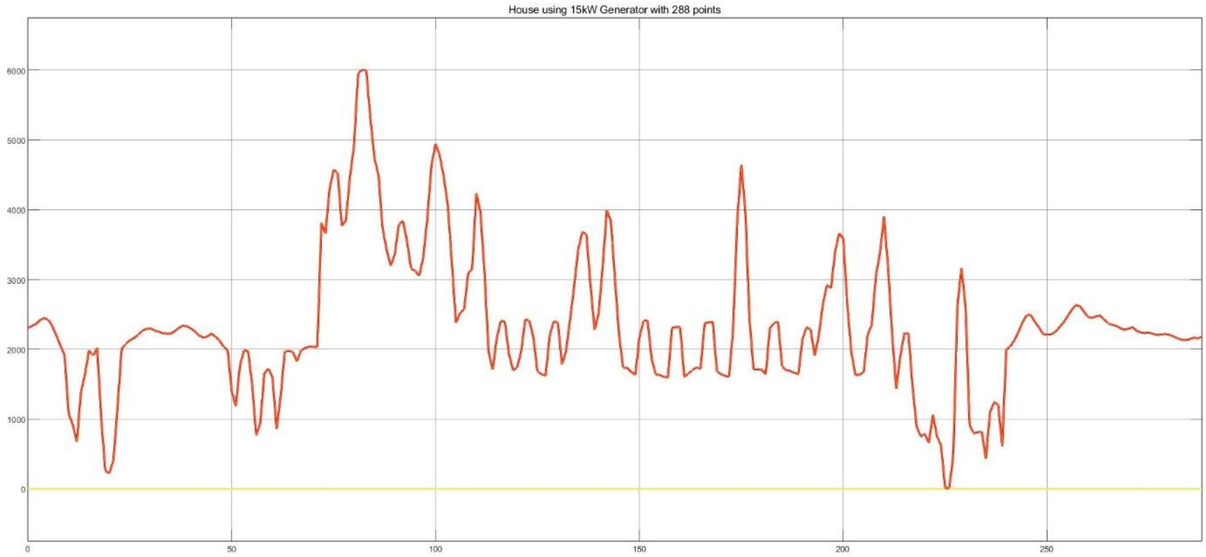

Figure 7: the loads of the 2-house having a backup 15kW generator (7May to 8May)

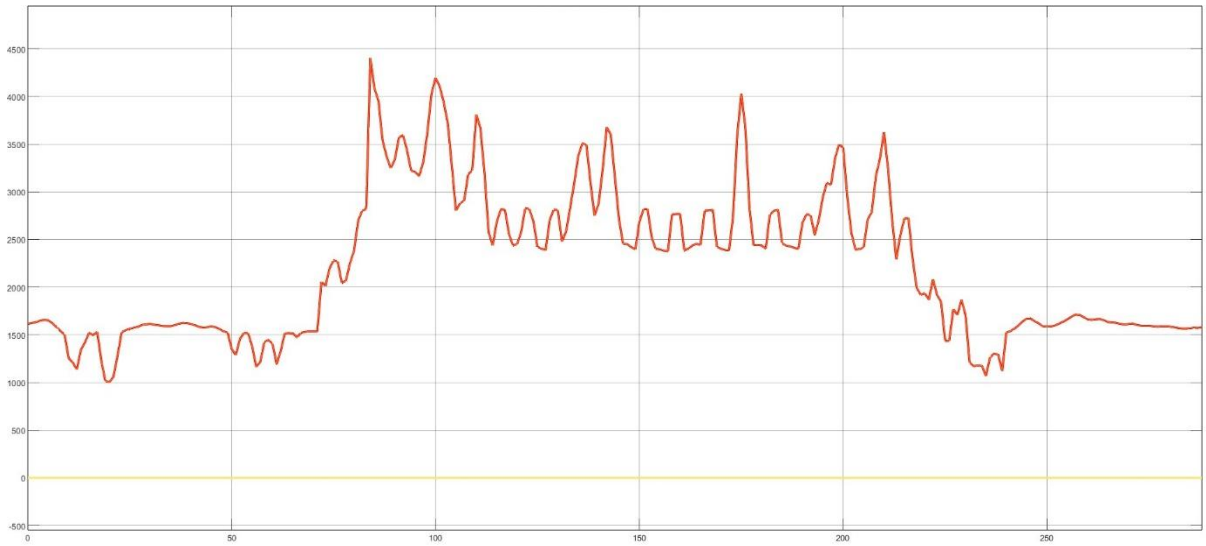

Figure 8: Single-phase loads(7May to 8May): Houses_1, Borehole_Pump1, and Security_Lights_Total

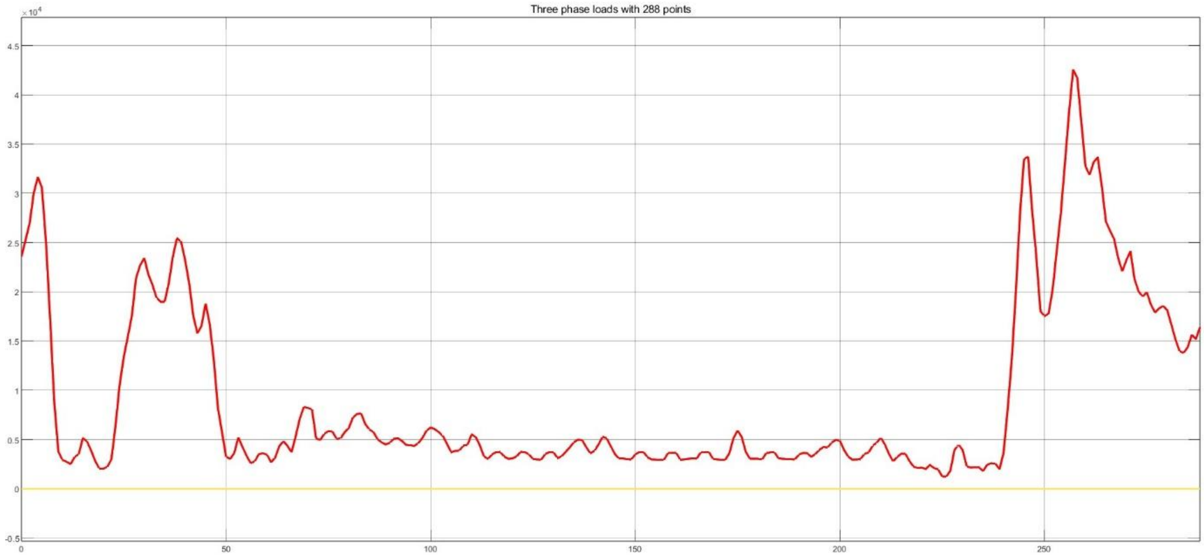

Figure 9: Three Phase Loads (7May to 8May)

5.3.2. PV System Integration and Simulation

The PV system was then integrated.

- **PV Array Model**: The "DecoupledPVArrayGrid" [17] model from MATLAB examples was chosen after evaluating other models like "Detailed Model of a 100-kW Grid-Connected PV Array" and "Average Model of a 100-kW Grid-Connected PV Array."
- **PV Module**: Settings were based on JA Solar 500W Mono PERC panels [18]. Inverter and Boost Converter Configuration (for a 60kW test system):
  - DC input to the boost converter was set to 400V.
  - Inverter output was 500V AC at 50Hz, stepped down to 380V by a transformer.
  - A pre-insertion resistor (40 ohms) was used between the inverter and transformer to limit inrush current.
  - The system was rated for 60kW active power (reactive power assumed 0 VAr for initial load response tests).
  - This 60kW system required approximately 120 panels (500W each), configured as 10 panels in series (for ~450V DC into boost) and 12 such series strings in parallel.
- **PV System Settings**: Other PV system settings were kept as the "DecoupledPVArrayGrid" [17] example.

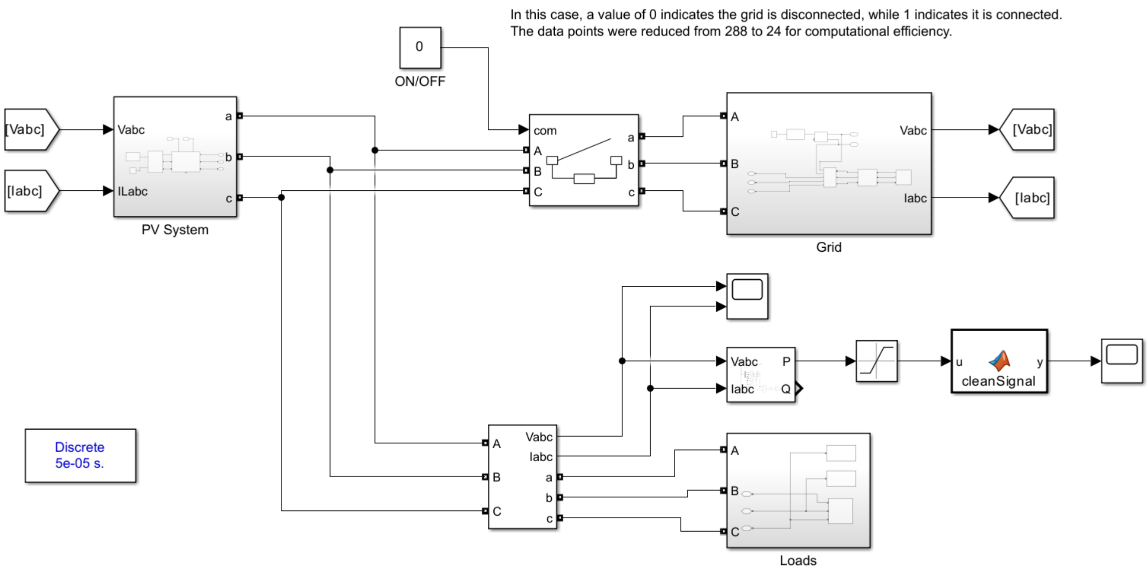

Figure 10: 60kW PV system connected to the loads and the grid is off

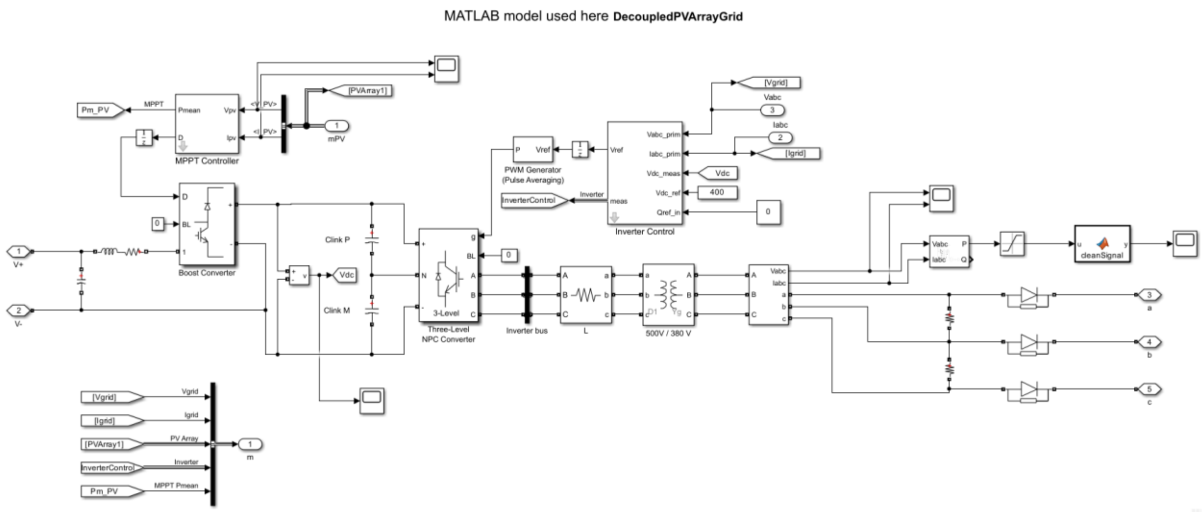

Figure 11:PV system (DecoupledPVArrayGrid) of the Farm [17]

