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Effect of load distribution strategy on the performance and sizing of standalone photovoltaic systems

Waleed Khalid Shakir Al-Jubori, Ahmed Hussein Duhis
Department of Electrical Engineering Techniques, Mussaib Technical College, Al-Furat Al-Awsat Technical University, Babylon, Iraq

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ABSTRACT

Accurate load representation is important for dependable sizing of standalone photovoltaic systems, mainly for healthcare facilities with seasonally varying equipment use. This study estimates the effect of load profile representation on the sizing and simulated performance of a standalone photovoltaic system for a rural healthcare center in Al-Musayab District, Babil, Iraq. Two load-modeling approaches were analyzed using PVsyst software V 7.2.11 under the same working schedule of 08:00–15:00, five days per week a conventional daily-load profile with weekly inflection and a seasonally adjusted monthly-load profile based on devices operating months and monthly working days. The monthly load model reduced the estimated yearly demand from 9847.5 to 7805.5 kWh. Consequently, the required PV-array capacity decreased from 9.45 to 6.75 kWp, while the nominal battery-storage capacity decreased from 39.6 to 31.7 kWh. Case 1 supplied 99.71% of its modeled demand and recorded 28.24 kWh of annual missing energy, whereas case 2 achieved complete modeled load coverage with zero missing energy. Yearly unused energy decreased from 5803.6 to 3416.1 kWh, and the performance ratio increased from 50.96% to 56.72%. Nevertheless, the smaller battery bank in case 2 showed greater use and a shorter estimated lifetime, indicating a storage sizing trade off. For the investigated facility and adopted PVsyst software conditions, the results demonstrate that device level, month-dependent load representation provides a more operationally representative basis for system sizing. Further validation using measured load data and additional locations is required before broader generality.

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Corresponding Author:

Ahmed Hussein Duhis
Department of Electrical Engineering Techniques, Mussaib Technical College
Al-Furat Al-Awsat Technical University
Babylon, Iraq
Email: ah.hu.khf@gmail.com, com.ahmd4@atu.edu.iq

1. INTRODUCTION

Renewable energy systems can provide clean and environmentally friendly power from sources including wind, solar power, and biomass. The photovoltaic (PV) system is an essential and promising technology that can generate electricity to meet worldwide demand. [1] In the last ten years, the solar business has had annual growth above 40% attributable to a reduced the cost for PV systems [2]. PV technology employs two types of systems: the Stand-Alone PV system and the grid-connected PV system. A grid-connected solar system integrates with the electrical grid, whereas a standalone system functions autonomously and directly provides power to the demand. In a grid-tied solar system, the PV module produces direct current (DC) power, which is converted into alternating current (AC) by an inverter. Alternating current power is supplied to the grid, and the load is linked to the grid. Grid-connected PV

systems offer several advantages, including environmental benefits. Researchers in [3], [4] reduced maintenance, and surplus electricity can be sold to the grid [5], hence decreasing the operational costs of the system. Many rural regions in southern Iraq remain underdeveloped and disordered post-invasion, necessitating the provision of energy to these communities. Compact independent P) electricity systems can significantly contribute to the region's advancement. The region receives a substantial amount of solar energy throughout the year. This resource, while capable of generating abundant and dependable electricity, is substantially underutilized. Solar systems can fulfil the electricity requirements of medical center's, educational institutions, and other communal facilities, so enhancing health center and education and assuring sufficient services for the populace. A wonderful utilization of these structures is in health-related clinics. The connection between energy and health is significant, and as dependent components, they primarily affect the progression of rural development. Dependable on-site energy generation has demonstrated the capacity to produce powerful power for illumination, the storage of vaccines, medical devices, communication, the provision of clean water, and sanitation [6]. The proposed system's design for powering the medical clinic was carried out according to the Solar principle [7]. The total capacity for the load was 31.6 kWh per day. The system includes PV modules, batteries, a controller for charge, an inverter, and the necessary wire and safety components.

The creation of standalone PV systems that are primarily intended for essential structures like hospitals has led to a greater degree of scientific interest in recent years. Given the longstanding problem of energy access in rural areas, numerous studies have focused on improving the system's performance, sizing methods, and the accuracy of simulation. A significant component of the system's outcomes is the exactness and clarity of the electrical demand profile, whether expressed as a daily, monthly, or seasonal average. El-Houari *et al.* [8] utilized hourly climate data and actual monthly consumption values in PVsyst to create and optimize a off-grid PV system in rural Morocco, the system had a solar fraction of 79.1 percent and a flat cost of electricity of around 0.36 USD/kWh. Azuatalam *et al.* [9] conducted a systematic study of the impact of load input resolution (daily, hourly, monthly) on the size and performance of PV-battery systems. Muselli *et al.* [10] demonstrated four different daily load profiles with the same amount of energy (1 kWh/day) and demonstrated a variety of variations in the PV array and battery, the significance of which is highlighted by the temporal distribution of load. Quiles *et al.* [11] presented models that are simple in design and based on average loads that are constant or seasonal, these models may be misrepresenting the actual behavior of health or residential systems. Ai *et al.* [12] studied the different PV system configurations that exist in different load scenarios in hotels, remote shelters, and communication systems. Their research demonstrates that the design of the system and the loss of the system are primarily dependent on the assumed load patterns [13]. Specifically studied the impact of load-profile shape and timing on standalone PV-system sizing. The results showed that the temporal distribution in peak loads can have a significant impact on the PV-array and battery-storage capacities needed. But where the study focused on representative load profiles, not the month-dependent operation of individual devices in a healthcare facility. These studies show that off-grid PV system sizing depends not only on the total energy requirement, but also on the temporal characteristics of the load. Nevertheless, the majority of the examined profiles was pre-aggregated, predefinition or representative profiles but not device level schedules based on real monthly operation of the equipment.

Babatunde *et al.* [14] estimated the daily load profile of a rural primary healthcare center based on measured data (rated power and duration of use) of medical and auxiliary equipment. The combined system reliability and battery behavior were examined with respect to those PV-array, battery-bank, and inverter capacities. However, the study modeled the facility demand as a daily load rather than as a comparison to seasonally adjusted monthly equipment schedule. Mahmood *et al.* [15] employed the HOMER Pro computer to create a PV-powered system for a rural medical facility in the Kurdish region. Despite PVsyst not being utilized, the load profile method increases the current investigation's scope. These studies from the literature on healthcare show that equipment-based load assessment is an important consideration. However, seasonal data in a month-dependent equipment schedule was not compared for facility demand, which was mostly modeled as a daily load.

Al-Janabi and Jumaa [16] evaluated a standalone PV system in Mandali's city utilizing PVsyst. The system generated 5731.6 kWh/ year for a load of 4614.5 kWh/year, which is a significant increase over the load of 3331.6 kWh/ year. Additionally, the system had a successful identification of monthly and seasonal losses [17]. Conducted a study of the HJT and SI-MONO panels' capabilities for a 20 kWh/day system that utilized PVsyst in Basra, the study revealed a solar fraction of around 93% and a performance ratio of around 72-73%. Ibrahim and Aljanabi [18] evaluated the effectiveness of a 13-kWh independent PV mini-grid in Karbala that utilized PVsyst and local information, it was determined that it was appropriate for use in health institutions. Abed *et al.* [19] used a mixed approach involving preliminary analytical sizing, PVsyst simulation and MATLAB/Simulink analysis to better demonstrate the justification and performance of

standalone photovoltaic systems in terms of energy production. During their method, the need to determine critical design conditions whilst comparing analytical estimates with detailed simulation results was highlighted in an emphasis. However, the application was only specific to residential and there was no look into device-level seasonal load scheduling in healthcare space.

More recently, Ali *et al.* [20] PVsyst was used to size PV Systems for Community Health Centers at five sites in Mali. A daily load profile was used to analyze several battery-autonomy durations and loss of load probabilities, then the technical-economic-environmental performance was evaluated. The studies reviewed have clearly dealt with load representation, electrification of healthcare facilities, the sizing of stand-alone systems, and performance assessment using the PVsyst software, but they have not directly compared, for the same healthcare facility and subject to identical simulation conditions, the conventional repetition over 24 hours of the total daily equipment demand with a month-long-duration, seasonal-adjusted monthly schedule where listed devices were used only in the months when they were actually operating.

Previous studies have shown the significance of load modelling, levels of reliability criteria, battery autonomy and simulation assumptions over stand-alone PV-system design. PVsyst has also been used in sizing and evaluating stand-alone PV systems for rural applications as well as stand-alone healthcare facility applications. Nevertheless, in literature reviewed, no studies were found that either use PVsyst to directly compare for the same healthcare facility under identical simulation conditions the standard repetition of full daily equipment demand with a monthly seasonal adjustment based on the operating months of separate devices as well as individually the number of working days per month and holidays and finally constant loads. As a result, the impacts of this load-modeling choice on annual energy demand, PV-array sizing, battery-bank capacity, unmet energy, unused energy and system performance have not yet been adequately quantified.

In order to fill this gap, the current study proposes and compares two load models using an identical equipment inventory and operating schedule (documented in detail from a real rural healthcare center in Iraq). The first model is the traditional daily-load model in which the full daily equipment demand is replicated throughout the full range of the annual working schedule. The second modeling acts as a seasonally adjusted monthly load profile, which incorporates the operating months of single devices, working days monthly, weekly and official holidays, and permanently feeding loads. The two models are implemented in PVsyst to study the same healthcare building under the same geographical, meteorological, albedo, tilt-angle and azimuth conditions. The quantification of annual energy-demand differences from the changes in the configuration of the PV-array, battery-bank capacity, energy supplied to the user, unmet and unused energy, battery operating behavior, and performance ratio is also provided by the study.

The following sections of the paper are organized as follows: i) Section 2 describes the Method, including the selection of the geographical location, the orientation of photovoltaic modules, the load profile, the size of system components, and the simulation of the design, as well as the evaluation of performance; ii) The results and discussions are presented in section 3 including an extensive validation of the system; and iii) Section 4 summary of main results concludes.

2. METHOD

In this section, the method for developing and evaluating an isolated solar PV system for a simple health center in Iraq has been explained. The healthcare center managed to work assignment is 8:00 AM to 3:00 PM, for five days a week (Sunday to Thursday). Due to the frequent power outages in the area and the need to access power independent of other systems, a standalone solar-powered system was selected, ensuring constant power supply. Consequently, the main purpose of this research is to compare both daily and monthly load modeling approaches and their implications on the system design, components selection and energy savings. Modeling & studying of the PV system with PVsyst software V 7.2.11. It allows for full representation of PV arrays, battery storage, load scenarios, and system losses in a variety of environmental and operating conditions. In this research, daily and monthly load profiles are simulated to investigate how the load definition influences the system. This methodology comprises five steps, as:

2.1. Step 1: Study site and meteorological data

The standalone PV system had been designed for a rural health care center in Al-Musayab District, Babil Governorate, Iraq. The respective geographical and meteorological inputs were acquired from the PVsyst Meteonorm 8.0 database. Table 1 summarizes the site parameters and simulation configurations used in both cases.

2.2. Step 2: Orientation of modules

The PV modules were installed on a fixed tilted plane. In order to maximize the annual in-plane solar irradiation, a tilt angle of 31° was chosen as shown in Figure 1 and the azimuth angle set to 0°, which is due-south orientation. The same set of orientation parameters were simulated for both cases.

Table 1. Geographical and meteorological parameters used in the PVsyst simulations

Parameter	Adopted value
Study application	Rural healthcare center
Study area	Al-Musayab District, Babil Governorate, Iraq
PVsyst geographical site	Abd al Muḥsin Ḥājjī Iraq
Latitude	32.88° N
Longitude	44.36° E
Altitude	39 m
Time zone	UTC+3
Data type Satellite-data contribution	Synthetic 100%
Ground albedo	0.20

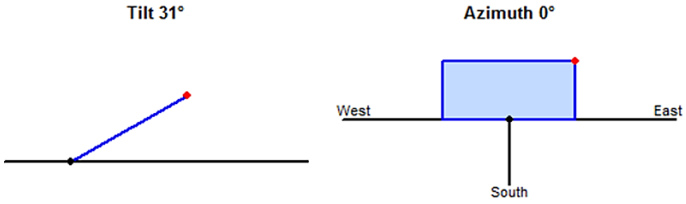

Figure 1. The orientation of PV system

2.3. Step 3: Estimation of load

The electrical-load assessment was performed in cooperation with the engineering group of the healthcare center, utilizing technical records and equipment listing at hand. For all the electrical equipment, rated power, number of units, and working hours on a daily basis were specified. It also took into account the real operation schedule and seasonal usage of the equipment; actual working calendar of the health care center, official holidays, non-working days/and constantly working loads.

Two load-modeling approaches were developed based on these operational data. Case 1 denotes the traditional daily-load method, where all annual working schedule equipment needs are assumed to be repeated for each day. Case 2, on the other hand, depicts a monthly load profile adjusted for seasonal changes to consider not only the months when equipment is in service but also how many working days occurred during that month. Consequently, the two cases are designed to have similar annual energy demands but different load profiles in order to assess the impact that realistic monthly scheduling of PV-emission on sizing and performance.

2.3.1. Case 1: Estimate daily load

For case 1, the daily load profile was prepared based on normal operation time of a healthcare center. As presented in (1), daily energy demand for that device was calculated from the rated power, number of devices used and duration of use. The equipment list and daily energy estimates are presented in Table 2 [21], [22].

$$E_{Load\ Daily} = \sum N_i * P_i * t_i \quad (1)$$

N_i = number of units, P_i= denotes the nominal power of the device I, t_i= indicates the daily operational hours of the device i.

This method facilitates comprehensive modelling of energy demands in accordance with the facility's real operational timetable. The steps for load assessment for case 1 are outlined in Table 2 as:

i) Enumerate all electrical items that will be powered by the PV system.
ii) Input the categories of loads into the designated table.
iii) Document the operational wattage of each device.
iv) Indicate the daily usage duration for each item.
v) Multiply steps 2, 3, and 4 to determine the daily energy need.

2.3.2. Case 2: Seasonally adjusted monthly load profile

For case 2, a load profile depending on months has been developed, including season-wise change in the equipment usage rate and number of working days associated with each month. Summary of the operating schedule of healthcare-center equipment on a monthly basis. Seasonal devices were included according to operational requirements of the month indicated in Table 3. According to the equipment-utilization schedule illustrated in Table 3, the relevant daily energy demand was determined for each month. Monthly energy demand can then be calculated using (2) [17], [18].

$$E_{Load\ Monthly} = E_{Load\ Daily} * D \quad (2)$$

$E_{Load\ Monthly}$ is the energy demand in month m, $E_{Load\ Daily}$ is the daily energy need that is applicable to a given month based on the equipment working within that specific time period and *D* is the number of working days in month m considering weekly and official holidays. Table 4 shows the daily demand period, number of working days, and also monthly energy consumption. Using the calculated monthly values of energy-demand, each value was then input into PVsyst for component sizing and its annual performance simulation.

Table 2. Daily estimated load

Device	Quantity	Power (W)	Operating (hours/day)	Daily energy (kWh/day)
LED lighting	10	20	7	1.4
Fan	4	75	7	2.1
Desktop computers	4	150	7	4.2
Medical refrigerator	1	200	7	1.4
Autoclave (sterilizer)	1	1500	2	3
Air conditioner (1.5 Ton)	1	1800	4	7.2
Basic medical equipment	2	100	4	0.8
Exhaust fan/ventilation	1	120	4	0.48
Patient monitor	1	100	7	0.7
Defibrillator	1	150	7	1.05
X-Ray machine (if used)	1	3000	2	6
Surveillance cameras	4	15	24	1.44
Electric water heater	1	2000	4	8
Total daily energy = 37.77 kWh/day				

Table 3. Monthly device utilization

Device	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
LED lighting	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fan	×	×	×	×	✓	✓	✓	✓	✓	×	×	×
Desktop computers	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Medical refrigerator	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Autoclave (sterilizer)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Air conditioner (1.5 Ton)	×	×	×	×	✓	✓	✓	✓	✓	×	×	×
Basic medical equipment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Exhaust fan/ventilation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Patient monitor	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Defibrillator	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
X-Ray machine	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Surveillance cameras	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Electric water heater	✓	✓	✓	✓	×	×	×	×	×	✓	✓	✓

Table 4. Monthly working days and energy consumption

Month	Daily energy (kWh/day)	No. of days (day/month)	Monthly energy (kWh/month)
January	28.47	23	654.81
February	28.47	20	569.4
March	28.47	23	654.81
April	28.47	22	626.34
May	29.77	23	684.71
June	29.77	22	654.94
July	29.77	23	684.71
August	29.77	23	684.71
September	29.77	22	654.94
October	28.47	22	626.34
November	29.77	23	684.71
December	29.77	22	654.94

2.4. Step 4: Designing a system according to load cases

Once each load profile was defined, the PVsyst stand-alone pre-sizing tool was employed to calculate the PV array and battery bank sizing based on load demand, meteorological data, battery limits, and system configuration. Components were mostly chosen from the PVsyst database, and adjustments to the series–parallel arrangements of those components were made and checked by the built-in sizing check until an acceptable level of warning was reached. Subsequently, annual simulations were conducted in great detail. These sizes were analytically verified by applying (3)–(5) using existing PV-sizing procedures [23], [24] and PVsyst pre-sizing rules [23], [25].

PV array sizing as in (3).

$$P_{PV} = \frac{E_d}{PSH * \eta_{sys}} \quad (3)$$

Number of PV modules:

$$N_{PV} = \frac{P_d}{P_{module}} \quad (4)$$

Battery bank sizing:

$$N_{PV} = \frac{E_d * N_{aut}}{V_{sys} * DOD} \quad (5)$$

In (3) and (5), *Ed* represents daily energy demand and it is the average daily value of peak-sun-hours or PSH, ηsys is the total system efficiency; Pmodule is the nominal power rated for a PV module, Naut is the number of days of autonomy required; Vsys is the nominal battery-bank voltage; and DOD is the maximum depth of discharge. An overall 75% system efficiency, one day of battery autonomy, and 20% minimum battery state of charge were assumed for the preliminary analytical verification. Thus, the maximum depth of discharge was considered 80 %.

2.4.1. Case 1: System design based on the daily load profile

For case 1 the daily load profile from the equipment inventory and operating schedule of the healthcare center was input in PVsyst. As practical component configuration selected per software pre-sizing recommendations, analytical sizing estimates and the internal sizing check. Table 5 details the PV-array, battery-bank and controller parameters used for this case. The selected configuration included 24 PV modules of 450 Wp each, providing a nominal capacity for the PV-array of 10.8 kWp. The battery bank consisted of 20 batteries in parallel connected to 5 parallel strings of 4 series connected units providing a nominal voltage of 48 V and a total capacity of 1000 Ah.

Table 5. System components adopted for case 1

PV module			Battery		
Manufacturer	LG Electronics		Manufacturer	Narada	
Model	LG 450 N2W-E6		Model	MPG 12 V 200	
Original PVsyst database	Unit nom. power	450 Wp	Technology	Lead-acid, sealed, Gel	
	Number of PV modules	21 units	Nb. of units	5 in parallel × 4 in series	
	Nominal (STC)	9.45 kWp	Discharging min. SOC	20.0 %	
	Modules	7 strings × 3 In series	Battery pack characteristics	Voltage	48 V
Total PV power	Nominal (STC)	9 kWp		Nominal capacity	1000 Ah (C10)
	Total	21 modules		Temperature	Fixed 20 °C
	Module area	46.2 m²	Controller universal controller	Technology	MPPT converter
	Cell area	41.1 m²		Temp Coeff.	-5.0 mV/°C/Elem.

2.4.2. Case 2: System design based on the monthly load profile

In case 2, the energy-demand values dependent on the month estimated based on the seasonal equipment-utilization schedule and their relevant number of working days were introduced into PVsyst. This case was sized independently using the same analytical and software-based sizing procedure. Specifications of PV-array, battery-bank, and controller adopted for the monthly load profile has been shown in Table 6.

The chosen configuration had 15 PV modules with a nominal power of 450 Wp, which allowed the PV-array capacity to be nominal at 6750 Wp of capacity. In addition, the battery bank consisted of four strings of three parallel units of twelve Narada MPG 12 V 200 batteries. Using this configuration, delivered a nominal voltage of 36 V, a nominal capacity of 800 Ah at the C10 rate, and a PVsyst-reported stored energy of 23.7 kWh. The minimum state of charge for the battery was 20%. The analytical sizing results derived from (3)–(5) are compared with the practical module configurations utilized in PVsyst as shown in Table 7.

Table 7 shows that preliminary analytical sizing results were reasonably consistent with the practical designs used in PVsyst. These differences can mainly be ascribed to rounding the calculated values to integer numbers of PV modules and batteries, and to the discrete rated capacities of the components sourced from the PVsyst database. If the exact calculated value not was available, or does not provide relevant arrangement, series–parallel then was selected rounded higher practical value, that would help to avoid the under sizing of the system and have a proper allowance in design.

2.5. Step 5: PVsyst simulation configuration and performance assessment

The detailed annual simulations for both the daily and monthly load cases were conducted separately after the application of the component-selection process. In both cases, the same geographical site and Metronome meteorological dataset and ground-albedo value, PV-array tilt, and azimuth angle were kept constant. Thus, the only differences between simulations were the input load profiles and the related PV-array and battery-bank configurations.

During evaluation, outputs from the simulation were compared with the available solar energy, energy provided to the user, required energy to cover the load energy, missing, unused energy, battery end-of-period state of charge, charging time, and performance ratio. The adequacy, reliability and energy utilization for each system configuration were determined using these indicators. Simulate two distinct project situations (daily and monthly load inputs).

Table 6. System components adopted for case 2

PV module			Battery		
Manufacturer	LG electronics		Manufacturer	Narada	
Model	LG 450 N2W-E6		Model	MPG 12 V 200	
Original PVsyst database	Unit Nom. power	450 Wp	Technology	Lead-acid, sealed, Gel	
	Number of PV modules	15 units	Nb. of units	4 in parallel × 4 in series	
	Nominal (STC)	6.75 kWp	Discharging min. SOC	20.0 %	
	Modules	5 strings × 3 in series	Battery pack	Voltage	48 V
Total PV power	Nominal (STC)	7 kWp	characteristics	Nominal capacity	800 Ah (C10)
	Total	15 modules		Temperature	Fixed 20 °C
	Module area	33.0 m²	Controller (universal	Technology	MPPT converter
	Cell area	29.4 m²	controller)	Temp Coeff.	-5.0 mV/°C/Elem.

Table 7. Comparison between analytical sizing and the configurations adopted in PVsyst

Parameter	Load case	Analytical estimate	PVsyst configuration	Difference
PV-array capacity	Case 1	10.07 kWp	10.80 kWp	7.2%
Battery-bank capacity	Case 1	983.6 Ah	1000 Ah	1.7%
PV-array capacity	Case 2	5.70 kWp	6.75 kWp	18.4%
Battery-bank capacity	Case 2	742.5 Ah	800 Ah	7.7%

3. RESULTS AND DISCUSSION

The PVsyst simulation results of the two-standalone PV-system configurations have been presented and discussed in this section. Case1 was created with a standard daily load profile regularly modulated on a weekly basis while case 2 was built on monthly average load data adjusted0 to seasonality based on the operating months of both appliance and their working days-of-month. The comparison takes into account annual load demand, size of the PV-array and battery-bank, available energy, energy supplied to the user, unused energy, unmet energy, solar fraction, and battery behavior and performance ratio. As the two load-modeling methodologies resulted in differing annual energy demands and thus different system sizes, the performance variations observed herein are interpreted as the sum of the influences of load representation, component sizing, and the temporal connection between solar-energy availability and facility demand.

3.1. Case 1: Conventional daily-load model performance

Case 1 indicates the typical daily-load method, where the total equipment demand was applied in the open hours of the health care center, as it is in the case of having open hours from 8:00 a.m. to 3:00 p.m. repeating every five weekdays. The load used in PVsyst was a daily profile modulated weekly, and matches an average demand of the year nearly equal to 27.0 kWh per calendar day. The standalone system was designed so that PV generation and battery storage provided the energy needed by the facility daily. To represent this load, a system made up of a 9.45 kWp PV array with 21 modules, and a 48 V, 1000 Ah battery bank with 20 batteries was used [42]. It assessed these parameters as the available energy, the energy provided to the user, the unused energy, the unmet energy, the battery state of charge, the solar fraction and the system performance ratio. Monthly and yearly energy balances obtained for this configuration are listed in Table 8.

The monthly results show that missing energy (E_Miss) occurred only in October and November. In October, the system supplied (E_User) 866.0 kWh of a total load demand (E_Load) of 867.8 kWh, resulting in a (E_Miss) of 1.80 kWh. The effective irradiation (GlobEff) during this month was 155.1 kWh/m², while the end-of-day state of charge (SOC_End) was 0.714. The occurrence of a small deficit despite a moderate monthly irradiation level indicates that sufficient annual or monthly energy availability does not necessarily guarantee uninterrupted supply. Short-duration mismatches between PV generation, load demand, battery

availability, and charge discharge constraints may still produce localized energy deficits. For case 1 the monthly variation of effective irradiation and battery charge duration shown in Figure 2.

The (E_Miss) increased significantly to 26.44 kWh in November, as the (E_User) 803.6 kWh of the total (E_Load) of 830.1 kWh. This month recorded a lower (GlobEff) of 134.5 kWh/m² and the minimum SOC_End value of 0.287. The concurrent reduction in solar input and battery state of charge indicates deeper battery depletion and explains why November accounted for most of the annual (E_Miss) in case 1. Although the reported charging duration in November was slightly longer than in October, charging duration alone does not represent the total energy stored because it does not account for charging power, battery acceptance conditions, or the timing of the load. The relationship between the monthly variation of battery charge duration and end-of-day state of charge for case 1 shown in Figure 3.

Even though (GlobEff) of only 136.5 kWh/m² was achieved in February, there was no (E_Miss), which confirms that monthly irradiation was not the only factor in determining system reliability. Over this month, the (E_Load) of 754.6 kWh could be met with the PV generation and battery storage available. Conversely, these September deficits indicate that system response similarly varied with short-term characteristics of solar generation, load demand and battery state of charge in October and November. Thus, even months with similar irradiation, did not produce similar reliability in results.

Table 8. Monthly and annual energy balances for case 1

Month	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	EArray kWh	PR %
January	96.4	143.7	1232	327.1	0	867.8	867.8	942	0.631
February	106.1	136.5	1159	366.3	0	754.6	754.6	825.2	0.576
March	147.3	167.9	1396	529.2	0	830.1	830.1	902.7	0.514
April	176.9	181	1477	653.3	0	792.3	792.3	857.5	0.454
May	196.3	184	1463	559	0	867.8	867.8	942.7	0.488
June	216.9	195.2	1521	659.7	0	792.3	792.3	898.7	0.42
July	214.8	197.2	1515	624.6	0	830.1	830.1	931	0.436
August	196.2	194.3	1493	575.4	0	867.8	867.8	956.8	0.463
September	166.1	183.9	1445	656.6	0	754.6	754.6	820.5	0.426
October	127.1	155.1	1247	346.2	1.8	866	867.8	937.9	0.581
November	96.1	134.5	1122	291.8	26.44	803.6	830.1	865.2	0.623
December	85.1	128.2	1093	214.4	0	792.3	792.3	915.2	0.645
Year	1825.3	2001.7	16161	5803.7	28.24	9819.3	9847.5	10795.3	0.510

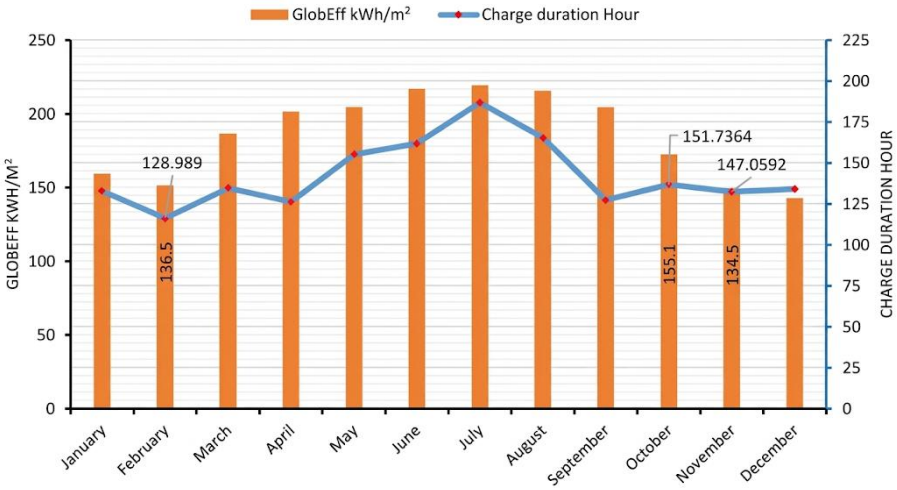

Figure 2. Monthly variation of effective irradiation and battery charge duration for case 1

In Table 7, we also note that there is unused energy (EUnused) throughout the year, especially in June (659.7 kWh), September (656.6 kWh) and April (653.3 kWh). These surpluses were seen to occur whenever the available PV energy was higher than the simultaneous load demand and the battery was unable to accept any more energy. Meanwhile, the presence of annual (E_Miss) of 28.24 kWh confirms very high annual energy surpluses did not preclude short duration supply deficits. Any unused and unmet energy thus reflects a temporal mismatch across the PV generation, battery-storage availability, and the daily-load profile. The monthly performance ratio (PR) varied from 0.420 in June to 0.645 in December, and the PR was 0.510,

overall, by year. Such variation indicates a change in the useful use of the exploitable solar energy with respect to the initially adopted load and storage conditions as opposed to the set of established values of the inherent efficiency of the PV modules.

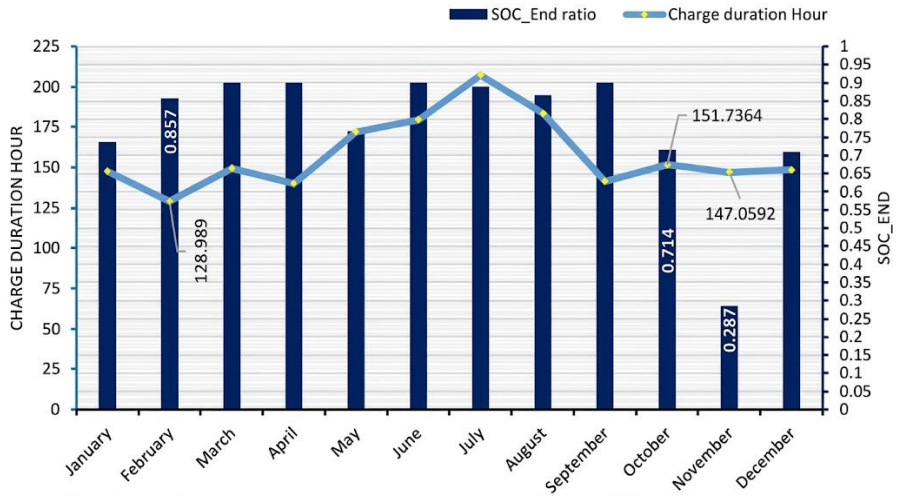

Figure 3. Monthly variation of battery charge duration and end-of-day state of charge for case 1

3.2. Case 2: Results

Table 9 demonstrates the effectiveness of the off-grid PV system based on a monthly profile of loads. The medical center in question has a schedule that functions on a five-day basis, from 8:00 AM to 3:00 PM, this schedule served as the basis for calculating the monthly energy consumption. The monthly results demonstrate that case 2 satisfied the full-modeled demand each month, and there was zero missing energy throughout the year. This result was sustained even in November and December, which observed low (GlobEff) values of 134.5 and 128.2 kWh/m², respectively. For November the system provided more than the total (E_Load) of 626.3 kWh and subsequently supplied 654.9 kWh for December. The lack of energy deficits in these months of low irradiance suggests that the monthly time-step representation of equipment operation diminished modeled demand to a level that could be satisfied by the available PV generation and storage. Throughout the year, at no point does the (end of day) battery state of charge (SOC_End) actually decline near the failure threshold below 0.498. That remaining energy was then drawn on to support the facility demand when solar was not producing. In Figure 4, monthly battery charge time and monthly battery state of charge at the end of the day for case 2 is shown.

3.3. Comparative analysis of the two load-modeling strategies

The resulting principal sizing and performance indicators from case 1 and case 2 are compared in Table 10 to ensure direct assessment of the influence of both load-modeling approaches. In both cases, the same geographical location, meteorological data, PV-module technology, tilt angle, azimuth, albedo, and PVsyst modeling conditions were simulated. Thus, the discrepancies noticed are related to the chosen load characterizations and their system size.

The seasonally adjusted monthly estimated annual demand decreased from 9847.5 kWh to 685.5 kWh, which was 20.74%. This reduction occurred because the actual months of operation and work days per month per device should be specified rather than repeating the total equipment demand for each day of the year. Therefore, the capacity of PV-array and battery-bank was reduced to 6.75 kWp and 800 Ah, respectively, from 9.45 and 1000 Ah. Therefore, the different reduction in system size was mainly linked to a lower and more realistic load estimate and not an increase in the internal efficiencies of the components.

While the system designed for case 2 was smaller overall, it satisfied 100% of its modeled demand and removed the 28.24 kWh of (E_Miss) in case 1. Unused energy per year reduced by 41.14%, the performance ratio improved from 50.96% to 56.72%, showing a closer match of installed capacity to the modeled demand. In case 2, the lower (EUser) is due to lower annual demand and should not be regarded as poorer supply performance. But in contrast, PVsyst predicted more use of battery storage and a cut in the expected battery lifespan from 12 years to 8 years also highlighting a trade-off between less installed capacity and more frequent use of batteries.

Table 9. Monthly and annual energy balances for case 2

Month	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	EArray kWh	PR %
January	96.4	143.7	878	189.8	0	654.8	654.8	717.1	0.666
February	106.1	136.5	827	236.5	0	569.4	569.4	614.5	0.609
March	147.3	167.9	995	316.4	0	654.8	654.8	706.4	0.568
April	176.9	181	1051	401.1	0	626.3	626.3	678.1	0.503
May	196.3	184	1042	332.6	0	684.7	684.7	740	0.539
June	216.9	195.2	1083	403.3	0	654.9	654.9	709.8	0.486
July	214.8	197.2	1080	370.8	0	684.7	684.7	740.3	0.503
August	196.2	194.3	1065	354.7	0	684.7	684.7	739.7	0.512
September	166.1	183.9	1027	347.4	0	654.9	654.9	707.6	0.517
October	127.1	155.1	889	210.9	0	654.8	654.8	706.4	0.616
November	96.1	134.5	800	165	0	626.3	626.3	661.4	0.680
December	85.1	128.2	778	87.4	0	654.9	654.9	719.4	0.747
Year	1825.3	2001.7	11515	3416.1	0	7805.5	7805.5	8440.7	0.567

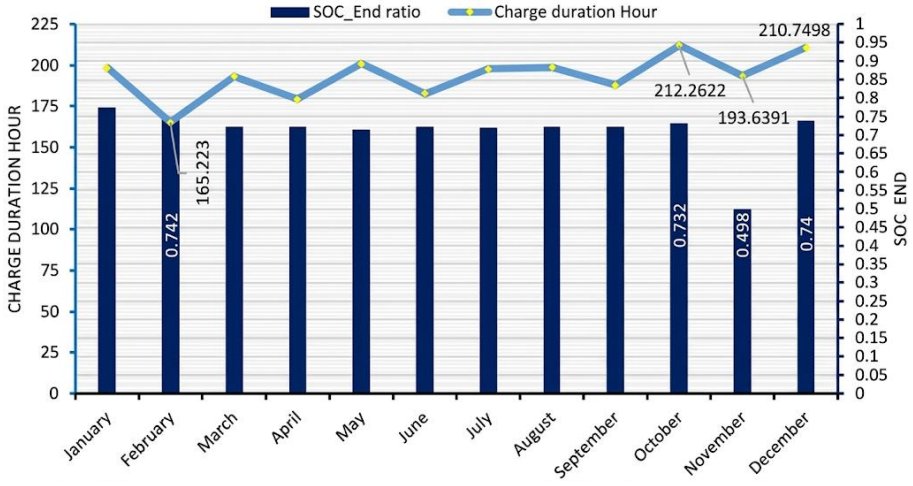

Figure 4. Monthly variation of battery charge duration and end-of-day state of charge for case 2

Table 10. Comparative sizing and performance indicators of the two load-modeling cases

Parameter	Case 1	Case 2	Change from case 1
Annual load demand, E_Load	9847.5 kWh	7805.5 kWh	−20.74%
PV-array capacity	9.45 kWp	6.75 kWp	−28.57%
Number of PV modules	21	15	−28.57%
Battery-bank capacity	1000 Ah	800 Ah	−20.00%
Stored battery energy	39.6 kWh	31.7 kWh	−19.95%
Energy supplied, E_User	9819.3 kWh	7805.5 kWh	−20.51%
Unmet energy, E_Miss	28.24 kWh	0 kWh	Eliminated
Unused energy, E_Unused	5803.6 kWh	3416.1 kWh	−41.14%
Solar fraction	99.71%	100.00%	+0.29
percentage points performance ratio	50.96%	56.72%	+5.76 percentage points

4. CONCLUSION

The study investigated the impact of load-profile representation on the sizing and simulated performance of an off-grid PV system for a rural hospital in Iraq using PVsyst. We investigated two approaches that fell under the same operating schedule: a traditional daily-load model with weekly modulation and a seasonally adjusted monthly-load model based on the months of operation of each device and month working days. The monthly-load model estimated the demand as high as 9847.5 kWh, which was reduced to 7805.5 kWh annually. The needed PV-array capacity was thus reduced from 9.45 kWp to 6.75 kWp, and the battery-bank capacity was reduced from 39.6 kWh to 31.7 kWh. Case 1 provided 99.71% of modeled demand in addition to 28.24 kWh unmet energy, while case 2 provided 100% of modeled demand and 0 kWh unmet. The annual unused energy was reduced from 5803.6 to 3416.1 kWh, and the performance ratio increased from 50.96% to 56.72%. These results suggest that there is a better match between the system capacity selected and the seasonally adjusted demand than there is with an improvement in intrinsic PV module efficiency.

The smaller battery bank of case 2 was utilized more and thus had a shorter estimated lifetime, which means it was in higher cycling versus storage capacity. The results are specific for one healthcare facility in one location using the PVsyst model that has been used. So, these results should not be extended to cover each other standalone PV systems without validation data. Future work should investigate metered load data, various locations and facility types, alternate simulation platforms, and the influence of increasing the battery-bank capacity on battery life and system performance. Future work will need to determine if increasing the battery-bank capacity results in increasing the lifetime of the battery without causing excess unused energy or system oversizing.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Waleed Khalid Shakir Al-Jubori	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Ahmed Hussein Duhis		✓	✓			✓		✓	✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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BIOGRAPHIES OF AUTHORS



Waleed Khalid Shakir Al-Jubori received his B.Sc. degree from the College of Engineering, University of Baghdad, Iraq, in 1987. He received his M.Sc. and Ph.D. degrees from the University of Technology, Iraq, in 2005 and 2017, respectively. He is a lecturer in the Department of Electrical Power Engineering Techniques, Al-Mussaib Technical College, Al-Furat Al-Awsat Technical University, Iraq. His research interests include power system stability and control, flexible AC transmission system (FACTS) devices, and the application of artificial intelligence algorithms in power system analysis. He can be contacted at email: wjubori@gmail.com.



Ahmed Hussein Duhis is an assistant professor in the Department of Electrical Engineering Techniques, Technical College of Al-Mussaib, Al-Furat Al-Awsat Technical University, Iraq. He received his B.Sc. degree in electrical engineering and his M.Sc. degree in laser engineering from the University of Technology, Iraq. His research interests include renewable energy systems, intelligent control, laser technology, and its engineering applications. He can be contacted at email: ah.hu.khf@gmail.com or com.ahmd4@atu.edu.iq.