

THE USE OF RENEWABLE ENERGY SOURCES FOR AUTONOMOUS POWER SUPPLY OF HEALTHCARE FACILITIES AND RESORT-RECREATIONAL COMPLEXES

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This paper considers the principles of equipping high-priority facilities, including healthcare institutions and other medical complexes, with uninterruptible power supply systems. A comprehensive approach to the energy supply of the facilities under consideration is proposed, which includes both autonomous power generation units for buildings and structures and additional backup power supply systems intended for direct use by these facilities, as well as for emergency power supply of electrical system equipment. The application of power generation technologies based on solar photovoltaic modules, solar thermal systems, and wind energy installations is considered for the design and modernization of distribution and main substations. These installations represent an integrated electricity generation system based on the direct and indirect conversion of solar radiation energy and atmospheric air mass movement into electrical energy. Experimental monitoring of the proposed RES prototype showed that, depending on the operating period and seasonal conditions, the system covered approximately 5–20% of the auxiliary energy demand. Over the five-month observation period, the overall contribution of the RES system reached 8.87%.

KEYWORDS

photovoltaic module, wind energy installation, energy storage systems, operating mode, station auxiliary power supply.

1 INTRODUCTION

Ensuring the energy security of healthcare facilities involves a comprehensive set of measures aimed primarily at maintaining an uninterrupted power supply to these facilities despite the influence of adverse external factors, such as natural disasters, military conflicts, terrorist threats, and other emergency situations. Medical institutions, as well as sanatorium and resort-recreational facilities, are among the categories of consumers where the importance of reliable and continuous power supply cannot be overstated [Kuvshinov 2017, Boloz 2024, Kozlov 2024, Spirydowicz 2025, Ciertazsky 2025]. According to the classification provided by the Electrical Installation Code (PUE), a significant portion of the equipment operated in healthcare

facilities belongs to the first category of power supply reliability. This implies that even a short-term interruption or failure of the power supply may pose a direct threat to human life and health. Such equipment includes life-support systems used in intensive care units (ventilators, extracorporeal circulation systems, and artificial kidney machines), maternity departments (incubators, neonatal ventilation systems, and newborn intensive care equipment), as well as operating rooms and anesthesiology departments (surgical tables, operating lamps, and anesthesia machines).

The stable operation of these critical electrical consumers cannot depend on a single power source. A power interruption is permissible only for a limited period required to restore the supply from a backup power system. Such systems must be equipped with automatic control mechanisms to ensure timely start-up and shutdown of generating units [Zidek 2024, Kondrat 2025]. The configuration of power stations should include advanced high-reliability equipment capable of preventing unexpected system failures under proper operating conditions and compliance with maintenance requirements.

The design, installation, and maintenance of such systems must be performed by qualified specialists. The minimum required capacity of an emergency power supply installation for a specific healthcare facility depends on the number of connected electrical consumers, the configuration of the equipment, operating duration, and other technical factors [Bialy 2024, Demcak 2024, Shaitor 2025]. For example, when conventional mobile power generation units with a capacity of up to 30 kW are used, it is recommended to install generators in heat-resistant, noise-insulated enclosures. In addition, sufficient space should be provided for storing an adequate fuel reserve to ensure operation during prolonged emergency conditions.

The organization of such systems requires the use of equipment providing the second level of power station automation. This ensures automatic generator start-up in the event of a loss of voltage in the main electrical network. Once a stable power supply from the primary source is restored, the generator is automatically disconnected.

The first and highest category of power supply reliability includes numerous critical services of healthcare facilities, such as electrical equipment installed in intensive care units, operating rooms, anesthesiology departments with intensive care wards, and maternity hospitals. Electrical consumers belonging to the first reliability category must be continuously supplied with electricity, and any interruption is permitted only for the time required for automatic restoration of the power supply. Traditionally, autonomous diesel power plants have been used as independent backup sources for such applications.