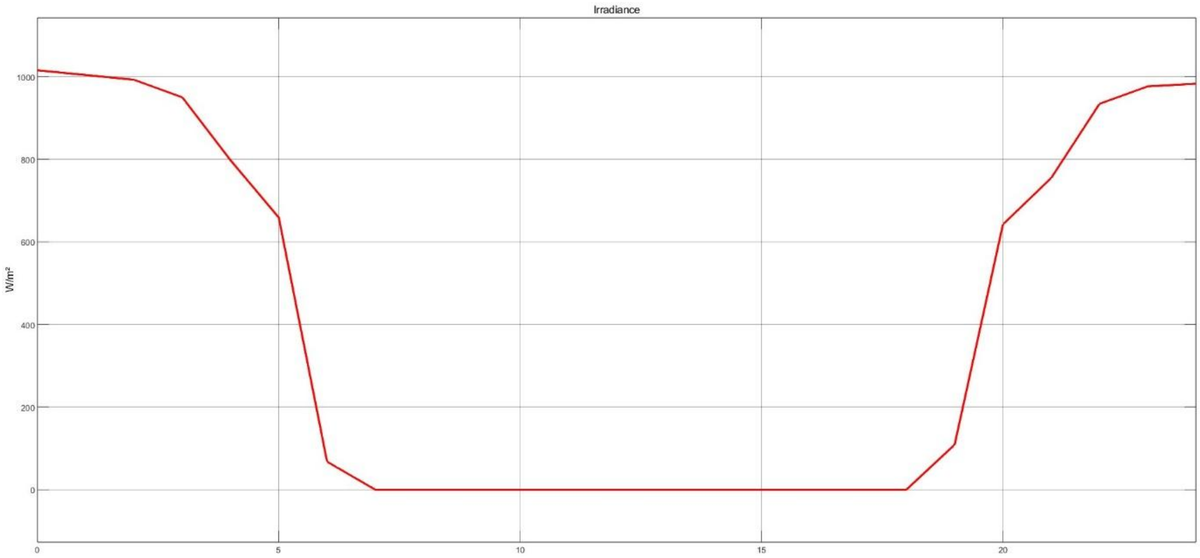

Figure 12: Irradiance graph for 7 May 2024 11h00 to 8 May 2024 12h00

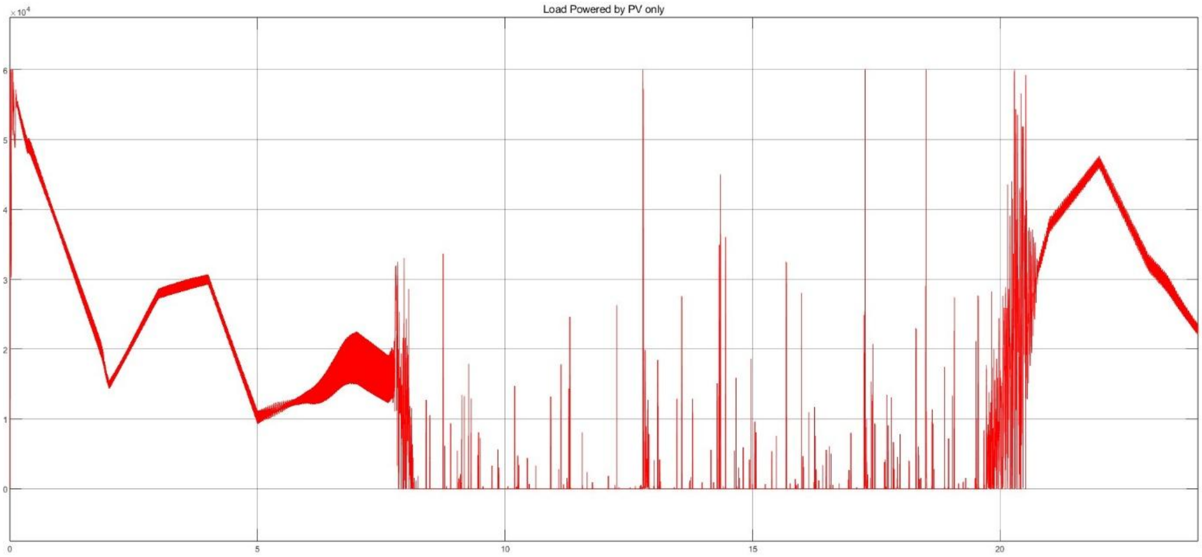

Figure 13: Loads powered by 60kW PV system only (7 May 2025 11h05 to 8 May 2025 11h00)

The PV system only provided electricity during the hours of most sunlight; yet there were considerable power spikes at the times when there was no sunlight, indicating excessive power demand.

5.3.3. Final Integrated System Model (Grid, PV, Battery, Generators)

The final model incorporated the grid, PV system, battery storage for golf carts, and backup generators.

- **Data Resolution**: A key decision was made to use the original, more accurate 288 data points per day for the final simulations, accepting longer run times (~90 minutes) in favour of higher accuracy.
- **Battery System**:
    - The four 48V 160Ah battery-powered golf carts were modelled.

- The charging mechanism utilized a MATLAB example: "Charging of Battery Using Buck Converter powered by PV MPPT" [24].
- Batteries were programmed to charge during off-peak load times (around 11h00 to 14h00).

- **Generator Integration**: The farm's backup generators (one 120kW for main loads, one 15kW for two houses) were included with a switching system to simulate their activation during power outages.
- **Filtering**: A MATLAB function block was used as a filter to obtain clearer output signals.
- **PV connected:** For 25kW system is 10 panels per string and 5 strings of 10 panels.

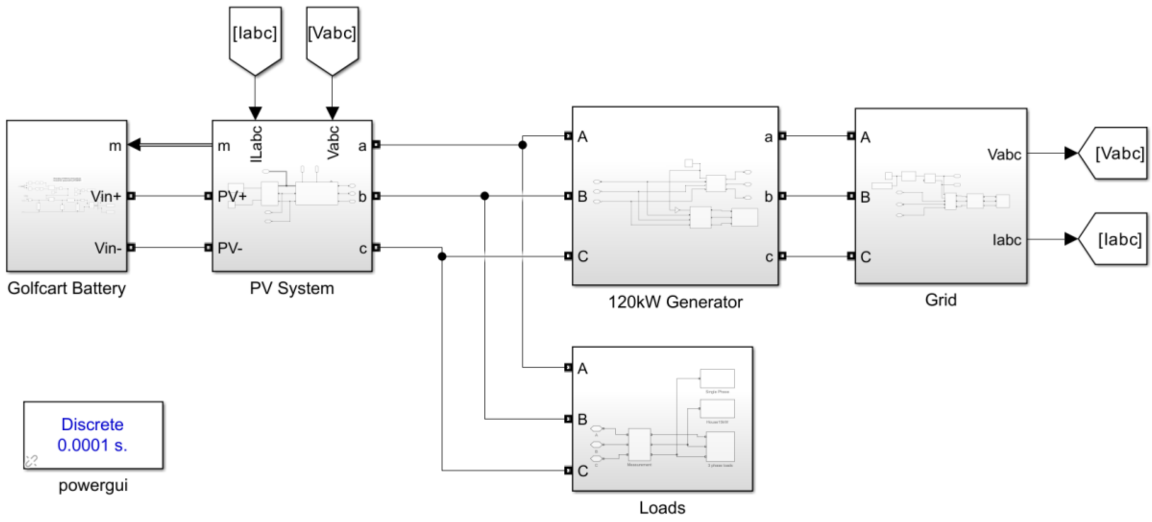

Figure 14: The final Simulink Model showing PV, Grid, Loads, Battery and Generator

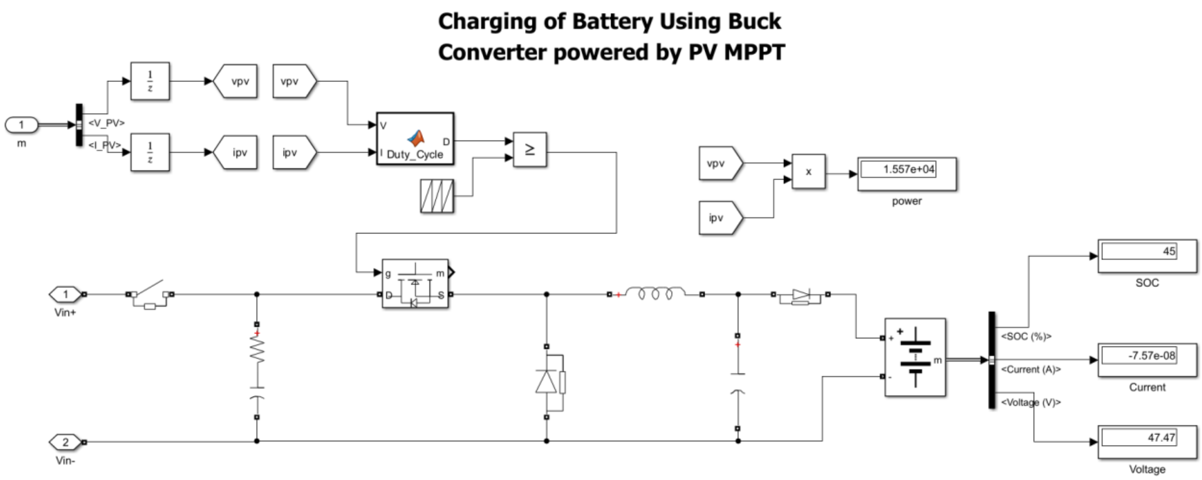

Figure 15: Golf cart battery charging system (Buck converter) [24]

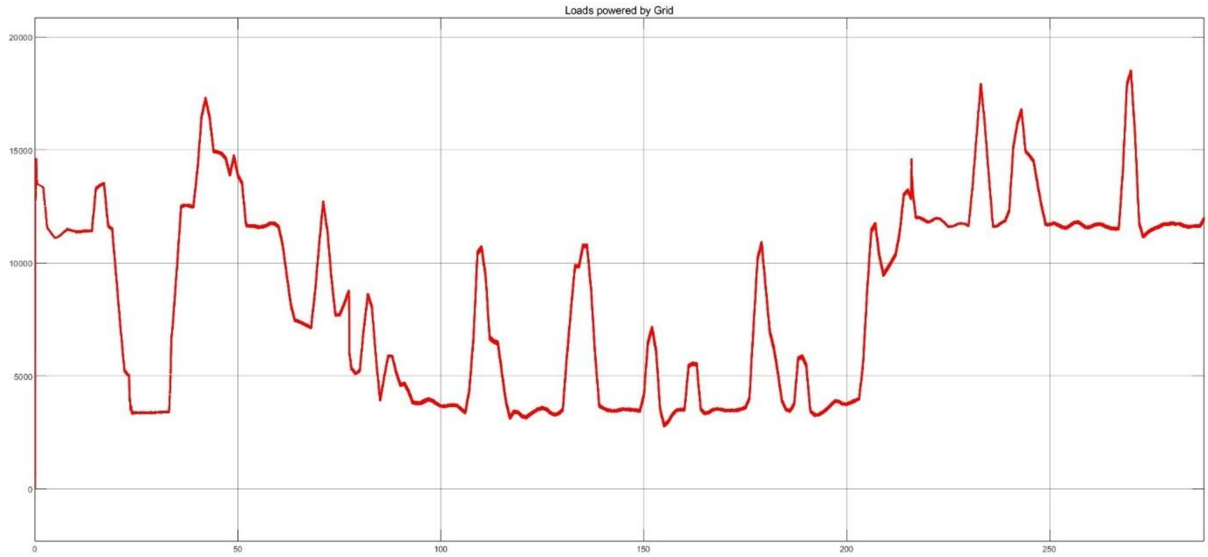

Figure 16: Grid side measurement (3May to 4May)

This measurement uses a 288-point dataset to represent the grid side, considering both grid and PV power supplied to the loads from May 3rd to May 4th. Despite only employing a 24-point dataset to run that model, it is more stable than the 60-kW system, as can be shown.

