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MONITORING AND CONTROL SOFTWARE FOR A STANDALONE HOUSE SUPPLY SYSTEM

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This paper presents a software solution for monitoring and controlling electrical power supply in standalone houses, integrating photovoltaic panels, lithium-ion batteries, and Diesel generators. The system aims to ensure reliable and efficient energy autonomy. By employing real-time data analytics, the software analyses load demand and environmental factors, facilitating informed decisions on resource utilization. Simulation results illustrate the applicability of this software in energy management, highlighting the system's adaptability and responsiveness to dynamic energy demands. This approach lays the groundwork for future research in decentralized energy systems.

1. INTRODUCTION

The growing interest in standalone house supply systems can be observed when looking at the increasing number of publications covering this subject over the past decade. Research in this domain has significantly accelerated since 2010, reflecting the urgency of addressing energy autonomy and sustainability challenges.

Standalone houses operating independently of the grid face fluctuating energy production and dynamic consumption patterns [1]. In remote or off-grid environments, innovative energy solutions have been adopted to meet the technical, economic, and environmental requirements, such as hybrid configurations combining solar/wind and backup generators [2,3], energy sharing [4,5], and optimization techniques [6,7]. Energy management strategies aim to achieve autonomy in satisfying the energy demand, while prioritizing the use of renewables and storage technologies to minimize costs [8].

However, despite growing interest, existing solutions often lack real-time data analytics and comprehensive automation. Recent advancements highlight the importance of efficient energy management strategies, as well as monitoring and control mechanisms [9–11] to ensure an uninterrupted and stable power supply.

To address this issue, this paper focuses on the development of a software designed to monitor, control and ensure a reliable supply of electrical power for consumers in an isolated house. The system integrates photovoltaic (PV) panels as a Renewable Energy Source (RES), an electrochemical battery for energy storage, and a Diesel generator to manage peak power demands. By introducing advanced monitoring and supply control mechanisms, the proposed solution analyses load demand and environmental factors influencing the generation continuously, visually displays data and takes decisions on resource utilization, addressing the limitations of autonomous energy supply systems.

2. SYSTEM ARCHITECTURE AND COMPONENT DESIGN

The proposed electrical energy supply system for standalone houses uses an off-grid topology with PV panels, Diesel generators, and lithium-ion batteries, connected in parallel (Fig. 1).

This configuration is designed to intelligently manage power sources and household consumers, ensuring uninterrupted energy production primarily through the PV system, while minimizing reliance on conventional sources.

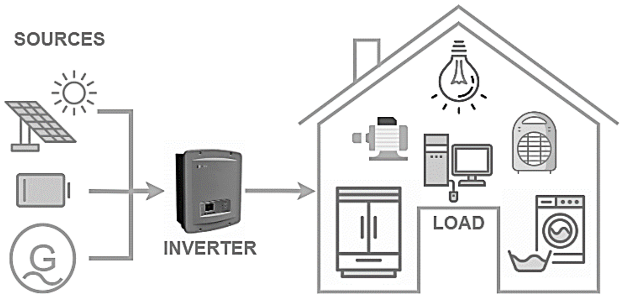

Fig. 1 – Architecture of the proposed standalone house supply system.

This architecture enables the system to seamlessly transition between energy sources or combine them as needed to maintain a continuous power supply under varying conditions. Mathematical models [12] for each energy source are presented to further detail their operational dynamics and contributions to the overall system.

2.1. PV SOURCE MODEL

The power output of the PV modules at time t, denoted as $P_{PV}(t)$, can be calculated using instantaneous and Standard Test Condition (STC) values with the following formula:

$$P_{PV}(t) = P_{STC} \cdot \frac{G_T(t)}{G_{STC}} \cdot [1 - \Upsilon \cdot (T_{PV}(t) - T_{STC})], \quad (1)$$

where: P_{STC} – rated capacity of the PV module at STC [W]; $G_T(t)$ – instantaneous global tilted irradiance on tilted PV module [W/m^2]; G_{STC} – global tilted irradiance at STC, G_{STC} = 1000 W/m^2; Υ – power temperature coefficient, Υ = 0.0037 1/°C; $T_{PV}(t)$ – instantaneous operational temperature of the PV cell [°C]; T_{STC} – reference temperature at STC, T_{STC} = 25 °C; T_A – ambient temperature [°C].