The development of guaranteed power supply systems for healthcare facilities represents a complex engineering task that differs significantly from autonomous power supply solutions used in commercial organizations, industrial enterprises, or oil and gas companies. Therefore, the implementation of autonomous backup power systems should be entrusted only to organizations with proven experience in this field. Practical experience demonstrates that healthcare facilities are often forced to address backup power supply issues independently. However, since this activity is not their primary area of expertise, such solutions are frequently implemented without sufficient technical justification. In many cases, these activities are carried out without measurements and analysis of power quality at specific facilities and without considering the specific characteristics of the medical equipment in use. This may result in either excessive or insufficient measures for ensuring the continuity of power supply to complex medical systems.

The primary purpose of installing diesel power plants (DPPs) as backup power sources in hospitals, outpatient clinics, various types of medical dispensaries, sanatoriums, and medical storage facilities is to provide a comprehensive solution for preventing emergency situations associated with power supply failures that may lead to catastrophic consequences for human health and life.

The automation level of diesel power plants considered in this context corresponds to the second category of automation, which provides automatic commissioning of the generating unit in the event of failure of the external power supply network. Depending on operating conditions, diesel power plants can be installed as open-frame units (Fig. 1), in weather-protective or noise-insulated enclosures, or in specialized frost-resistant vandal-proof containers when a dedicated power plant room is unavailable.



Figure 1. External view of a diesel generator set in an open-frame design

It is also recommended to install additional fuel tanks in advance to extend the period of continuous operation without connection to the external power grid. The installation of autonomous power supply systems for hospital departments and buildings based on diesel generator sets is carried out according to an individual design developed for each healthcare facility.

More than thirty diesel power plants with individual capacities ranging from 20 to 800 kW have already been installed across Russia. Diesel power plants providing autonomous power supply for various medical equipment and life-support systems are widely used in different areas of the healthcare sector. For example, to ensure reliable power supply for four psycho-neurological residential care facilities located in the central region of Russia, high-capacity diesel generator sets with rated power ranging from 200 to 320 kW were specially manufactured. These units were equipped with the second level of automation, enabling automatic activation of the power stations when required (Fig. 2).



Figure 2. External view of the automatic transfer switch (ATS) for a diesel generator set

In these healthcare facilities, not only medical care is provided, but patients are also maintained under a specialized therapeutic and protective care regime. Therefore, ensuring an

uninterrupted power supply is of critical importance, since any disruption of this regime may lead to situations in which patients can pose a risk to themselves as well as to others.

For backup power supply of two veterans' care homes and one children's residential facility, diesel power plants with a capacity of up to 315 kW were installed. These generators provide backup power for physiotherapy rooms and ensure continuous electricity supply to residential and auxiliary premises.

To provide comfortable conditions for treatment and recreation in various types of sanatorium facilities, four diesel generator sets with a capacity of up to 400 kW were manufactured and supplied. As a result, power interruptions will no longer affect patients undergoing treatment and preventive procedures for chronic rheumatic diseases of the heart and joints, digestive system disorders, respiratory diseases, as well as visitors using spa treatment facilities.

The high quality of equipment assembly and the application of advanced mechanical engineering technologies in the production of diesel generator sets have also been recognized by the Russian Academy of Sciences, which ordered a 100 kW diesel power plant for backup power supply of the Institute of the Human Brain. The main activities of the institute include fundamental research into the organization of the human brain and its complex mental functions, including speech, emotions, attention, memory, and creativity. Research of such importance must not be disrupted, especially by a simple power outage.

Social rehabilitation centers, similar to other healthcare institutions, also require protection against power supply interruptions to ensure the continuity of their operations. Three such centers located in the Moscow region have been equipped with diesel generator sets with the second level of automation and a capacity of up to 50 kW.

The organization of medical pharmaceutical storage facilities requires compliance with numerous regulatory requirements. Storage facilities for medicines must be equipped with electrical supply systems, heating systems, water supply and sewage systems, as well as supply and exhaust ventilation or air-conditioning systems. The operation of these systems must be maintained continuously without violating the required temperature conditions, since any deviation may result in the deterioration or loss of pharmaceutical products.

Backup power supply for one of the major medical pharmaceutical storage facilities is provided by a 200 kW diesel generator set equipped with the second level of automation, which enables automatic start-up in the event of failure of the centralized power supply (Fig. 3).



Figure 3. External view of the DGS-200 diesel generator set in an enclosure configuration

The deterioration of stationary electrical networks, transformers, and power transmission lines (PTLs) represents a significant risk factor for modern healthcare facilities that cannot be neglected. Under emergency conditions, a power outage may lead to deterioration of patients' health and may even threaten their lives. A backup power supply system based on diesel power plants is therefore an essential component for modern healthcare facilities of various types. Without such systems,

even highly qualified medical personnel may be unable to ensure patient safety during technical failures or power transmission line faults. In electric power systems, high-voltage distribution substations with voltage levels of 35 kV, 110 kV, 220 kV, 330 kV, 500 kV, and other ratings are equipped with internal power supply systems known as substation auxiliary power supply systems. These systems are designed to provide reliable electricity for the operation of substation auxiliary equipment. For this purpose, substations are equipped with auxiliary service transformers (ASTs). At substations with a rated voltage level of 330 kV, three auxiliary service transformers are often used: AST-1, AST-2, and AST-3.

2 RESEARCH OBJECTIVES AND PROBLEM STATEMENT

As demonstrated by the measures described above, a reliable method for ensuring the power supply of high-priority facilities, including healthcare institutions and electrical substations, is the implementation of an integrated approach to energy supply. This approach involves the installation of additional backup or autonomous power sources capable of ensuring uninterrupted operation not only of critical facilities themselves but also of the main equipment within general power systems that influence the reliability of their electricity supply.

Such systems include distribution substations, power transmission lines, and other components of the electrical infrastructure, since backup power supply for hospitals and other healthcare facilities can be maintained by local generating sources (diesel generator sets, solar power plants with energy storage systems, and other technologies) only for a limited period.

Therefore, the objective of this study is to develop and evaluate the integrated application of combined power supply systems required to ensure uninterrupted electricity supply for healthcare facilities of various types and distribution substations.

The study considers an approach for reducing the power consumption of substation auxiliary systems through the application of renewable energy sources (RES), specifically photovoltaic (PV) modules and wind power installations (WPI). A block diagram of the power supply system for the considered facility is presented in Fig. 4 [Baader 1982].

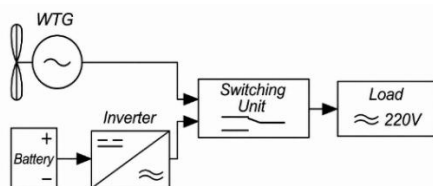


Figure 4. Block diagram of the facility power supply system: wind power installation and photovoltaic modules supplying the consumer

This configuration offers several advantages due to the combination of different generation systems, resulting in increased stability of the power supply system. In the absence of wind, electricity generation can be provided by solar energy, and vice versa.

The integration of renewable energy sources (RES) into substation auxiliary power supply systems (SAPS) increases the overall reliability of electricity supply while operating in combination with conventional autonomous power sources. The use of solar generation is particularly effective for facilities with year-round energy consumption. Figure 5 presents a schematic diagram of RES application for power system facilities.

As can be seen, the priority system is one that employs the most widespread renewable energy-based generation technologies,

including wind power installations, photovoltaic modules, and solar thermal systems for heating the heat-transfer medium, with the possibility of integrating additional photovoltaic converters on the working surface. All these installations are equipped with electrical energy storage systems (EES) based on batteries of various types.

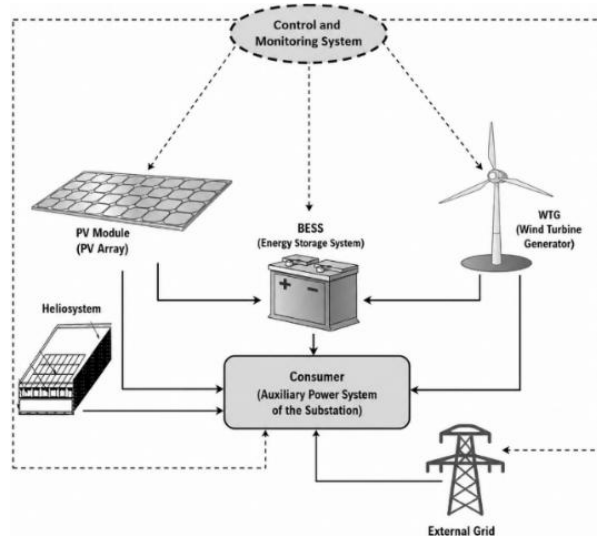


Figure 5. Scheme of RES integration into the power supply system of a healthcare facility

However, for large-scale practical implementation, the most rational approach is the use of solar energy systems for converting solar radiation flux into electrical energy. Such systems can be installed both near and directly on buildings, as well as within the territories of various healthcare facilities.

Use of Photovoltaic Systems for Autonomous Power Supply of Adjacent Areas of Healthcare Facilities

One of the most relevant approaches to solving the problem of lighting pedestrian areas around healthcare facilities is the application of compact photovoltaic power generation systems. Within the framework of this study, an analysis was performed of photovoltaic installations developed and implemented at various healthcare facilities for illuminating adjacent outdoor areas. The concept of creating an independent outdoor lighting system that does not rely on centralized power sources and is capable of supplying itself with electricity is both promising and highly attractive. Such systems are based on a combination of lighting equipment and renewable energy technologies, providing new opportunities for autonomous lighting solutions. Figure 6 presents a lighting pole equipped with photovoltaic panels and energy storage systems.



Figure 6. Lighting pole with a complete set of equipment for autonomous lighting

Since the lighting fixtures are not connected to a power supply line, there is no need to install them at a fixed location. In addition, the requirement for large amounts of expensive power cable is eliminated.

However, when considering an autonomous lighting system, it is important not to focus solely on the advantages of its application. It should also be taken into account that each lighting unit must be equipped with its own set of solar batteries and an energy storage capacity sufficient to ensure lamp operation throughout the entire night period. The longer the duration of darkness, the greater the required battery capacity and the larger the photovoltaic panel area, which increases the complexity of the design and significantly raises the overall cost of the system.

As a result, a situation may arise where the implementation of an autonomous lighting system becomes considerably more expensive than the installation of a conventional stationary power supply line. Therefore, it is necessary to determine an optimal balance between equipment cost and required power characteristics.

Table 1 presents a list of equipment and construction materials required for the installation and illumination of the perimeter area and the main entrance.

No.	Equipment and Construction Materials	Weight /Length	Quantity
1	Fast-drying black primer enamel	0.9 kg	10
2	Steel square hollow section (SHS), 60 × 60 × 3 mm	6 m	30
3	Steel rectangular hollow section (RHS), 40 × 20 × 2 mm	6 m	20
4	ATLANT welding electrodes, Ø3 mm	1 kg	6
5	ATLANT welding electrodes, Ø2 mm	1 kg	6
6	Universal degreasing agent	0.5 L	3
7	Flat paintbrush No. 50	-	2
8	IEK SDO 06-20 LED floodlight, 20 W, 1600 lm, 6500 K, cool white	-	3
9	Outdoor junction box, IP54, 88 × 88 × 40 mm, polyethylene, grey	-	10
10	Steel enclosure U-996, 200 × 200 × 100 mm, IP54	-	10
11	Gauss Elementary LED floodlight, 10 W, 780 lm, IP65, 6500 K, black	-	26
12	One-Sun OS-250M monocrystalline photovoltaic module, 6 BB, PERC technology, service life ