

Design and Performance Evaluation of An Off-Grid Photovoltaic System Based on Weekday Load Profiles for Rural Schools: A Case Study in Babil, Iraq

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Abstract. This study highlights the design, simulation, and performance assessment of a standalone photovoltaic system developed for a rural educational facility in Babil, Iraq, under actual site conditions, the work fulfilling a novel weekday only for the electrical requirements of Al-Nasra Primary School, situated adjacent to the Al-Musayyib Grand Irrigation Project. The system was modeled and analyzed using PVsyst software, utilizing a realistic weekday-only load profile that simulates school operations for five hours daily (08:00–13:00), five days a week. The entire daily energy requirement was assessed at 62.0 kWh, encompassing classrooms, administrative offices, and heating and cooling systems. The results of the simulation indicated that the designed system produced a yearly energy output of 21,306 kWh, with 15,927 kWh effectively employed to meet the load and 4,295 kWh recorded as surplus energy. The system showed the performance ratio (PR) of 62.0%, solar fraction of 99.72% and a load loss of 0.6%. The battery bank maintained a state of health exceeding 91.7%, with an estimated lifespan of 12 years. These results verify the technical viability and dependability of a suitably sized standalone photovoltaic system in fulfilling the distinct operating requirements of a rural school. Furthermore, the setting up of a pragmatic weekday-only load profile yields a more precise evaluation of system performance, preventing oversizing and promoting improved energy management strategies for schools in off-grid or locations with an unsteady power grid. The weather data employed for the simulation was obtained from the PVsyst linked Meteonorm 8.0 data for the Al-Musayyib region.

Keywords: Solar Energy, Standalone Photovoltaic System, off-grid design for school, Load Profile, Performance Ratio, PVsyst simulation Software, Babylon/Iraq

1. INTRODUCTION

Photovoltaic (PV) -based systems are being utilized in a variety of domestic and commercial applications due to the increasing demand for low-cost energy and the growing concern regarding environmental issues [1]. PV systems can be generically categorized as either stand-alone or grid-connected [2, 3]. The stand-alone system is frequently employed in remote locations where electricity is not accessible. The power supply's reliability cannot be guaranteed, despite the fact that the stand-alone configuration can provide a well-regulated load voltage [3]. Storage batteries are frequently implemented to enhance the dependability of standalone systems [4]. The effectiveness of the PV system is depends upon the time of day and the seasons of the year. The prediction of optimal operating conditions, primarily affected by radiation, system fault situations, and temperature, is difficult to ascertain by conventional estimating methods. An robust control mechanism is essential to stabilize the output during fault circumstances, such

as the adverse environmental conditions, loss of a string or module in the PV panel, and load disturbances. Numerous studies and research have been conducted on the design and development of PV systems. This section presents only some of the majority relevant current studies employing the PVsyst software. [5] The existing methodologies for developing photovoltaic systems, encompassing both grid-connected and standalone variants, were examined. The evaluation of current design tools and approaches revealed that the PVsyst application offers the most appropriate tools for simulating PV systems. [6, 7] executed a simulation research utilizing several commercial photovoltaic system design software, including SAM, PVsyst, and PVLlib. A novel photovoltaic estimate model, the SoL model, was developed by [7]. The analysis involved a comparison of the standard intended output information of the design. It was determined that all bundles were advantageous; however, PVsyst possessed the most robust instruments for data analysis and presentation. [8] employed the PVsyst to ascertain the optimal proportions and specifications for the elements of a grid-connected PV system 100 MW in Abu Dhabi UAE, and established the fundamental design parameters, which encompassed the intensity of solar radiation, the orientation of the panels, the loss factors, the output power, and the installation and operating costs. It was discovered that PV systems had substantial economic benefits in addition to their evidently beneficial environmental impact. [9] employed PVsyst tools to analyze a 20 kW grid-connected PV system at the Karunya Institute of Technology and measuring the output energy and many design factors. They determined that PVsyst could furnish design data that was entirely reliable. [10] conducted modeling a 700 kW on-grid PV system in Afghanistan with the PVsyst program. According to their assessment of the system's functionality, it was capable of functioning flawlessly when the power factor was between 0.7 and 0.9. [11] compared the results of simulation obtained utilizing PVsyst application with actual data of a 700 kW on-grid PV system that had already been deployed. The simulation results and the data itself were practically indistinguishable, as evidenced by the findings. [12] assessed the economic and environmental advantages of installing a grid-connected PV system by utilizing PVsyst software to determine the yearly electricity usage of the Faculty of Science in Rabat.. They determined that this installation had the potential to reduce carbon dioxide emissions by up to 6142 tCO₂. [13] employed PVsyst software to execute an economic analysis of an on-grid rooftop PV system in Ghazni. They demonstrated that a PV system with a capacity of 10 kW could generate an annual energy output of 19323 kWh. The PV system was projected to have a payback period of 6.3 years. [14] compared the empirical data of a real 5 MWp PV system with the corresponding simulated outcomes Obtained by PVsyst software. The close connection between the model and real systems suggests that PVsyst can be employed in the design of PV systems . [15] Conducted a comparison analysis utilizing two different modeling tools, Helioscope and PVsyst, to assess the efficacy of a grid-connected residential PV system within the climate of Saudi Arabia. The results demonstrated that both models produced analogous data, with quite a minor deviation in the majority of evaluated parameters. The yearly performance ratio was anticipated to vary from 74.8% to 78.04%. The suggested 15-kW PV system may produce up to 28 MWh yearly, according to the results of PVsyst simulation.

The use of PV systems in educational institutions has garnered considerable global interest, driven by the objectives of minimizing operational expenses and promoting environmental sustainability. PVsyst has been accepted as an effective simulation tool for the design, optimization, and performance analysis of PV systems across several applications, including educational institutions. Recent studies indicates an increasing trend of employing realistic load profiles in PVsyst simulations to enhance sizing accuracy and economic viability. A multitude of studies worldwide investigated PV system concepts for schools. [16] used PVsyst software for a grid-connected PV system design to a school building in Indonesia, contrasting a actual world configuration (8 * 545 W PV modules, 15 kW inverter) using idealistic (about 52 modules). Their results demonstrated that accurate load data significantly improved system sizing and performance ratio . [17] completed a techno-economic analysis for designing a PV system for primary school in Algerian by using PVsyst software , resulting that optimal sizing minimized LCOE more than 15% with compared for oversizing cases. [18] Constructed and assessed a 581 kWp PV system for an educational facility using

PVsyst software, revealing yearly savings of \$70,000 USD and a performance ratio surpassing 80%. [19] performed a techno-economic feasibility analysis of a PV system for an Indonesia a university building by using PVsyst, highlighting the influence of accurate hourly load data on investment decisions.

Iraqi research on using PVsyst software for PV system design for schools is scarce and restricted in area. Two studies address on education. The initial research by [20] , outlines a detailed design for a 40 kW grid-connected PV system aimed at supplying power to a school in Babil Governorate. The research involved modeling and simulation using PVsyst software, determining the number of PV modules (450 Wp rated at each,90 modules) and 12 kW three inverters, thereafter doing a thorough evaluation of yearly performance, environmental advantages, and economic viability. The results indicated that the yearly output energy is around 70.23 MWh, a payback period less than 10 years, and a significant minimized of CO₂ over a 25-year operational lifetime. This study is defined as a pragmatic, field oriented scenario specifically designed for the local solar radiation, temperature, and operational characteristics of Babil schools.

The subsequent study , conducted by [21], presents a theoretical and comprehensive examination of a planned grid-connected PV system of 5 kW for a primary school in Baghdad . The author evaluated performance across multiple Iraqi provinces by using PVsyst software, Baghdad as the reference site. The results indicate that the performance ratio is 0.825, the output energy of 9.82 MWh/year , 0.058 USD/kWh LCOE , and a period for payback is about 5.5 years. This theoretical study provides valuable insights for electrifying the educational sector through its simple application to a primary school and a comparison across provinces.

Both this studies confirm that the technical and economic feasibility of PV systems for educational sector in Iraq. The first scenario illustrates the viability of medium to large scale on-grid PV systems under actual local conditions, The primary school evaluation provides a practical framework relevant to multiple provinces, along with defined performance and financial requirements. The literature is geographically constrained, concentrating mostly on Babil and Baghdad, and depends entirely on on-grid models, neglecting off-grid alternatives for schools in areas with poor grid reliability. Moreover, neither study included a genuine daily school load profile limited to operational hours (e.g., 08:00–13:00, five days per week), which could substantially affect system sizing, storage needs, and performance indicators like as PR, self-consumption, and unmet load.

Although global studies has shown the advantages of integrating realistic load profiles in PVsyst simulations, no previous study in Iraq has methodically assessed the design of standalone PV systems for schools utilizing a weekday-only operational schedule (five hours daily, five days weekly). Many current studies presume continuous, averaged, or annual loads for PV system design, frequently leading to the oversizing of system components and heightened overall costs, as well as the wrong estimation of performance metrics such as performance ratio, unmet load, and surplus energy. This research aims to provide a more accurate and context-specific evaluation of PV system performance for educational facilities in off-grid or unstable grid areas by including a realistic weekday only demand profile that corresponds with actual school hours.

The following sections of this paper are organized as follows: Section 2 delineates the Research Methodology, encompassing the selection of the geographical site, orientation of solar modules, load profile, sizing of components system, and simulation design along with performance evaluation. Section 3 emphasizes the Results and Discussion of simulation , offering a comprehensive assessment of the system's performance. Section 4 delineates the Conclusion, encapsulating the key results.

2. RESEARCH METHODOLOGY

This study employs a methodical approach to design and simulate of a standalone PV system that meets to the electrical requirements of Al-Nasra Primary School, located in Al-Musayyib grand irrigation project in Babil Governorate, Iraq. The approach was executed using PVsyst software to ensure accurate modeling and reliable performance evaluation under conditions at the site.

The methodology subsequent steps are :

2.1 Selection of Geographical Site

The actual geographical coordinates of the school, $32^{\circ}49'41.6''\text{N}$, $44^{\circ}23'09.5''\text{E}$, were recorded in the PVsyst site database. This guaranteed that the simulation employed the pertinent weather data particular to the Babil Governorate.

2.2 Orientation of PV Modules

The PV array was arranged with a 30° tilt angle oriented directly south (azimuth = 0°) as shown in figure 1 to optimize annual solar energy collection, taking into account the site's latitude and sun trajectory.

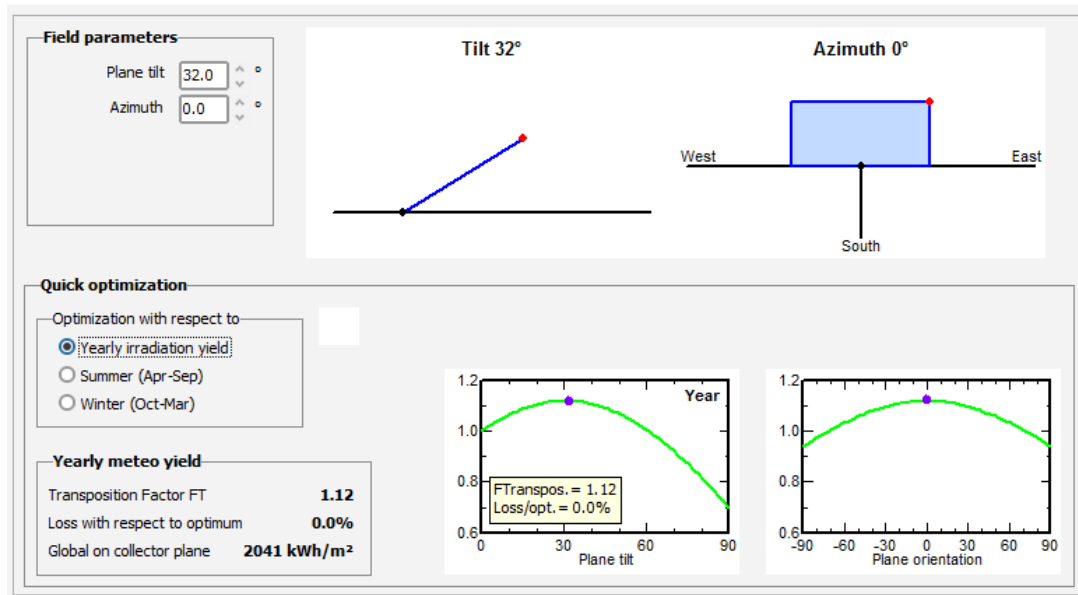


Fig. 1: Orientation of PV Modules

2.3 Load Profile

The daily load profile is constructed using both measured and estimated consumption data for the specified application. Table 1 illustrates that the initial segment of the load profile specifies the devices, quantities, and rated power for each load, whereas the subsequent segment allocates these loads on an hourly basis from 08:00 to 13:00 hours as shown in table 2 , in alignment with the school's operational schedule. The operational profile for the 1.5-ton inverter air conditioning and heating units was modeled using a 50% duty cycle, indicating 30 minutes of active operation per hour throughout the school's operational hours from 09:00 to 13:00. Through the using of this scheduling, the total daily energy consumption is remains at a level comparable to that of two hours of continuous operation, while simultaneously drastically reducing

peak demand and optimizing the load curve. It has been suggested that an automated smart timer should provide oversight for the management of this operational pattern. This would allow for automatic switching to take place without the requiring for human intervention.

Table 1: load profile specifies the devices with daily-weekly energy

Device	Qty	Power (W)	Hours Day	Daily Energy (Wh)	Weekly Energy (Wh)
LED Light (20W)	60	20	5	6000	30000
Fan	10	100	5	5000	25000
LED Light (20W)	12	20	5	1200	6000
Desktop PC	3	100	5	1500	7500
Printer/Copier	1	300	3	900	4500
Network Router/Switch	1	50	5	250	1250
Water Pump	1	750	2	1500	7500
Electric Water Heater	1	3000	1	3000	15000
Mobil Charger	1	240	1	240	1200
AC (1.5-ton inverter) COOLING – HEATING	13	1600	2	41600	208000
				61190	305950

Table 2: schedule of operation time and total daily energy

Device	8-9	9-10	10-11	11-12	12-13
LED Light (20W)	1200	1200	1200	1200	1200
Fan	1000	1000	1000	1000	1000
LED Light (20W)	240	240	240	240	240
Desktop PC	300	300	300	300	300
Printer/Copier	300	300	300	×	×
Network Router/Switch	50	50	50	50	50
Water Pump	750	750	×	×	×
Electric Water Heater	3000	×	×	×	×
Mobil Charger	240	×	×	×	×
AC (1.5-ton inverter) COOLING – HEATING	×	10400	10400	10400	10400
Total Energy / Hour (Wh)	7080	14240	13490	13190	13190

2.4 Sizing of System Components

PVsyst software was used for sizing the PV array, battery bank capacity, and MPPT inverter, ensuring complete load handling, autonomy, and system reliability based on the specified load and available solar radiation resources. Components specifications that chosen to performance optimize, cost, and operating lifetime, as shown in table 3, the details of the components of the PV system.

Table 3: System Components Characteristics

PV MODULE		BATTERY	
Manufacturer	LG Electronics	Manufacturer	Narada
Model	LG 450 N2W-E6	Model	AcmeG 12V 200
(Original PVsyst Database)		Technology	Lead-acid, sealed, Gel
Unit Nom. Power	450 Wp	Nb. of units	16 in parallel x 4 in series
Number of PV modules	28 units	Discharging min. SOC	20.0 %
Nominal (STC)	12.60 kWp	Battery Pack Characteristics	
Modules	14 Strings x 2In series	Voltage	48 V
TOTAL PV POWER		Nominal Capacity	3200 Ah (C10)
Nominal (STC)	13 KWp	Temperature	Fixed 20 °C
Total	28 modules	CONTROLLER	
Module area	61.6 m ²	Universal controller	
Cell area	54.8 m ²	Technology	MPPT converter
		Manufacturer	SMA Solar Technology
		Nominal Power	(16 kW)
		DC Input	48 V
		AC O/P	230 V, 50 Hz, 1Ø
		Temp Coeff..	-5.0 mV/°C/Elem.

The schematic diagram for system as shown in figure 2

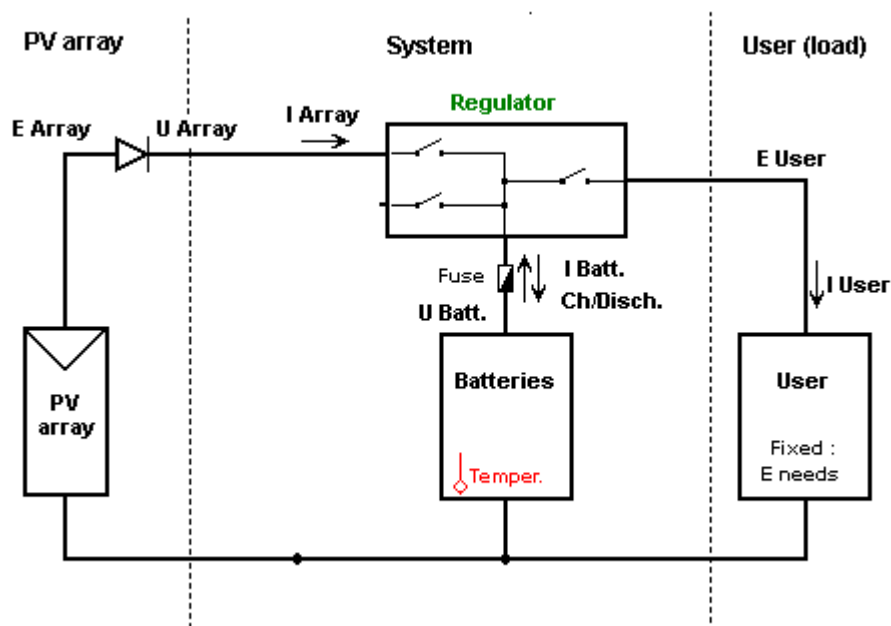


Fig.2 schematic diagram of the PV system

2.5 Simulation Setup and Performance Analysis

In PVsyst software, all the required variables, such site data, load profiles data, and the system components, are entered. The simulation performed over an entire yearly cycle to evaluate critical performance parameters such as energy yield, Performance Ratio , Solar Fraction , and missing energy

The analysis of simulation outputs assesses the degree to which the system satisfies energy demand, the volume of surplus energy, and instances of load loss. These outputs form the basis for the simulation results and discussion section of this study.

3. RESULTS AND DISCUSSION

The simulation results derived from PVsyst for the autonomous PV system designed for Al-Nasra Primary School, situated near the Al-Musayyib Grand Irrigation Project in Babil, Iraq, are summarized in Table 4 . The table displays the monthly and annual balances for available energy (E_Avail), unused energy (E_Unused), missing energy (E_Miss), energy supplied to the user (E_User), together with Solar Fraction (SolFrac), Performance Ratio (PR)

Table 4: Balance and Main Results

Month	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac	PR
	kWh/m ²	kWh/m ²	kWh	kWh	kWh	kWh	kWh	ratio	ratio
January	97.1	146.3	1651	148.2	0	1407	1407	1	0.754
February	106.6	137.9	1543	225.2	0	1224	1224	1	0.694
March	147.6	167.8	1836	352.1	0	1346	1346	1	0.626
April	176.6	180	1937	603.1	0	1285	1285	1	0.556
May	195.6	182.4	1907	449	0	1407	1407	1	0.599
June	217	193.8	1988	569.4	0	1285	1285	1	0.514
July	215.6	196.6	1994	593.4	0	1346	1346	1	0.531
August	195.9	192.6	1956	492.5	0	1407	1407	1	0.568
September	166	183.9	1902	565.2	0	1224	1224	1	0.518
October	127.2	154.9	1642	187.9	0	1407	1407	1	0.71
November	95.6	135.2	1487	45.6	3.51	1343	1346	0.997	0.777
December	85.5	130.3	1462	63.8	40.57	1244	1285	0.968	0.748
Year	1826.4	2001.5	21306	4295.4	44.08	15927	15971	0.997	0.62

From table 4, the (E_Avail) was 21,306 kWh/year, with 15,927 kWh/year (about 74.8%) supplied to the loads. The (EUnused) is 4,295 kWh/year approximately 20.2% of the total signifies surplus energy, primarily produced during periods of high solar irradiation and low load demand, particularly from April to August. This indicates the potential for system optimization by integrating additional flexible loads, such as water heating other auxiliary devices, to improve the using of surplus energy.

The system shown a minimal (E_Miss) of only 44.08 kWh/year approximately 0.28% of total demand, mainly observed in December when solar irradiation reached lowest level about 85.5 kWh/m² and the (PR) was relatively elevated at 0.777, indicating efficient energy conversion despite diminished input. This minor defect confirms that the system's specifications to PV array capacity, battery storage capacity , and rating of inverter were sufficient to satisfy the school's demand profile nearly throughout the year.

The yearly (PR) is 0.620, deemed advantageous for off grid PV systems in arid regions, where battery charging and discharging losses, together with elevated module temperatures, generally diminish PR values. Maximum PR values was in December (0.777) and in January (0.740), signifying reduced ambient temperatures and improved photovoltaic module efficiency in the winter months. Conversely, the minimum PR was seen in July (0.519), attributable to ambient temperatures and increased the losses of the system. The (SF) reached 99.72%, indicated that the system was almost fully autonomous in satisfying the school's annual energy requirements, with minimal need on supplementary sources. The array efficiency (EffArrR) averaged 14.14%, consistent with anticipated performance for crystalline PV modules under local climatic

circumstances, however the system efficiency (EffSysR) averaged 12.69%, indicating additional losses resulting from battery cycling and power conditioning, as shown in figure (3).

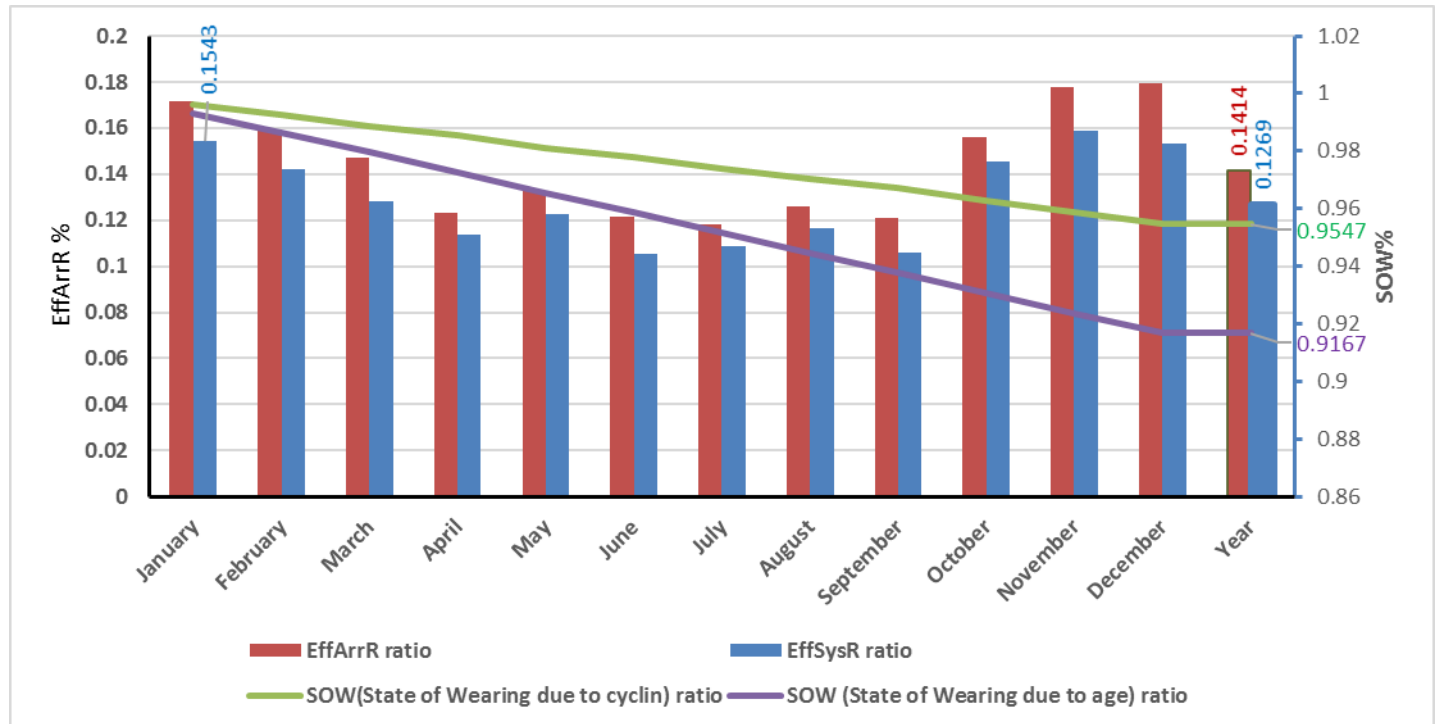


Fig. 3: System Efficiency, Array Efficiency with State of Wear, and State of cycle

The simulation's battery performance indicated that a State of Wear (SOW) is 95.5% for cycling and 91.7% for static operation, with an estimated lifetime about 12.0 years. The results indicates that the capacity of battery bank was Suitable for the daily load profile, preventing excessive deep discharges and maintaining long-term reliability.

The results demonstrate that the proposed PV system can reliably provide the energy requirements year-round of the school's, with only negligible seasonal shortfalls. The surplus energy generated during peak solar months offers opportunities to improve system economics and sustainability by using load management strategies or the integration of productive use applications.

4. CONSOLATION

This research effectively developed and modeled an off grid PV system to satisfy the daily energy need to Al-Nasra Primary School, situated in Babil, Iraq. The system was designed by using PVsyst software under prevailing climatic conditions and load profiles data customized to the school's working timetable. The main points of conclusions can be summarized as follows:

1. System Performance – The design of the PV system achieved a (PR) of 62.0%, reaching within the permissible parameters for optimally designed standalone systems under comparable climatic conditions. This indicates an optimal balance among system efficiency, component selection, and site-specific factors..

2. Energy Usage — The simulation results indicated that the system successfully met 99.72% of the school's yearly load demand, with a minimal 0.6% reduction in load. The increased coverage ratio confirms the adequacy of the PV array and battery bank dimensions in satisfying the school's operational requirements.
3. Surplus Energy - The system generated 4,295 kWh/year of excess energy, offering potential for other applications, such as powering auxiliary loads (e.g., community lights, ICT facilities) or future resale to the grid in a hybrid configuration.
4. Battery Efficiency and Dependability- The battery bank exhibited a (SOW) of 91.7% and a cycle SOW of 95.5%, with a projected operational lifetime around 12.0 years. The results confirm that the chosen (DoD) and battery management procedures are proficiently adjusted to extend battery lifetime while maintaining high supply reliability.
5. Seasonal Variations - Monthly analysis indicated that solar energy availability corresponds effectively with the school's demand profile, while minor performance variations were noted due to seasonal swings in irradiance. Significantly, June and July had the greatest GlobHor levels, while December exhibited the lowest, impacting overall energy production.
6. System Optimization Potential – While the performance ratio is adequate, additional optimization may be attained by:
 - Enhancing load management to mitigate midday peaks.
 - Investigating the amalgamation of energy storage systems with enhanced round-trip efficiency.
 - Leveraging excess energy on non-school days to enhance overall system utilization efficiency.

In conclusion, the proposed PV system exhibits technological feasibility and sustainability as a power source for educational institutions in rural or semi-urban regions of Iraq. The results indicate that with appropriate design, scaling, and load control, standalone PV systems can attain significant dependability and efficiency, even under varying seasonal conditions.

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