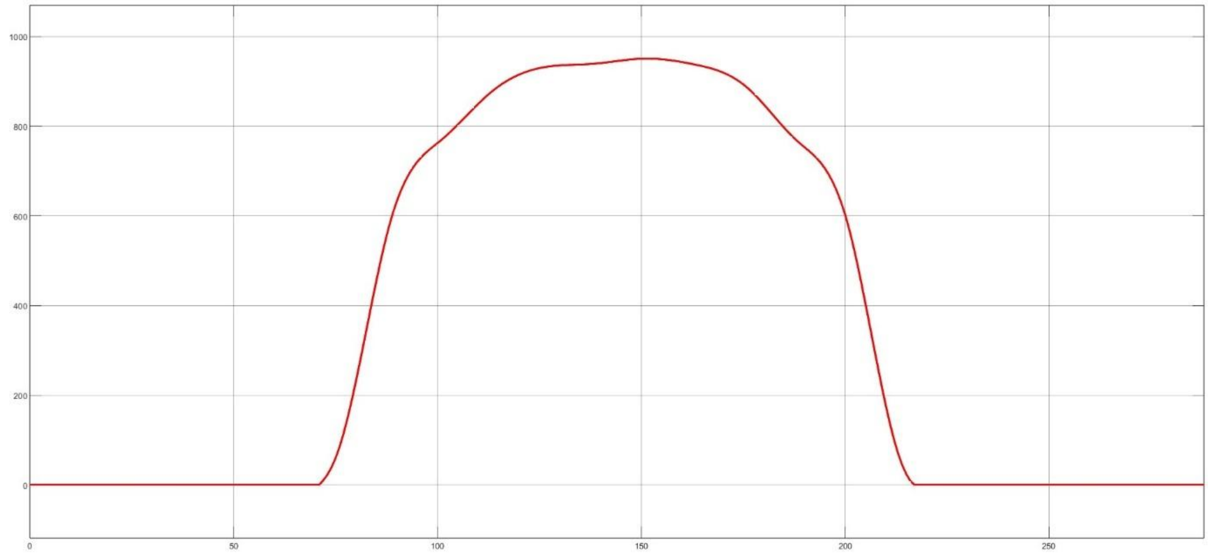

Figure 17: Irradiance Up sampled to 288 points (3May2024 to 4May2024)

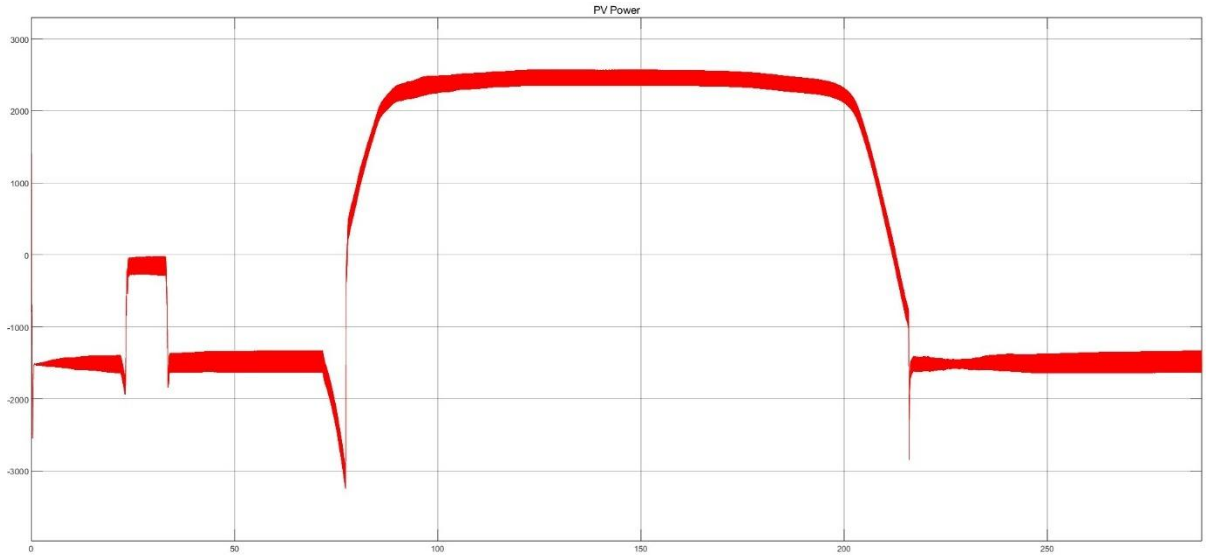

Figure 18: PV side power measurement (3May to 4May)

This is the power supplied by the PV system. From the graph it looks like for the peak hours the PV system power used by the loads and bit going to the grid around 2.5kW to 2,7kW.

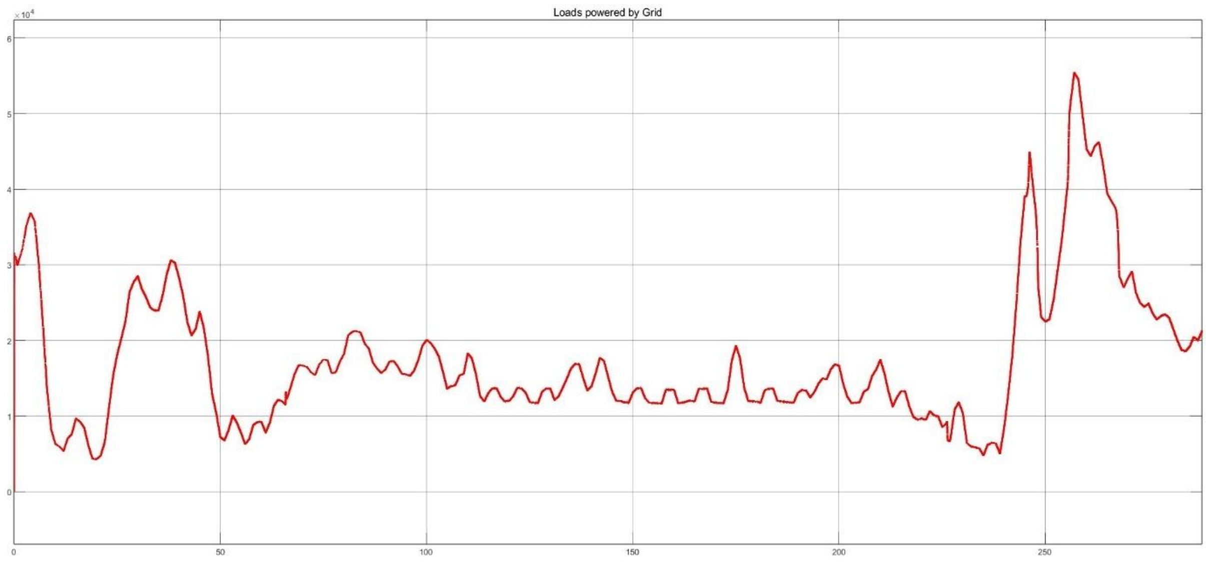

Figure 19: Grid side measurement (7May 11h05 to 8May 11h00)

This is the measurement form the grid side which accounts for both Grid and PV power supplied to the loads for 7May to 8may.

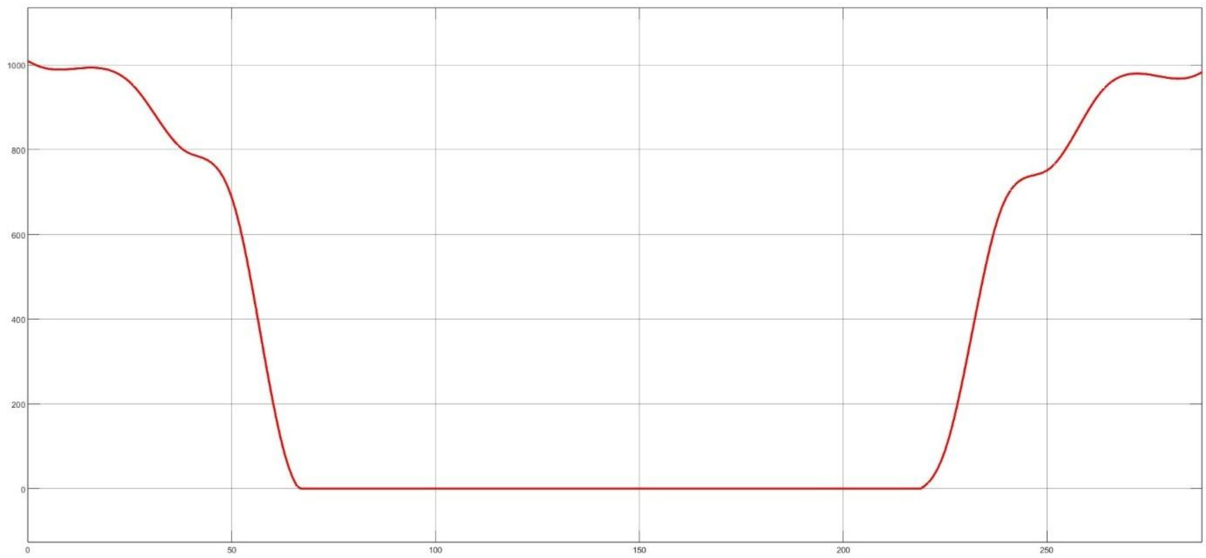

Figure 20: Irradiances (07May 11h05 to 08May 2024 11h00)

Above is the irradiances of 07May to 08May 2024. This data is upsized from 24 points to 288 points to match the size of the original data. Using a python code.

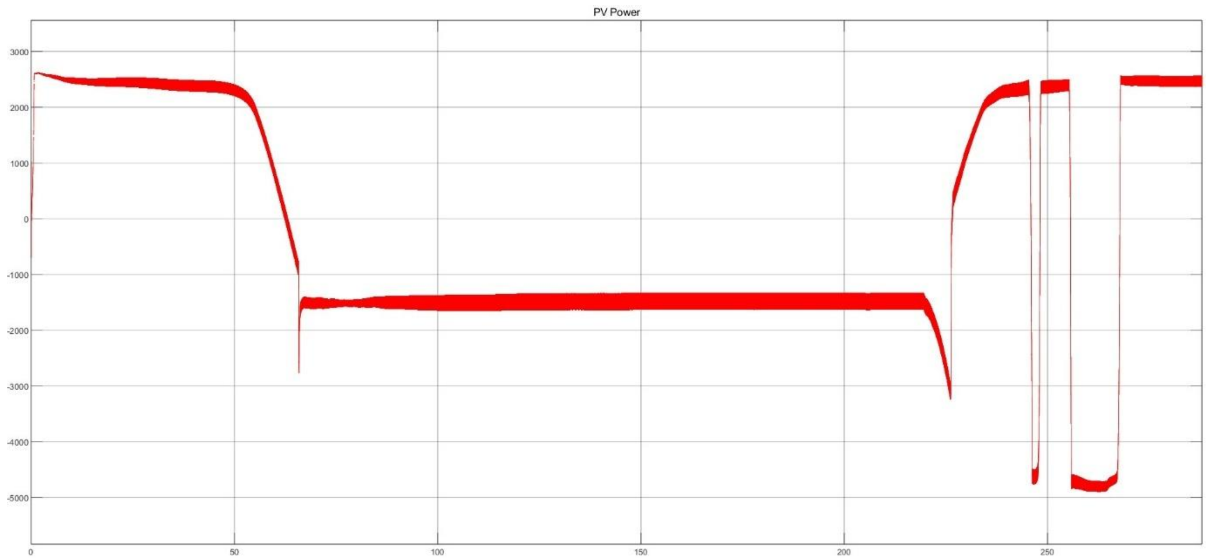

Figure 21: PV side power (7Mat 11h05 to 8May11h00)

This is the power supplied by the PV system. And this show sodden drop in power shows maybe the PV was not used during that time. But it's for a very short period maybe a heavy load kicked in. From the graph it looks like for the peak hours the PV system power used by the loads and bit going to the grid around 2.5kW to 2.7kW.

5.4. Simulation Results and Analysis

The simulations provided insights into energy consumption patterns and the potential contribution of the PV system.

5.4.1. Measured Daily and Monthly Energy Consumption & Cost

Based on the measured farm data (30 April - 8 May 2025) and processed using Python with a tiered City Power tariff:

- The daily energy consumption and corresponding costs were calculated [22].

Table 1: Daily energy consumption and corresponding costs [22]

Dates	Energy (kWh)	Cost (R) each day
2025-04-30	186.57	R391.28
2025-05-01	258.57	R542.28
2025-05-02	232.62	R487.86
2025-05-03	128.58	R269.67
2025-05-04	161.29	R338.26
2025-05-05	232.66	R487.96
2025-05-06	258.91	R543.00
2025-05-07	276.65	R580.21
2025-05-08	164.06	R344.08

City Power prepaid

	Block 1 0-350kWh	Block 2 351-500kW	Block 3 >500kWh	kWh	Average price per kWh
per kWh	182,37c	209,19c	238,37c		
Rand, inc Vat	2,097255	2,405685	2,741255		
Customer A					
R1 500	350 kWh	150 kWh	147.78 kWh	647.8	R2.32
Customer B					
R1 000	350 kWh	110.56 kWh		647.8	R2.32
R500		39.44 kWh	148.17 kWh		
Customer C					
R500	238.41 kWh			647.8	R2.32
R500	111.59 kWh	110.56 kWh			
R500		39.44 kWh	147.78 kWh		
Customer D					
R2 500, but only uses R1 500	350 kWh	150 kWh	512.58 kWh	1012	R2.46

Figure 22: Tariff Table used to calculate energy cost [25]

- **Monthly Projection (Based on Measured Data)**: The total power consumption by the farm for the month of May (projected from 7 representative days) on the grid was 6816.89 kWh. Using the block IBT tariff method, the cost was R 18411.10. Using an average flat rate of R2.32/kWh (derived from tariff table), the cost was R 15815.18.

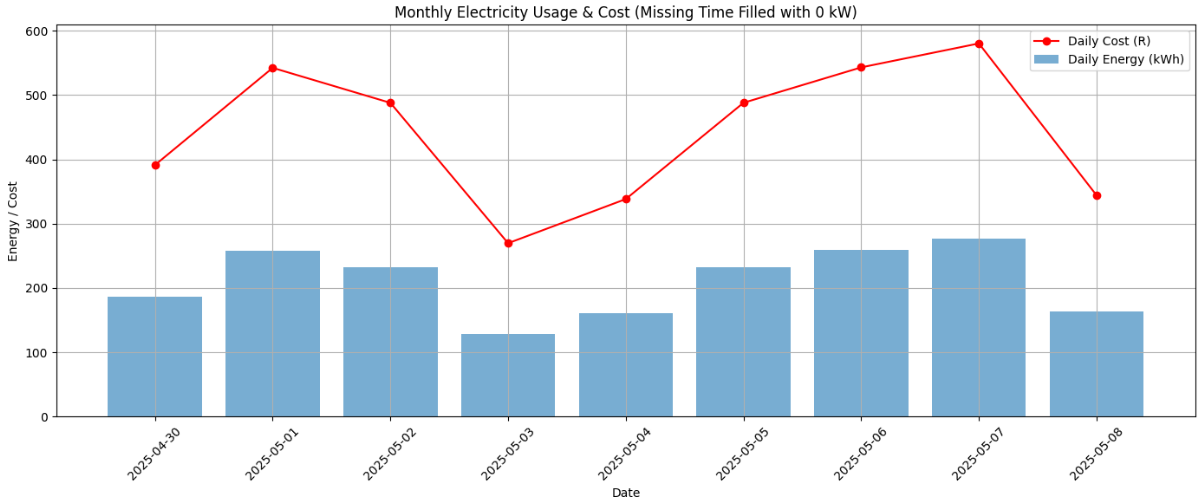

Figure 23: Graph of Monthly Electricity Usage & Cost (Missing Time Filled with 0 kW)

5.4.2. Simulated Energy Consumption and PV Contribution

The final Simulink simulation results for daily load consumption and PV generation were:

Table 2: Daily load consumption and PV generation for each day

Days	Dates	Loads (kWh) - Simulated	PV (kWh) - Simulated
Wednesday	2025-04-30	186.7848	35.2016
Thursday	2025-05-01	259.7219	62.9228
Friday	2025-05-02	233.2452	63.3222
Saturday	2025-05-03	129.5364	62.4094
Sunday	2025-05-04	161.9154	63.2889
Monday	2025-05-05	233.3514	63.1264
Tuesday	2025-05-06	259.2660	63.1547
Wednesday	2025-05-07	277.3820	63.3203
Thursday	2025-05-08	162.6095	37.9872

- A MATLAB code was used to calculate the data in the table. It used the trapezoidal method to determine the area under the curve (in kWh) after computing the difference between the grid and load readings.
- The simulated load consumption closely matched the original measured data.
- The average daily PV power generation (excluding partial days 2024-04-30 and 2024-05-08) was 63.0778 kWh.
- Total simulated PV power for 31 days in May: 63.0778 kWh/day * 31 days = 1955.4118 kWh.
- Total simulated farm consumption for May (projected): 4 x (161.9151+233.3514+259.2660+277.3820) + 5 x (259.7219 + 233.2452+129.5364) = 6840.1755 kWh.
- The PV system produces approximately 28.587% of the total simulated power consumption

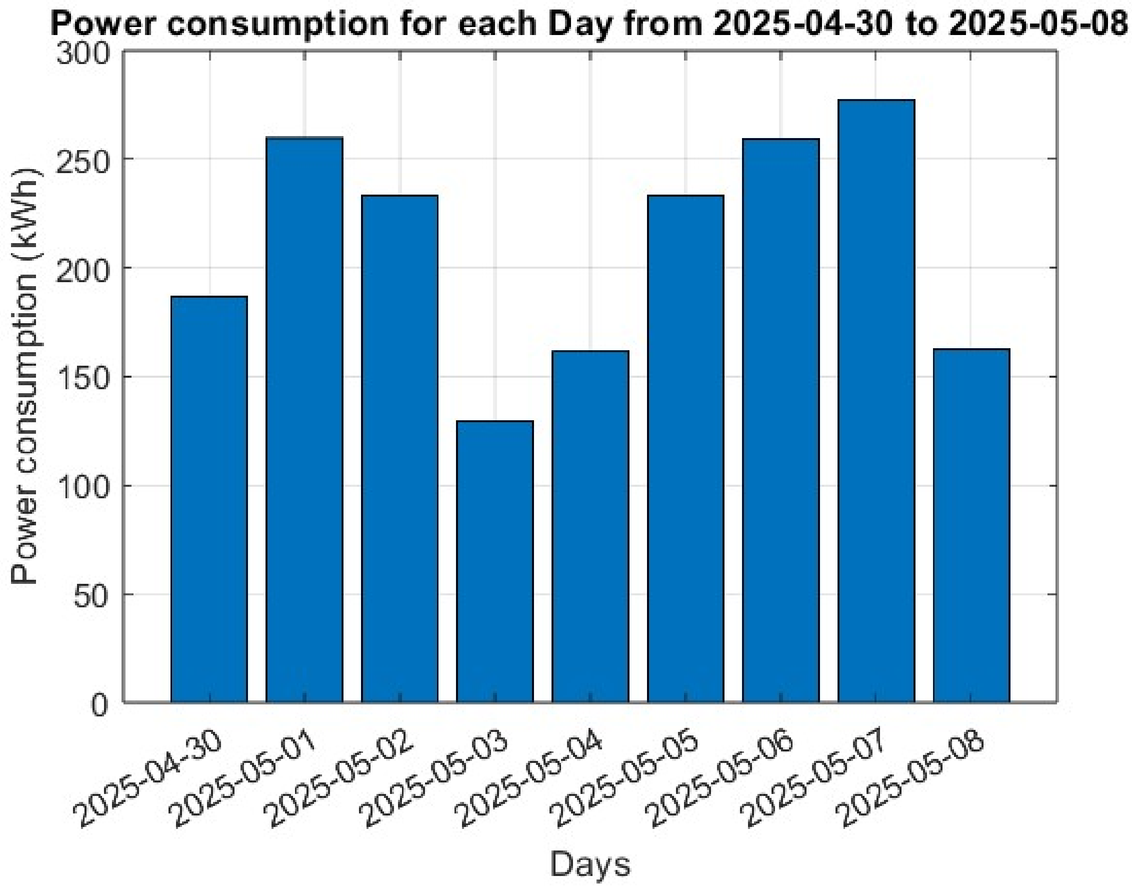

Figure 24: Bar chart of Power consumption for each Day (Simulated)