The tilt angles are set at 30° in summer and 60° in winter to optimize solar capture. A lower angle enhances efficiency during the higher solar elevation of summer, while a steeper angle improves exposure to lower-angle sunlight in winter.

The rated capacity of a PV module at STC is provided in the datasheet of the product and can be calculated as:

$$P_{STC} = N_{PV} \cdot \eta_{PV} \cdot A \cdot G_{STC} \quad (2)$$

where: N_{PV} – number of PV modules; η_{PV} – module efficiency [%]; A – surface area of the PV module [m^2].

The temperature of the PV cell is derived from:

$$T_{PV}(t) = T_A(t) + (T_{STC} - T_A(t)) \cdot \frac{G_T(t)}{G_{STC}}, \quad (3)$$

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and the total hourly energy production of PV modules is:

$$E_{\mathrm{PV}} = \int_{t_0}^{t_1} P_{\mathrm{PV}}(t)\,\mathrm{d}t. \tag{4}$$

This model allows for an accurate estimation of the energy produced by the PV system, considering environmental factors such as solar radiation and temperature, which significantly influence performance.

2.2. STORAGE BATTERY MODEL

In standalone renewable energy systems, integrating a backup system is essential to enhance overall reliability. The energy produced by the PV system must meet the hourly load requirements, with any surplus production being stored in the batteries. The energy balance for charging and discharging the batteries can be expressed as follows:

$$E_{\mathrm{B_{ch}}}(t) = E_{\mathrm{B}}(t-1)(1-\sigma) + \left[E_{\mathrm{PV}}(t) - \frac{E_{\mathrm{LOAD}}(t)}{\eta_c}\right], \tag{5}$$

$$E_{\mathrm{B_{disch}}}(t) = E_{\mathrm{B}}(t-1)(1-\sigma) - \left[E_{\mathrm{PV}}(t) - \frac{E_{\mathrm{LOAD}}(t)}{\eta_c}\right], \tag{6}$$

where: $E_{\mathrm{B}}(t)$ – stored energy in the battery at time step t; $E_{\mathrm{B}}(t-1)$ – stored energy in the battery during the previous time step (t-1); σ – battery self-discharge rate, σ = 0.16 % per year; η_C – battery charging efficiency, $\eta_C = 0.86$ for a lifespan of L = 4 years.

This model effectively accounts for both the charging and discharging processes of the battery, incorporating factors such as self-discharge and efficiency to analyse the energy storage dynamics within the system.

2.3. DIESEL GENERATOR MODEL

The Diesel generator (DG) is a synchronous electromechanical machine that serves as a supplementary energy source, providing stable and reliable power when renewable sources are insufficient. The power produced by the DG at any given time t denoted as $P_{\mathrm{DG}}(t)$ can be calculated based on its fuel consumption and efficiency as:

$$P_{\mathrm{DG}}(t) = E_{\mathrm{fuel}} \cdot \eta_{\mathrm{DG}}, \tag{7}$$

$$E_{\mathrm{fuel}} = E_{\mathrm{density}} \cdot C_{\mathrm{fuel}}, \tag{8}$$

where: E_{fuel} – energy content of the fuel consumed per unit time [W]; η_{DG} – efficiency of the DG [%]; C_{fuel} – fuel consumption rate [L/h]; E_{density} – energy density of Diesel fuel [Wh/L], [12].