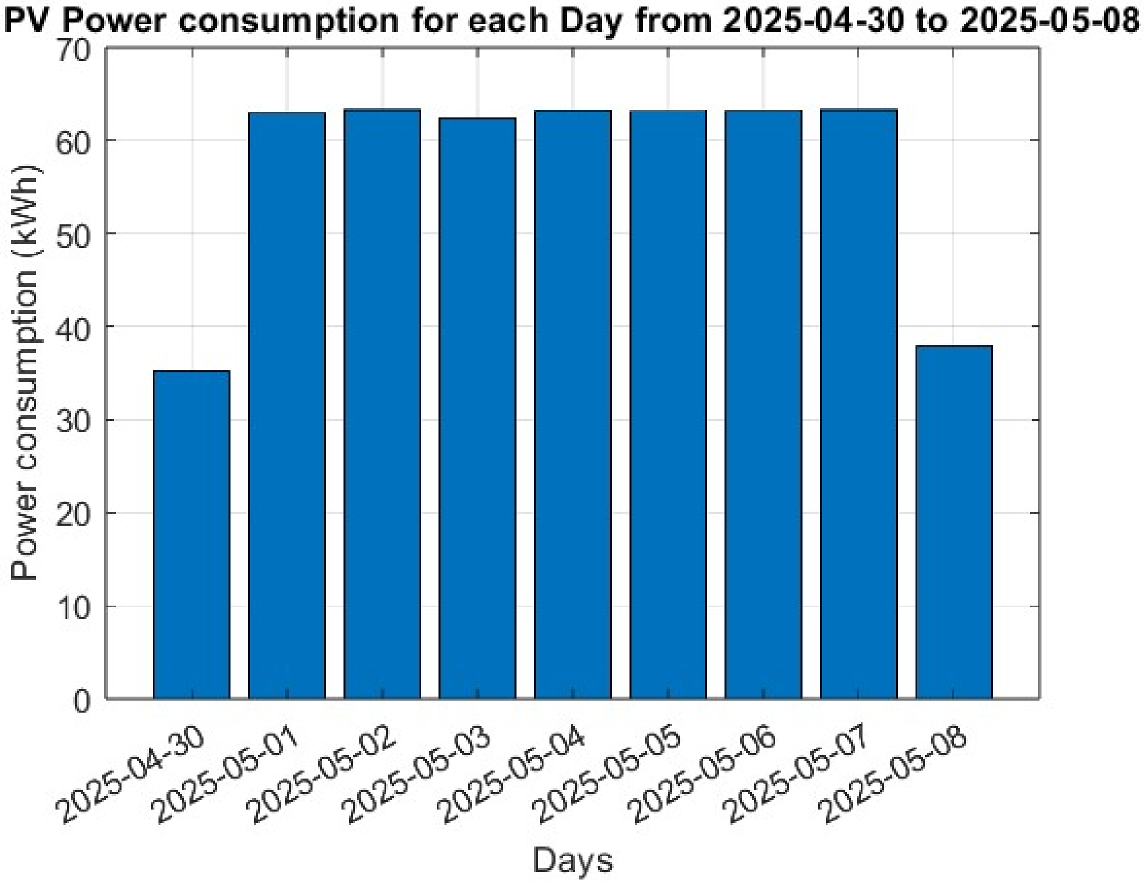

Figure 25: Bar chart of PV Power consumption for each Day (Simulated)

5.4.3. Cost Savings Analysis

- Simulated power provided by grid after PV = 6840.1755 kWh - 1955.4118 kWh = 4884.7637 kWh.
- Estimated electricity cost for grid power (with PV) using block IBT method: R 13114.65.
- Estimated electricity cost for grid power (with PV) using flat rate (R2.32/kWh): R 11332.65.
- Compared to the measured grid-only cost (R 18411.10 using block IBT), the farm will save between R 4536.56 (R 15815.18 – R 11332.65) and R 5360.28 (R18411.10 - R13114.65 and ignoring the -23.28kWh between the simulated results and measured results) per month.

5.5. Cost of Implementation and Payback Period (25kW Hybrid PV System)

5.5.1. Component Costs for 25kW Hybrid PV System

The following table details the estimated costs for installing a 25kW hybrid PV system, compliant with South African standards. The chosen components include JA Solar 500W panels and a Sunsynk 25kW HV inverter.

Table 3: Cost of Implementation for 25kW PV System

Component	Specifications	Qty	Unit Cost (ZAR)	Total Cost (ZAR)	Compliance
Solar Panels [18]	JA Solar JAM72S30-500/MR Mono PERC (500W)	50	R 2575	R 128750	SANS/IEC 61215, 61730
Hybrid Inverter [19]	Sunsynk 25kW HV (3-Phase) with anti-islanding & grid sync	1	R 55995	R 55995	NRS 097-2-3, SANS 62109-2
Mounting Structure [26]	Galvanized steel (ground-mount), wind-load certified for farm terrain	1 set	R 50000	R 50000	SANS 10409, SANS 10160-3
DC/AC Cables estimated	$6mm^2$ PV1-F DC cables (UV-resistant), $16mm^2$ AC cables (Copper)	1 lot	R 10000	R 10000	SANS 10142, SANS 1507-2
Protection Devices [27]	DC isolators (1000V), AC isolators, SPD Type I+II (DC & AC sides)	1 set	R 4000	R 4000	SANS 10142-1, IEC 61643-11
Bidirectional Meter [28]	Landis+Gyr E350 (Utility-approved, MID-certified)	1	R 3000	R 3000	NRS 097-2-1, Municipal SSEG
Lightning Protection [29]	Furse ESP T2/T3 Surge Arrestors + grounding kit (≤10Ω earth resistance)	1 set	R 14000	R 14000	SANS 62305, IEC 62561
Installation Labour [4]	SAPVIA-accredited installer (PV GreenCard certified)	1	R 60000	R 60000	OHS Act 85/1993
Structural Engineering	Load-bearing report & foundation design	1	R 15000	R 15000	SANS 10400, SANS 10409
Compliance Certs [30]	CoC, NERSA registration, Municipal SSEG approval	1 set	R 6000	R 6000	EEB 705, NRS 097
total estimated cost:				**R 343 745**	

5.5.2. Payback Period Calculation

- **Monthly Savings**: The farm is projected to save between R 4536.56 and R 5360.28 per month.
- **Average Monthly Saving** = (R 4536.56 + R 5360.28) / 2 = R 4948.42
- **Annual Savings**: R 4948.42/month * 12 months = R 59,381.04 per year.
- **Payback Period**: R 343,745 / R 59,381.04 per year = approximately 5 years and 9 months.

This payback period does not include the cost of batteries. If batteries were included, the initial investment would be higher, and the payback period longer, though savings might also increase if time-of-use tariffs or self-consumption is further optimized.

5.6. Engineering Skills and Tools Utilized

5.6.1. Skills Applied

The project drew upon several key skills:

- Understanding of PV systems (components, grid-tie operation, safety, risk).
- Data analysis and interpretation.
- Cost estimation for renewable energy projects.
- Knowledge of relevant South African electrical standards and regulations (SANS, NRS).
- Electrical system design (connecting PV to distribution board, phase balancing).
- Simulation and modelling with MATLAB Simulink.
- Algorithm design and programming with Python (for load profiling, data processing, automation).

5.6.2. Software and Hardware Tools

- **MATLAB Simulink**: Used to build and simulate the digital twin of the farm's energy system.
- **Python**: Employed for data acquisition from CSV, load profiling algorithms, data reduction, data conversion (Excel/CSV to .mat), and cost/consumption calculations. Libraries used include pandas, NumPy, Matplotlib, and SciPy.
- **Google Gemini 2.5 Pro**: Assisted with algorithm design for Python scripts.
- **Dranetz EP1 & EP-Writer Software**: Used for measuring farm loads and exporting data to CSV.
- **NASA POWER Website**: Source for solar irradiance data.
- **Microsoft Excel**: For initial data handling and as an input/output format for Python scripts.

This comprehensive methodology allowed for the development of a detailed digital twin, providing valuable insights into the farm's energy dynamics and the techno-economic feasibility of the proposed solar PV solution.

6. Expected Outcomes:

This research project, through the development and simulation of the digital twin, is expected to deliver several key outcomes that address the initial objectives of optimizing energy management and reducing operational costs for the farm. These outcomes are:

6.1. A Comprehensive and Functioning MATLAB Simulink Model

The primary outcome will be a detailed and operational digital twin of the farm's hybrid solar-grid energy system, constructed within MATLAB Simulink.

- This model will accurately represent:
  - **Dynamic Farm Loads**: Incorporating realistic load profiles derived from processed measurement data for various single-phase and three-phase equipment on the farm. This includes the use of the "Single Phase Dynamic Load Block" from MATLAB examples and three-phase dynamic load blocks from simulink.
  - **Solar PV System**: A functional model of the solar PV array using the "DecoupledPVArrayGrid" example, configured with specifications from JA Solar 500W panels and driven by real-world irradiance data.
  - **Grid Connection**: The interaction with the utility grid.

  - **Battery Charging System**: A model for the golf cart battery charging system, adapted from the MATLAB example "Charging of Battery Using Buck Converter powered by PV MPPT."
  - **Backup Generator Logic**: Simulation of the farm's backup generators and their switching mechanisms.
- This integrated Simulink model serves as a virtual testbed for the farm's entire energy infrastructure.

6.2. Demonstrated Methodologies for Evaluating Control and Management Strategies

The project will showcase effective methods for analysing and evaluating different energy management approaches.

- **Data-Driven Scenario Analysis**: The digital twin will be used to simulate farm operations under various conditions, such as days with the highest and lowest power consumption. This is achieved by preparing specific data sets (e.g. for peak and off-peak load days) to test the system's response and efficiency.
- **Energy Calculation and Costing**: The use of the trapezoidal rule (implemented in Python) to accurately calculate energy consumption (kWh) from power data provides a reliable method for assessing energy usage and associated costs under different simulated scenarios (e.g. grid-only and grid + PV).

While advanced AI-driven control strategies are a potential future development, this project lays the groundwork by creating the platform to test such strategies. The immediate control strategies evaluated involve understanding system performance under different existing load patterns and PV contributions.

6.3. Foundational Capabilities for Predictive Maintenance

Although fully developed predictive maintenance algorithms are beyond the current scope and would require further AI integration, the digital twin is expected to provide the essential foundation for such capabilities.

- By modelling individual components and their operational loads, the digital twin can generate data that could, in future work, be used to simulate component stress, wear, and potential degradation patterns. This is the first step towards predicting maintenance needs.

6.4. An Adaptable and Potentially Scalable Simulation Framework

The project is expected to produce a simulation framework that is both adaptable and offers potential for future scalability.

- **Code Adaptability**: The Python scripts developed for data processing (load profiling, energy calculation, data reduction/upsampling) are structured to allow for easy modifications, such as changing file paths, adjusting time windows for analysis, or adding/removing individual loads.
- **Simulink Model Adaptability**: The Simulink model itself is designed with a degree of flexibility. For instance, the size of the PV array (number of panels) can be adjusted, and different load components can be modified or increased to simulate changes in farm operations or scale.

- **Room for Improvement**: The current model structure allows for future enhancements, such as more detailed battery-to-inverter interaction or the integration of more sophisticated AI-based control logic.

This adaptability will also enable the model to be potentially tuned to represent different agricultural environments or farm types with similar energy system components, fulfilling one of the aims of the original proposal.

6.5. Clear Economic Insights and Cost-Benefit Demonstration

A significant outcome will be a quantitative demonstration of the potential economic benefits of implementing a hybrid solar PV system on the farm.

- The simulations will provide clear estimates of:
  - Total farm energy consumption.
  - The contribution of the solar PV system to meeting this demand.
  - The reduction in electricity purchased from the grid.
- Based on these figures and local electricity tariffs, the project will deliver a tangible estimate of monthly and annual cost savings for the farm, along with a calculated payback period for the proposed 25kW PV system (excluding batteries for the initial payback calculation). This directly addresses the core objective of agricultural cost optimization.

These outcomes collectively will demonstrate the value of using a digital twin approach for designing, analysing, and optimizing hybrid energy systems in an agricultural context.

7. Alternatives Evaluated:

During the development of the digital twin and the design of the proposed hybrid solar-grid system, several alternative approaches and system configurations were considered and evaluated. These evaluations helped in refining the final proposed solution.

7.1. Alternative Data Input Methods for the Digital Twin

- **Scheduled Load Operation vs. Measured Data**:
  - **Alternative Considered**: One initial thought was to model farm loads based solely on their theoretical operating times as listed in the load table (p.3), without using the dynamically measured power data.
  - **Evaluation**: This approach was quickly deemed insufficient. While simpler to implement, it would not create a true digital twin or a "close enough model" of the farm's actual, variable energy consumption patterns. The measured data provides a much more realistic basis for simulation and optimization. The decision was made to prioritize the use of actual measured load data processed by the Python algorithm for greater accuracy.

7.2. Alternative PV System Sizing and Configurations

- **60kW PV System with Large Battery Bank**:

  - **Alternative Considered**: Based on the peak farm demand of 50-60kW, a 60kW PV system was conceptually explored (as simulated in early tests where only PV powered loads, see OCR page 9 of the simulation document).
  - **Evaluation**: It was determined that a 60kW PV system would likely require a substantial battery storage system (estimated around 40-50kWh) to provide consistent power throughout the day and cover periods without sunshine.
    - **Feasibility Concerns**: While potentially capable of powering the farm, this larger system was considered less feasible for the initial stage due to significantly higher upfront costs (for both PV panels and batteries), increased maintenance complexity, and safety considerations related to large battery installations (including installation safety and security from theft).
    - **Stability**: Early simulations of PV-only systems (without grid or significant battery buffering) also showed instability due to inrush currents and voltage fluctuations when solely powering dynamic loads.
  - The current digital twin model, while incorporating battery charging for golf carts, does not yet fully simulate a large battery system discharging to power the main farm inverter. This remains an area for future testing.
- **Dedicated Solar for Residential Houses (Off-Grid Potential):**
  - **Alternative Considered**: An alternative strategy discussed was to potentially power all three residential houses primarily with a dedicated solar PV system, possibly aiming for off-grid operation for the houses.
  - **Evaluation**: Measurements indicated that the houses collectively require approximately 6-9kW of power. This smaller, dedicated system might be a viable option to significantly reduce the residential load on the main grid or larger hybrid system. The heavy agricultural loads could then be managed by the main grid and a separate, appropriately sized PV system. This alternative was not fully simulated in the current project phase but represents a plausible future configuration.
- **Smaller Initial PV System (e.g. 15kW):**
  - **Alternative Considered**: Instead of the proposed 25kW PV system, installing a smaller system, such as 15kW, in the initial phase was contemplated.
  - **Evaluation**: The rationale was that a 15kW system might still provide significant benefits in reducing grid consumption, particularly on days with lower overall farm demand (15-30kW range). It would have a lower upfront cost. However, the detailed performance comparison and economic viability of a 15kW system versus the 25kW system would require further specific simulation runs and cost analysis. The 25kW system was chosen for detailed analysis as it offered a balance between addressing a significant portion of the load (especially during lighter days) and manageable upfront costs.

7.3. Alternative Component Selections:

While not explicitly framed as A/B testing of complete systems, the research into different solar panels and inverters represented an implicit evaluation of alternatives:

- **Solar Panels**: Various 500W panels were researched (Canadian Solar, ARTSolar, Jinko, JA Solar, Longi). The JA Solar 500W panel was ultimately selected for modelling, likely based on a balance of cost, availability, and specifications.

- **Inverters**: Different inverter capacities (25kW, 60kW) and types (grid-tie, hybrid) were investigated. The Sunsynk 25kW HV hybrid inverter was chosen for the 25kW system costing, indicating a preference for a hybrid-ready system for potential future battery integration.

The evaluation of these alternatives, whether through direct simulation, feasibility discussions, or component research, guided the design towards the proposed 25kW hybrid PV system coupled with the detailed digital twin model as the most balanced and practical solution for the project's objectives and the farm's constraints

8. Validation Approach:

To ensure the digital twin developed in MATLAB Simulink accurately represents the real-world energy system of the farm and that its outputs are reliable for decision-making, a multi-faceted validation approach was planned. The goal is not necessarily a perfect 1:1 match, which is often unattainable in complex simulations, but rather to confirm that the model is "fit for purpose" – meaning it provides sufficiently credible results to support the project's objectives, such as assessing energy consumption patterns and the economic viability of the solar PV system.

The validation steps include:

8.1. Comparison with Measured Farm Data

This is the primary method for validating the overall system behaviour.

- Total Energy Consumption (kWh):
  - The total energy consumed by the farm as simulated by the digital twin over specific periods (like daily, weekly, or monthly projections) will be compared against the actual energy consumption calculated from the measured Dranetz EP1 data for corresponding periods. This involves comparing the area under the curve of the power profiles.
  - It was noted in the data analysis that the initial total monthly PV power projected from simulation (1955.4118 kWh) showed a discrepancy when compared to raw EP1 data (error of -23.2855 kWh). This highlights the importance of this comparison and helps quantify the overall model deviation for energy totals.
- Load Profile Matching (Shape and Peaks):
  - Beyond total energy, the shape of the simulated load profile over a 24-hour period will be qualitatively and quantitatively compared to the measured load profile.
  - Importance of Peaks: Particular attention will be paid to validating the peak power demands. As you noted, accurately capturing these peaks, even if short-lived, is crucial because they dictate the highest power requirements for the system and are essential for correct sizing of components like inverters and for understanding potential stress on the grid connection.
  - The simulation results indicated that the daily load consumption graphs from the final simulation "matches closely to the original measured data", which is a positive indicator for load profile validation.

  - Initial rapid tests using heavily reduced data (24 points per day instead of 288) showed a high Mean Absolute Percentage Error (MAPE). This confirmed the decision to use the full 288 daily data points for the final simulations to improve the accuracy of profile matching, despite longer simulation times.

8.2. Benchmarking and Reasonableness Checks

This addresses the feedback to compare against theoretical models and expected performance benchmarks.

- **PV System Output Verification**: The simulated output of the PV system (e.g., daily kWh generation) will be assessed for reasonableness based on:
  - The input solar irradiance data for the simulated days.
  - The specifications of the PV panels (JA Solar 500W) and the total system size (e.g., 25kW).
  - General efficiency expectations for PV systems in the given geographical location. This acts as a comparison against a theoretical or expected performance benchmark.

- **Component Behaviour**: Individual sub-models within the digital twin (e.g., battery charger, generator logic) will be checked to ensure they behave in a logically consistent manner according to their design and MATLAB example origins. For instance, the battery charging model should show charging during daylight hours when surplus PV might be available or as per its control logic.

8.3. Internal Consistency and Logic Checks

The interactions between different parts of the model (grid, PV, loads, batteries, generators) will be reviewed to ensure they follow expected energy flow principles and control logic implemented in the simulation. For example, power from the PV system should reduce grid import when available.

8.4. Addressing Discrepancies and Model Refinement

- Any significant deviations identified during the validation process will be investigated. Potential sources of error could include:
  - Simplifications made in the load profiling algorithm.
  - Assumptions about component efficiencies or characteristics in the Simulink models.
  - The inherent differences between a simulated environment and the real physical world.
- The validation process is iterative. Ideally, identified discrepancies would lead to refinements in the model parameters or structure to improve its accuracy. For this project, the validation aims to establish the current model's level of credibility.

By performing these validation steps, confidence in the digital twin's ability to simulate the farm's energy system can be established. This ensures that the expected outcomes regarding energy savings and system performance are based on a credible simulation foundation.

9. Design Process, Issues, Constraints, and Risks:

The development of the digital twin for the farm's hybrid energy system followed a structured design process, but also encountered several issues, operated under certain constraints, and involved managing potential risks.

9.1. Design Process Overview

The design process was iterative and can be summarized as follows:

- **Initial Sizing and Feasibility**: Preliminary tests and analysis of measured peak (50-60kW) and off-peak (15-30kW) farm loads to estimate potential PV system sizes (e.g., initial thoughts around 20-25kW minimum, up to 60kW for full coverage).
- **Data Acquisition**: Collection of detailed farm load data using a Dranetz EP1 and solar irradiance data from NASA POWER.
- **Data Preprocessing**: Extensive data cleaning, correction (for voltage measurement errors, missing timestamps) using linear interpolation, and load profile generation using Python algorithms (assisted by Google Gemini 2.5 Pro). This also involved strategies for data point reduction for initial computationally heavy simulations.
- **Grid-Only Load Modelling**: Initial Simulink models were created to simulate farm loads powered solely by the grid, which helped in verifying load block behaviour and basic system response.
- **PV System Integration**: The "DecoupledPVArrayGrid" MATLAB model was integrated, configured with JA Solar 500W panel data and driven by processed irradiance data. Early tests included a 60kW PV system to assess its behaviour and identify issues like inrush current.
- **Battery and Generator Integration**: The final Simulink model incorporated the golf cart battery charging system (using a MATLAB example) and the farm's backup generators (120kW and 15kW) with appropriate switching logic.
- **Simulation and Analysis**: The final, more detailed model (using 288 daily data points) was run for representative high and low consumption days to assess energy flows, PV contribution, and potential cost savings.
- **Economic Assessment**: Calculation of installation costs for a proposed 25kW hybrid PV system and estimation of the payback period based on simulated energy savings.

9.2. Key Design Issues and Constraints

Several factors constrained the design and development process:

- **Computational Limitations**:
  - Simulating the detailed model with numerous loads and 288 daily data points was computationally intensive. Initial full data simulations took 30-45 minutes, and the final model runs took approximately 90 minutes.
  - This necessitated strategies like data reduction (to 24 points per day for some early tests, which introduced significant error) and aggregation of load blocks in Simulink to make iterative testing more manageable.
- **Data Accuracy and Reduction**:
  - Measurement Inaccuracies: An initial error in one of the measured voltage phases required correction through interpolation.
  - Missing Data: The original 10-minute timestamp data had gaps, which were filled using linear interpolation.

  - Irradiance Data Proxy: Using 2024 irradiance data for a 2025 simulation period was a necessary approximation due to data availability.
  - Data Reduction Impact: While data reduction sped up initial tests, it significantly impacted accuracy (e.g., MAPE of ~50% for 24-point data), leading to the decision to use the more complete 288-point dataset for final analyses despite longer run times.
- **Model Abstraction and Simplification**:
  - Component Realism: The Simulink models for components like inverters, PV panels ("DecoupledPVArrayGrid"), and battery chargers ("Charging of Battery Using Buck Converter") are based on MATLAB examples or generic blocks. These are effective for system-level simulation but do not perfectly replicate the nuanced behaviour of specific real-world hardware. For instance, the inverter model in Simulink may not fully capture all characteristics of a physical Sunsynk inverter.
  - Load Aggregation: Combining multiple three-phase loads or house loads into single blocks in Simulink was done to reduce simulation time, which is a form of model simplification.
- **Software and Tooling**:
  - Simulink Block Availability: The lack of a readily available single-phase dynamic load block in the standard Simulink toolbox necessitated the adaptation of a MATLAB example.
  - Block Integration: Ensuring seamless and correct interaction between different Simulink blocks from various sources (examples, standard library) required careful configuration.
- **Farm's Limited Budget:** Although not a direct constraint on the simulation itself, the farm's limited budget (mentioned in the proposal) was an overarching consideration that influenced the practical scale of the proposed PV system (like favouring a 25kW system over a much larger, more expensive 60kW + large battery setup for initial recommendation).

9.3. Potential Risks and Mitigation Approaches

Several risks were identified during the project:

- **Risk 1: Inaccurate Simulation Predictions**.
  - Potential Cause: Residual errors in input data (measurements, irradiance proxy), simplifications in Simulink component models, assumptions made in the Python load profiling algorithms.
  - Potential Impact: Misleading economic viability assessments, suboptimal sizing of the real PV system, or inaccurate energy saving forecasts.
  - Reduction during Project:
    - Using the most detailed available data (288 points/day) for final simulations.
    - Careful data cleaning and correction procedures.
    - Cross-referencing simulated outputs with basic energy calculations and observed farm behaviour where possible.
    - The validation approach is designed to quantify and understand these factors.
- **Risk 2: Model Validation Challenges**.

    - Potential Cause: Difficulty in obtaining truly independent real-world data for robust validation across diverse operational and weather conditions beyond the initial measurement week.
    - Potential Impact: Reduced confidence in the digital twin's predictive power for scenarios not explicitly covered by the input data.
    - Mitigation during Project: Focusing validation on key metrics like peak matching and overall energy balance against the measured week. Using multiple aspects of validation as outlined in Section 8.
- **Risk 3: Scalability of the Current Simulation Approach**.
    - Potential Cause: If the farm expands significantly or more granular component modelling is required, the current ~90-minute simulation time per day could become a bottleneck for analysis.
    - Potential Impact: Limits the ability to perform extensive "what-if" scenarios or real-time operational decision support.
    - Mitigation Considered: The Python scripts are designed for some adaptability. For much larger scale-ups, further optimization of Simulink models or exploration of dedicated high-performance computing might be needed (future consideration).
- **Risk 4: Environmental Impact if PV Underperforms and Generators Run Excessively**.
    - Potential Cause: Overestimation of PV yield in the simulation, or higher-than-expected loads leading to more frequent backup generator use.
    - Potential Impact:
        - Increased operational costs due to diesel consumption.
        - Higher CO2 emissions than anticipated. For context:
            - Grid electricity in South Africa (2022): ~0.8665 kg CO2/kWh [31].
            - Diesel Generators (15kW - 120kW): Typically 0.8 – 1.0 kg CO2/kWh, highly dependent on load factor and efficiency [32].
    - Mitigation within Project: The digital twin is used to project PV contribution and grid reliance, helping to size the PV system appropriately to minimize generator use for cost and environmental reasons. The model can simulate scenarios to understand this balance.

9.4. Scalability and Adaptability of the Design

The design process and the resulting models incorporate elements of scalability and adaptability:

- **Code Modularity**: Python scripts for data handling are designed so that parameters like file paths, analysis periods, and load definitions can be adjusted with relative ease to accommodate new datasets or slightly different scenarios.
- **Simulink Model Flexibility**: The Simulink model allows for parameters such as the number of PV panels, load characteristics, or generator capacities to be modified, enabling simulation of scaled-up/down systems or different equipment choices.
- **Future Enhancements**: The current structure provides a foundation upon which more complex features can be built, such as detailed battery discharge models powering the inverter, or the integration of more sophisticated AI-driven control strategies for energy optimization.

By acknowledging these issues, constraints, and risks, the project aimed to develop a digital twin that is as robust and reliable as possible within the given limitations, providing a valuable tool for the farm's energy management strategy

10. Impact Assessment:

The implementation of the proposed 25kW hybrid solar-grid system, guided by insights from the digital twin simulation, is projected to have a range of impacts across various domains.

10.1. Economic Impacts and Benefits

- **Significant Cost Savings:** The primary economic benefit is the substantial reduction in the farm's electricity expenditure. Simulations indicate monthly savings between R 4536.56 and R 5360.28 (averaging R 4948.42) by reducing reliance on grid electricity. This directly addresses the farm's limited budget and the project's core goal of cost optimization.
- **Return on Investment:** With an estimated upfront cost of R 549,750 (excluding batteries), the system has a projected payback period of approximately 9.26 years. While a medium-term investment, the long-term savings will contribute positively to the farm's financial health.
- **Improved Budget Predictability:** Reducing dependence on fluctuating grid electricity prices can lead to more stable and predictable operational costs for the farm.
- **Increased Farm Profitability/Sustainability:** Lower energy costs can free up capital for other farm investments, potentially increasing overall productivity and profitability, and contributing to the long-term economic sustainability of the farming operation.
- **Value of Digital Twin:** The digital twin itself, while an upfront development effort, provides economic value by enabling optimized system design, reducing the risk of suboptimal investments, and offering a platform for ongoing operational efficiency improvements.

10.2. Environmental Impacts and Benefits

- **Reduced Carbon Footprint from Grid Electricity:**
    - The PV system is projected to generate approximately 1955.4118 kWh per month (based on 63.0778 kWh/day). This energy directly displaces grid electricity.
    - In South Africa (2022), grid electricity has an emission factor of approximately 0.8665 kg CO_2 per kWh.
    - Estimated annual CO_2 reduction from displaced grid electricity: 1955.4118 kWh/month * 12 months/year * 0.8665 kg CO_2/kWh ≈ **20,338 kg CO_2 per year (or 20.34 metric tons CO_2 per year)**.
- **Potential Reduction in Backup Generator Use (and Associated Emissions):**
    - While the primary focus is grid displacement, a more reliable power supply supplemented by solar could potentially reduce the runtime of the farm's

existing diesel backup generators (120kW and 15kW) during grid outages or instability.

  - Diesel generators emit approximately 0.8 – 1.0 kg CO_2/kWh. Any reduction in their use would lead to further CO_2 savings and reduced local air pollutant emissions. *The exact reduction depends on current generator usage patterns, which are not detailed.*

- **Promotion of Renewable Energy:** The project serves as a practical example of renewable energy adoption in the agricultural sector, potentially encouraging similar initiatives.
- **Resource Efficiency:** Optimized energy use contributes to broader resource efficiency.
- **Considerations for Component Lifecycle:** While beneficial in operation, the environmental impact of manufacturing, transporting, and eventually disposing of solar panels and electronic components (inverters) should be acknowledged as part of a complete lifecycle assessment. Choosing durable components and planning for responsible recycling are important.

10.3. Social Impacts and Benefits

- **Enhanced Energy Security and Reliability:** Supplementing grid power with on-site solar generation can improve the reliability and stability of the farm's energy supply, reducing disruptions to critical agricultural operations.
- **Improved Working Conditions (Potentially):** A stable power supply can lead to smoother operation of farm equipment and facilities.
- **Skill Development:** The implementation and maintenance of a solar PV system and the use of a digital twin for management may lead to skill development for farm personnel or local technicians.
- **Demonstration and Education:** The project can serve as a demonstration model for other farms in the region, promoting awareness and adoption of renewable energy technologies and advanced energy management practices.

10.4. Legal Impacts

- **Compliance Requirements:** The physical installation of the hybrid PV system necessitates strict adherence to numerous South African standards and regulations, including:
  - **Electrical Safety:** SANS 10142-1 for all electrical installations.
  - **Grid Interconnection:** NRS 097-2-3 for safe and stable connection to the utility grid.
  - **Component Standards:** SABS-approved components for panels, inverters, etc.
  - **Municipal Approvals:** Obtaining necessary permits and approvals from the local municipality (e.g. SSEG registration, CoC).
  - **NERSA Registration:** Mandatory registration of the solar PV system with NERSA by March 2026.

- Meeting these legal requirements is crucial for lawful operation and ensuring the safety and integrity of the system and the grid.

10.5. Health Impacts

- **Minimal Direct Negative Impacts:** A properly designed and installed solar PV system poses minimal direct health risks.
- **Potential Indirect Positive Impacts:**
    - Reduced reliance on potentially polluting grid sources (depending on the grid mix) could contribute to minor improvements in regional air quality.
    - If generator use is reduced, it would lower localized exposure to diesel exhaust fumes, which can have negative health effects.

10.6. Safety Impacts

- **Installation Safety:** Adherence to the Occupational Health and Safety Act (OHS Act 85/1993) and employing SAPVIA-accredited installers is critical to ensure safety during the installation phase.
- **Electrical Safety:** The system involves electrical components and wiring. Compliance with SANS 10142-1, proper use of protection devices (isolators, SPDs), and regular maintenance are essential to mitigate risks of electrical shock or fire.
- **Structural Safety:** Mounting structures for solar panels must be engineered to withstand wind loads (SANS 10409, SANS 10160-3) and ensure long-term stability.
- **Lightning Protection:** Adequate lightning protection (SANS 62305, IEC 62561) is necessary to protect the equipment and ensure safety.
- **Battery Safety (if larger systems were implemented in future):** Large battery banks would introduce additional safety considerations regarding thermal management, fire risks, and chemical hazards, requiring specific safety protocols.

In conclusion, the proposed hybrid solar-grid system, informed by the digital twin, offers significant positive economic and environmental impacts. Social benefits are also anticipated through improved energy security. The key to realizing these benefits lies in careful planning, adherence to all legal and safety standards during implementation, and ongoing system monitoring and maintenance.

11. Assessment of Method and Tools:

The method used in this project, which focused on creating a digital twin with MATLAB Simulink and Python for data processing, was mainly successful in meeting the project's goals. Both the method and the tools, however, have advantages and disadvantages.

11.1. Assessment of the Digital Twin Simulation Method

- **Applicability and Strengths:**
    - **Complex System Analysis:** The digital twin approach was highly suitable for modelling and analysing the complex interactions within the farm's hybrid

energy system, including diverse loads, solar generation, grid interaction, and potential battery/generator use.

- **Scenario Testing & Optimization:** It provided a risk-free virtual environment to test different scenarios (e.g. high/low consumption days), evaluate the impact of the PV system, and begin to explore optimization strategies (e.g. sizing the PV system).
- **Data-Driven Insights:** By integrating real measured farm load data and actual solar irradiance data, the method allowed for data-driven insights into energy consumption patterns and potential savings, moving beyond purely theoretical calculations.
- **Iterative Design:** The development process of the digital twin itself was iterative, allowing for progressive model refinement and incorporation of different components (grid, then PV, then battery/generator).
- **Foundation for Advanced Features:** The created digital twin serves as a solid foundation for future development, such as integrating more sophisticated AI-based control strategies or detailed predictive maintenance algorithms.

- **Limitations and Challenges:**
  - **Model Fidelity vs. Reality:** As with any simulation, the digital twin approximates the real world. Discrepancies can arise from:
    - Simplifications in component models (e.g. generic Simulink blocks for inverters).
    - Accuracy of input data (initial measurement errors, use of proxy irradiance data).
    - Assumptions made during data processing (e.g. linear interpolation for missing data, aggregation of loads).
  - **Computational Resources:** Detailed simulations with high data resolution (288 points/day) were computationally intensive (90-minute run times), which can limit the speed of iterative testing, or the number of scenarios explored. This was a significant constraint noted throughout the project.
  - **Validation Complexity:** Thoroughly validating a complex digital twin against all possible real-world conditions is challenging. The project focused on key metrics, but comprehensive validation would require more extensive data and potentially real-world comparative testing.
  - **Development Effort:** Creating a detailed and reasonably accurate digital twin requires significant effort in data collection, processing, model building, and debugging.

11.2. Assessment of Tools Used

- **MATLAB Simulink:**

- **Strengths:** A powerful and widely accepted environment for dynamic system modelling, especially for power systems and control logic. Its graphical interface and block-based approach facilitate model construction. The availability of relevant examples (DecoupledPVArrayGrid, Single Phase Dynamic Load, Battery Charging) significantly accelerated development.
- **Limitations:** Can be computationally demanding for complex models. Finding specific pre-built blocks for all desired components (e.g. single-phase dynamic load) sometimes required using or adapting examples. Licensing costs can also be a factor for wider adoption.

- **Python (with Pandas, NumPy, Matplotlib, SciPy) [22]:**
  - **Strengths:** Extremely versatile and powerful for data acquisition, cleaning, processing, analysis, and visualization. Its extensive libraries streamlined tasks like CSV handling, numerical calculations (trapezoidal rule, interpolation), optimization (L-BFGS-B), and plotting. The ability to script complex data workflows was invaluable.
  - **Limitations:** Requires programming expertise. The performance of custom algorithms depends on their design and the quality of the input data. Data exchange with Simulink often requires intermediate file formats (e.g., .mat files), adding an extra step.
- **Google Gemini 2.5 Pro:**
  - **Strengths:** Provided useful assistance in designing Python algorithms, potentially speeding up development and offering alternative approaches to data processing logic.
  - **Limitations:** Output requires verification and adaptation to the specific project context. Reliance on an external AI tool means its availability and specific capabilities could change.
- **Dranetz EP1 and EP-Writer Software:**
  - **Strengths:** Specialized hardware and software for accurate power measurement, providing the foundational load data for the project.
  - **Limitations:** Data export and initial processing required specific software and steps. Measurement setup errors (as initially encountered with one phase) can impact data quality if not carefully managed.
- **NASA POWER Website:**
  - **Strengths:** Provides readily accessible and scientifically validated solar irradiance data, crucial for PV modelling.
  - **Limitations:** Data availability might have lags (e.g., 2025 data not available, necessitating use of 2024 data). Data resolution (hourly) required up-sampling.

Overall Assessment:
The chosen combination of the digital twin methodology and the specific software/hardware tools was appropriate and effective for achieving the project's core objectives. The approach

allowed for a detailed investigation into the farm's energy system and a quantitative assessment of the proposed solar PV solution. The primary limitations encountered were related to computational demands and the inherent abstractions in any simulation model. The project successfully navigated many of these by employing careful data processing techniques and making informed decisions about model complexity versus accuracy.

12. Conclusion:

This project successfully demonstrated the development and application of a digital twin to simulate and analyse a hybrid solar-grid energy system for agricultural cost optimization. By integrating measured farm load data, solar irradiance data, and detailed component models within a MATLAB Simulink environment, supported by Python for data processing, a comprehensive virtual representation of the farm's energy infrastructure was created.

The key achievements and conclusions are:

1. **Functional Digital Twin:** A working digital twin was developed, capable of simulating the dynamic interactions between farm loads, grid supply, a 25kW solar PV system, battery charging for auxiliary loads, and backup generators.
2. **Energy Optimization Insights:** The simulation provided valuable insights into the farm's energy consumption patterns, identifying peak demand periods and quantifying the potential contribution of solar PV generation. This directly informed the economic viability assessment.
3. **Significant Cost Savings Potential:** The analysis projected substantial monthly electricity cost savings for the farm (between R 4536.56 and R 5360.28) with the implementation of the 25kW PV system, leading to an estimated payback period of approximately 9.26 years (excluding batteries). This fulfils the primary objective of optimizing for agricultural costs.
4. **Methodology Validation:** The iterative design process, combining data-driven load profiling with established Simulink modelling techniques, proved effective. The importance of accurate, high-resolution data was highlighted, as was the trade-off between simulation fidelity and computational resources.
5. **Environmental Benefits Quantified:** The project estimated a significant annual CO_2 emission reduction of approximately 20.34 metric tons by displacing grid electricity with solar power.
6. **Foundation for Future Work:** The developed digital twin provides a robust platform for future explorations, including the integration of advanced AI-based control strategies, more detailed battery-to-inverter modelling for farm-wide backup, and the development of predictive maintenance capabilities.

While challenges such as computational limitations and the inherent abstractions of simulation models were encountered, the project successfully utilized the digital twin approach to provide actionable insights for the farm. The findings underscore the potential of digital twin technology as a powerful tool for designing, optimizing, and managing sustainable and cost-effective energy solutions in the agricultural sector. The adaptability of the developed models also suggests their potential applicability to other farms with similar energy challenges.

13. References:

[1] S. N. Tripathi, "Project Proposal: Digital Twin Simulation of Hybrid Solar-Grid System for Agricultural Cost Optimization " 2025.

[2] S. A. N. STANDARD, *SANS 10142-1:2006 THE WIRING OF PREMISES PART 1: LOW-VOLTAGE INSTALLATIONS*, 1.5 ed. Standards South Africa, 2006.

[3] M. Bonner and N. Ijumba, "Safety of low voltage switchgear STAs in South Africa-Part 2."

[4] PVGreenCard, "Solar PV Installation Guidelines," Available: https://pvgreencard.co.za/wp-content/uploads/Solar%20PV%20Guidelines%20-%20Digital%20Spread%20High-res.pdf.

[5] D. O. LABOUR, "OCCUPATIONAL HEALTH AND SAFETY ACT, 1993 ELECTRICAL INSTALLATION REGULATIONS," 2009.

[6] C. o. C. Town, "REQUIREMENTS FOR SMALL-SCALE EMBEDDED GENERATION," 2023.

[7] I. A. C. DEPARTMENT OF TRADE, "STANDARDS ACT, 2008 STANDARDS MATTERS," 2020.

[8] B. F. C. o. E. Eskom, Cooper S Cape Agulhas Municipality, *GRID INTERCONNECTION OF EMBEDDED GENERATION PART 2: SMALL-SCALE EMBEDDED GENERATION*, NRS 097-2-3:2023:2 ed. 2023.

[9] Valsa, "Solar Installation Regulations in South Africa," 2023.

[10] G. Gazette, "No. 40 of 2004: National Energy Regulator Act, 2004.," 2005.

[11] R. V. S.-A. VAN DIE, "Government Gazette," *Constitution,* vol. 3, p. 10, 1998.

[12] SAPVIA, "The South African Photovoltaic Industry Association (SAPVIA)," 2025.

[13] A. Rasheed, O. San, and T. Kvamsdal, "Digital twin: Values, challenges and enablers from a modeling perspective," *IEEE access,* vol. 8, pp. 21980-22012, 2020.

[14] J. Pilbeam, *FCS Electrical Systems and Construction L3*. Pearson South Africa, 2008.

[15] C. Verdouw, B. Tekinerdogan, A. Beulens, and S. Wolfert, "Digital twins in smart farming," *Agricultural Systems,* vol. 189, p. 103046, 2021.

[16] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," *Ieee Access,* vol. 6, pp. 3585-3593, 2018.

[17] MATLAB. (2025, June). *Running a Grid-Connected PV Array Model in Real-Time Using Decoupling Line Blocks*. Available: https://in.mathworks.com/help/sps/ug/power-pvarray-grid.html

[18] BHGPower. (June). *JA Solar 500W Mono PERC*. Available: https://bhgpower.co.za/product/ja-solar-500w-mono-perc/?srsltid=AfmBOooKYeWT0pI5__cqlqJpPsS2kzvJ9YPb_aGiQLd4phdn10gIxfx2

[19] JCsolarpanels. (2025, June). *Sunsynk 25kW 3Phase Hybrid HV Inverter*. Available: https://jcsolarpanels.co.za/shop/solar-inverters/sunsynk-25kw-3phase-hybrid-hv-inverter/?srsltid=AfmBOoqbiny3q9ZQvDkELJQUcN_C6tlPHks3HJhJb6SzWB4IPOzoByzi

[20] power.larc.nasa.gov. (2025, June). *NASA Power*. Available: https://power.larc.nasa.gov/

[21] dranetz, "Energy Power Platform (EP1)," 2009.

[22] S. N. tripathi. (2025, June). *GitHub: HonoursResearchProject*. Available: https://github.com/shivendra1T/HonoursResearchProject

[23] MATLAB. (2025, June). *Single Phase Dynamic Load Block*. Available: https://in.mathworks.com/help/sps/ug/single-phase-dynamic-load-block.html
[24] MATLAB. (2025, June). *Charging of Battery Using Buck Converter powered by PV MPPT*. Available: https://in.mathworks.com/matlabcentral/fileexchange/91410-charging-of-battery-using-buck-converter-powered-by-pv-mppt
[25] Moneyweb. (2023, June). *Why it's 'cheaper' to buy prepaid electricity at the beginning of the month*. Available: https://www.moneyweb.co.za/mymoney/moneyweb-personal-finance/why-its-cheaper-to-buy-prepaid-electricity-at-the-beginning-of-the-month/
[26] JESFER. (June). *South Africa Aluminum Mounting System For Ground Solar*. Available: https://www.jesferindustry.com/south-africa-aluminum-mounting-system-for-ground-solar_p186.html
[27] O. electrical. (June). *Isolator Switches*. Available: https://online-electrical-store.co.za/collections/domestic-switch-isolators
[28] EcoFlow. (June). *Prepaid Electricity Meter Price in South Africa: Types, Price Range, and Benefits*. Available: https://www.ecoflow.com/za/blog/prepaid-electricity-meter-price
[29] RS. (June). *WJ Furse, ESP Surge Suppressor Unit 16.7 V Maximum Voltage Rating 5kA Maximum Surge Current RS485 Surge Protector*. Available: https://za.rs-online.com/web/p/surge-suppressor-units/7886744
[30] B. F. C. o. E. Eskom, Cooper S Cape Agulhas Municipality, "Solar registration fees continue to remain zero for the majority of Eskom's residential customers and include a free smart meter until March 2026," 2025.
[31] F. A. T. E. DEPARTMENT OF FORESTRY. (1 November 2024, June). *PUBLICATION OF SOUTH AFRICA'S 2022 GRID EMISSION FACTORS REPORT*. Available: https://www.gov.za/sites/default/files/gcis_document/202411/51495gon5498.pdf
[32] B. Nana, H. Zalle, I. Ouarma, T. Daho, A. Yonli, and A. Bere, "Assessment of carbon dioxide emission factors from power generation in Burkina Faso," *Clean Air Journal,* vol. 33, no. 2, pp. 1-10, 2023.