2.4. POWER FLOW CONTROL MODEL

The model (Fig. 2) for analysing the power supply system of the standalone house considers a DC equivalent circuit for sources and consumers with the assumption that the efficiency of the inverter is unitary. It is noted that the sources have equivalent resistance depending on the operating principle and external conditions. The control of the power circulation between sources and consumers and maintaining the stability of the voltage are ensured by calculating and monitoring the current delivered to the consumers:

$$I = \frac{\frac{E_1}{r_1}\cdot a_1 + \frac{E_2}{r_2}\cdot a_2 + \frac{E_3}{r_3}\cdot a_3}{\frac{a_1}{r_1} + \frac{a_2}{r_2} + \frac{a_3}{r_1}} \cdot \frac{1}{R + \frac{a_1}{r_1} + \frac{a_2}{r_2} + \frac{a_3}{r_1}} \tag{9}$$

where: E_1, E_2, E_3 are the electromotive forces and r_1, r_2, r_3 are the internal resistances of the three sources, namely the PV modules, batteries, and Diesel generator, respectively, R is the equivalent resistance of the consumers, and a_1, a_2, a_3 represent the states of the switches controlling the on-off status of each source. These parameters take values based on whether the respective source is connected or disconnected from the system.

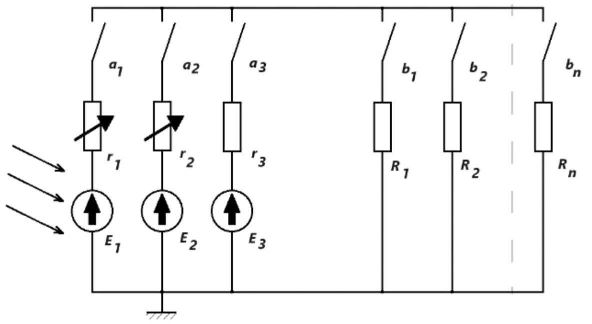

Fig. 2 – Equivalent electric circuit with three sources and *N* consumers.

Voltage supply level control aims to keep the voltage close to its nominal value. For a 230 V source, the terminals should be maintained within ± 10%, or 207–253 V. This is achieved through a command-and-control function, represented by the same relation (9), where the a_i parameters take values depending on the control function designed.

3. MONITORING AND CONTROL SOFTWARE

3.1. STRATEGY FOR MONITORING AND CONTROLLING THE POWER SUPPLY

To monitor and control the power supply of a stand-alone home, the authors developed an energy management strategy whereby the energy generated by hybrid sources covers different consumption profiles. The energy management strategy entails that during periods with abundant solar generation, the PV panels, managed by a voltage controller, cover the load demand and charge the batteries. When sunlight is low, the battery provides the necessary energy, and during high demand, the system integrates the Diesel generator via a rectifier and inverter to supplement power. This adaptive hybrid approach maximizes renewable energy usage, showcasing the role of smart technologies in addressing energy challenges in autonomous systems.

This system allows monitoring of multiple signals from various devices through a single server, making it adaptable for both small and large applications. Data acquisition is facilitated via transducers, sensors, and actuators located throughout the system, with the ability to issue warnings and alarms when data deviates from normal operating ranges.

The software employs the Open Platform Communications (OPC) Unified Architecture (UA) framework, providing unified services for real-time access, alerts, and historical data storage. This protocol has been widely adopted in the industrial sector and standardized by the IEC through the IEC 62541 standard.

3.2. THE OPAC UA MODEL

The OPC UA model is a robust framework based on the client-server architecture for internet services, particularized through its specific *opc.tcp* protocol. This model enhances interoperability and communication in industrial automation and enables operation on all types of platforms (desktops, laptops, tablets, and mobile devices).

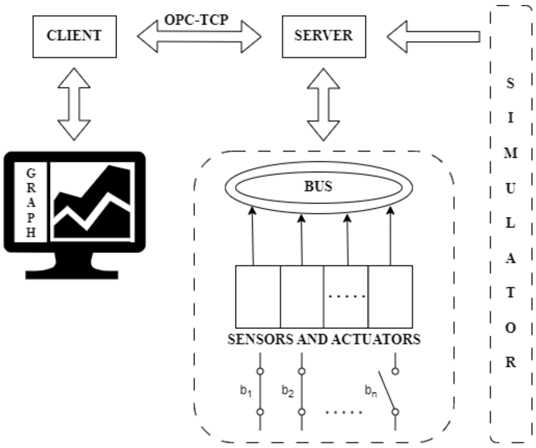

Fig. 3 – Block diagram of the OPC system.

Communication between clients and servers occurs over internet-specific networks, employing advanced security measures, including encryption and decryption technologies, to ensure data integrity and safety. The block diagram of an OPC system is described in Fig. 3.

Transducers, sensors, and actuators collect real-time data from monitored processes, providing information on electrical parameters (voltage, current, power) and non-electrical parameters (position, irradiance, temperature). An external module can simulate these actuators at this level and directly control sources. The server processes signals collected and interfaces with the OPC client(s), allowing users to access the OPC UA server data and display historical graphs.

3.3. OPC UA MICROGRID SIMULATION

The microgrid simulator's user interface (UI), as shown in Fig. 4, features a historical data monitoring view alongside a digital control panel containing the status of connected and disconnected sources and consumers.

Fig. 4 – Client historical data monitoring view and digital control panel with connected/disconnected sources and consumers.

The monitoring quantities of the system include:

- Power Consumption: The power consumed by the load at each moment in time for each consumer and the total power denoted as $P(t)$,
- PV Panels: $G(t)$ and $T(t)$, voltage, current, and power,
- Batteries: voltage, current, and discharged/stored power,
- Diesel generator: voltage, current, and power.

The control quantities of the system include:

- Output Voltage: Regulation of the voltage on the DC 12-volt bus before the inverter, ensuring the system operates with $P_{PV} \pm P_B$,
- Battery State: Monitoring the battery state via the battery current I_B, which provides a state of charge (*SOC*) between 30% and 85%,
- Generator Operation: Control of the generator triggered when *SOC* falls below or exceeds certain thresholds or to address power imbalances.

The software effectively models and verifies the electrical power supply processes, ensuring that the condition that $P_{PV} + P_B + P_{DG} = P_{LOAD}$ holds true.

4. SOFTWARE FUNCTIONALITY VALIDATION

4.1. CASE STUDY DESCRIPTION

To validate the developed software, the authors propose a case study involving a standalone house without access to the electrical grid, using PV panels, a battery storage system, and a backup Diesel generator as an electrical power supply source.

The analyzed strategy involves the following settings: P_{PV} = 4.5 kW, P_B = 6.4 kW, and P_{DG} = 7.75 kW. A proposed load curve for 24 hours is also established for both summer and winter operations, detailed in Table 1.

Table 1

Operation schedule for appliances.

Consumer	Symbol	Nominal Power [kW]	Summer Operation Period	Winter Operation Period
Water Pump	WP	0.64	24h *ON/OFF: 5min/5min*	24h *ON/OFF: 5min/25min*
Refrigerator	R	0.75	24h *ON/OFF: 5min/10min*	24h *ON/OFF: 5min/20min*
Electric Heater	EH	0.75	N/A	06:00 – 24:00 *ON/OFF: 5min/20min*
Air Conditioning	AC	2.00	12:30 – 17:30 *ON/OFF: 10min/5min*	N/A
Washing Machine	WM	2.00	10:00 – 12:00	10:00 – 12:00
Vacuum Cleaner	VC	0.95	10:30 – 11:30	10:30 – 11:30
Other Kitchen Appliances	OKA	0.75	07:30 – 09:30 18:00 – 22:00	07:30 – 09:30 18:00 – 22:00
Lighting	L	0.55	06:45 – 08:00 18:00 – 24:00	06:45 – 09:00 17:00 – 24:00
Router	R	0.05	24h	24h
Server	S	0.30	24h	24h

In this simulation scenario, data is transmitted to the software via the simulation module through the OPC protocol that simplifies the clients-server communication. Thus, sensors are not directly connected to the actual household consumers. Instead, the digital ON/OFF status of each consumer is automatically sent to the server on a minute-by-minute basis over 24 hours, resulting in a total of 1440 entries for analysis and display on the client side (Fig. 5, Fig. 6).

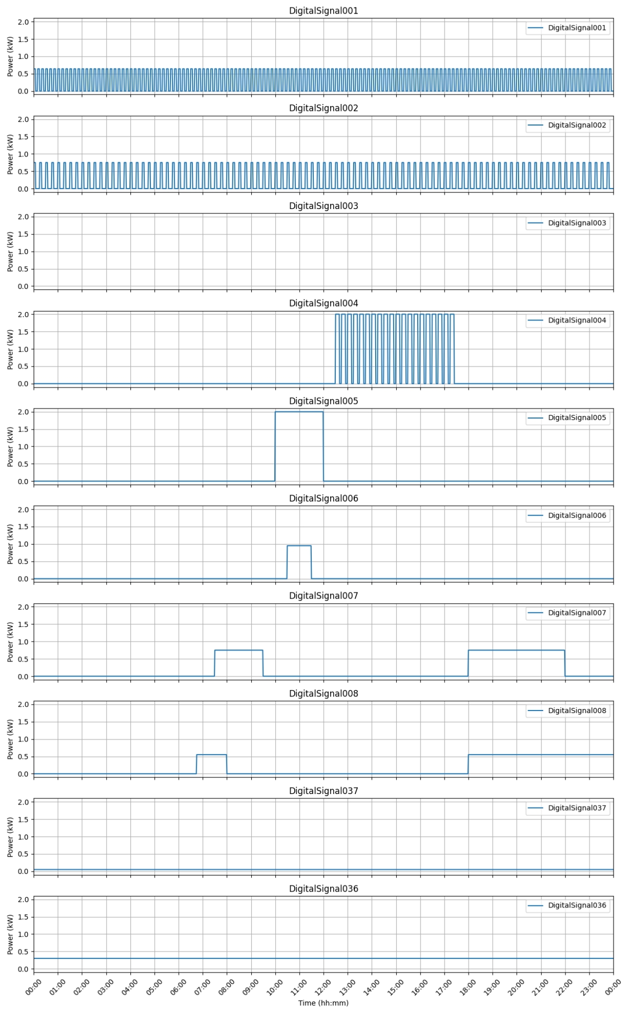

Fig. 5 – ON/OFF monitored load consumer data for summer operation.

The mean power values $\bar{P}$ for consumers with a cyclic operation regime are calculated and outlined in Table 2 based on the nominal power P_n values.

Table 2

Mean power for appliances with cyclic operation regime.

Consumer	P_n [kW]	Summer $\bar{P}$ [kW]	Winter $\bar{P}$ [kW]
Water Pump	0.640	0.320	0.106
Refrigerator	0.750	0.250	0.150
Electric Heater	0.750	N/A	0.150
Air Conditioning	2.000	1.333	N/A

These are provided to understand the average power consumption of these devices over their respective operation intervals, considering their ON/OFF cycles.

Mean power values facilitate better energy management and scheduling, avoiding potential issues related to overloading or under-provisioning. The average power consumption is calculated with the formula:

$$\bar{P} = \frac{P_n \cdot t_{ON}}{t_{ON} + t_{OFF}} \quad (10)$$

where: t_{ON} – duration for which the system is ON (within the total period considered); t_{OFF} – duration for which the system is OFF (within the total time period considered).

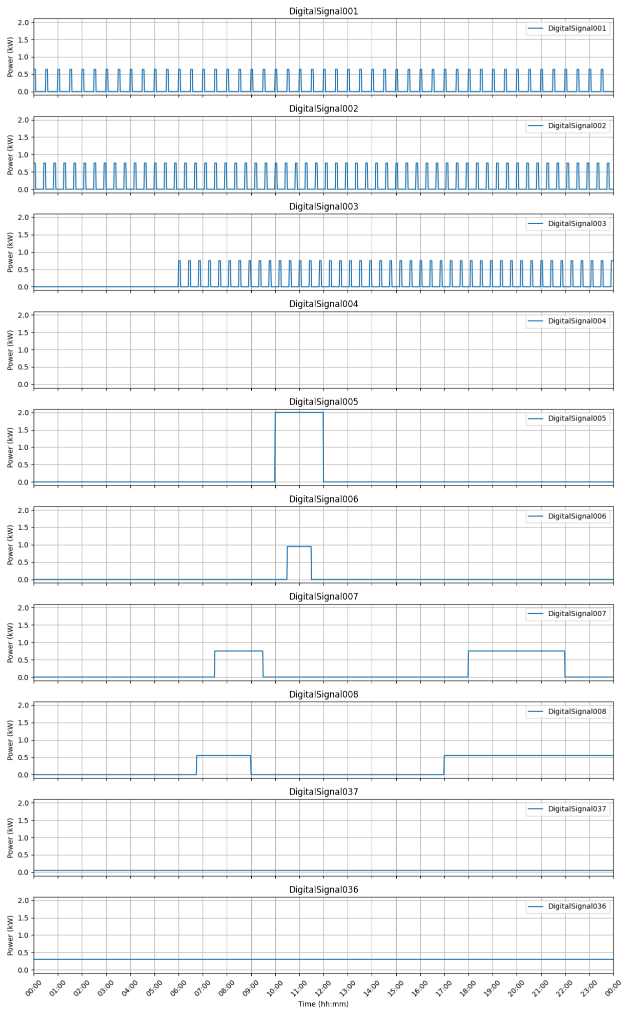

Fig. 6 – ON/OFF monitored load consumer data for winter operation.

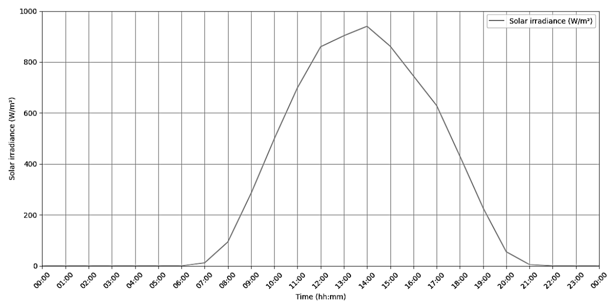

Fig. 7 – Monitored global tilted solar irradiance levels for summer operation.

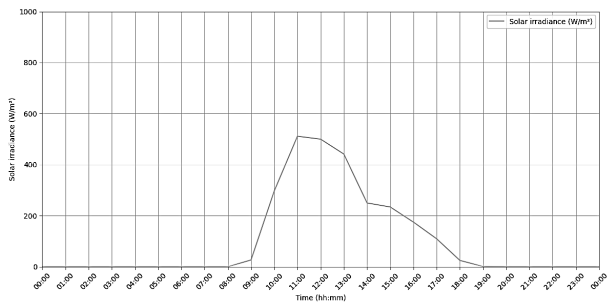

Fig. 8 – Monitored global tilted solar irradiance levels for winter operation.

The global tilted solar irradiance levels for summer and winter operations were monitored every minute for 24 hours, resulting in 1,440 entries (Fig. 7, Fig. 8).

This data was simulated by sending analog readings to the designated signal port ID on the OPC server, representing actual measurements from August 12, 2024, and February 12, 2024, for Brașov, Romania, with panels tilted at 30 deg. and 60 deg., respectively.

4.2. SIMULATION RESULTS

The results include several key graphs illustrating the system's performance during summer and winter operations.

For summer results (Fig. 9), the daily load curves demonstrate the variations in energy consumption throughout the day, highlighting peak usage times. The AC voltage curves for summer show the voltage levels maintained within the +/- 10% allowed limits, ensuring stable operation. Additionally, the contribution of each energy source towards meeting the required power is displayed, showcasing how each source supports the load demands.

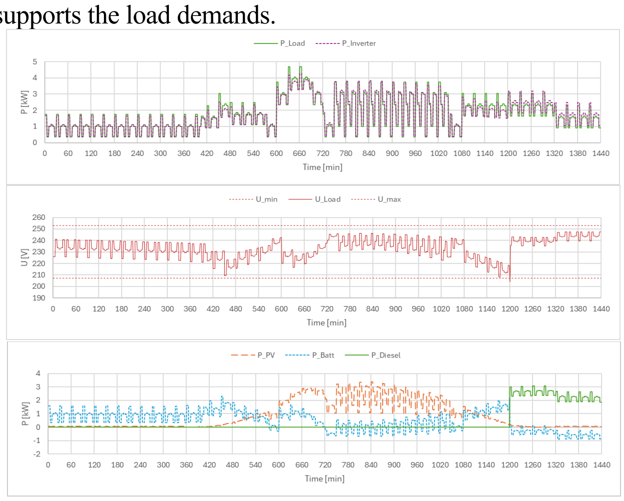

Fig. 9 – Power and voltage trends over time for summer operation.

Fig. 10 – Power and voltage trends over time for winter operation.

The winter results (Fig. 10) present similar insights. The daily load curves reflect changes in energy consumption patterns due to seasonal differences. The AC voltage curves for winter also illustrate compliance with the +/- 10% voltage limits, maintaining system reliability. Finally, the graph detailing the contribution of each energy source highlights how the system adapts to meet power requirements in the colder months, emphasizing the vital role of the Diesel generator alongside the reduced output from PV panels.

4.3. DISCUSSIONS

The simulations conducted for the analysed case study demonstrated that it is feasible to monitor and control the operation of the power supply system within acceptable limits for the required power, voltage variation, and the coupling of sources, ensuring that the battery operates within the imposed limits.

Furthermore, the energy balance of the power flows in the considered system has been determined for the monitored periods of one summer day and one winter day, as presented in Table 3. This provides an example of the system's operation under different seasonal conditions.

Table 3

Supply power contributions for summer and winter days.

Power type [kW]	Summer day		Winter day	
P_{L_TOTAL}	42.45		31.92	
P_{PV_TOTAL}	20.91	49.26%	7.41	23.22%
P_{B_TOTAL}	11.91	28.06%	11.40	35.71%
P_{DG_TOTAL}	9.63	22.68%	13.11	41.07%

The results demonstrate efficient energy management in both scenarios by displaying the system's ability to adapt its energy source contributions to varying conditions, ensuring reliability.

The system prioritizes solar power for a summer day, with PV generation covering almost half of the load. At the same time, batteries ensure a stable energy supply, reducing reliance on diesel generators. For the winter case, even with reduced PV output, the system provides available solar energy, adjusting the dependence on batteries and the Diesel generator accordingly.

This research's key contribution lies in utilizing the open platform communications (OPC) server and industrial communication standards to facilitate real-time data accessibility over a network. While established technologies such as smart inverters offer certain benefits, OPC UA enables more flexible, scalable, and standardized communication across systems, aiding in improved calculations and informed decision-making processes that can be achieved at reduced costs. The software stands apart from others available due to several key factors. Each factor is detailed in Table 4.

Table 4

Key software factors

Factor	Description
Demonstrative Tool	The software allows users to simulate the operation of an independent power system under various conditions, providing valuable insights into system behaviour and performance before implementation.
Pre-Design Phase	The software aids in decision-making by offering a platform to explore different configurations and strategies for energy management, helping users determine the most suitable approach for their specific needs.
Feasibility Studies	The software allows users to assess the viability and effectiveness of different energy management strategies within the context of their proposed system, enabling informed decisions regarding investment and implementation.
Experimental Data Integration	The software's capability to incorporate experimental or approximative data, such as radiation levels in a particular area, allows users to work with preliminary real-world data, providing an overview of energy management scenarios and outcomes.
Educational Resource	The software can be used for teaching purposes, allowing students to gain hands-on experience with simulation and management strategies, enhancing their understanding of renewable energy systems.
Potential for Expansion	Designed with the potential for further development, the software can integrate additional features, strategies, optimization mechanisms or functionalities, ensuring its relevance and applicability in new scenarios.

5. **CONCLUSIONS**

In this research, software was designed and developed to monitor, control, and ensure a reliable power supply for consumers in a standalone house. By integrating PV panels, batteries for energy storage, and Diesel generators to manage peak demands, the system establishes an energy management strategy that optimizes efficiency and reliability.

The results of this simulation offer valuable insights into the role of OPC technologies (as specified in standard IEC 62541) in enhancing overall system communication and responsiveness to dynamic energy demands. These technologies create a framework for smart standalone houses and local energy communities. The successful integration of OPC servers and communication standards in smart standalone settings lays the foundation for future studies in energy management systems.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Author_1: Scenarios conceptualization, methodology, software design and validation, writing - original draft preparation.
Author_2: Design of user interface of the microgrid simulator, software testing and validation, formal analysis investigation, and data analysis.
Author_3: Methodology, load curves, supervision, writing, revision, and manuscript editing.

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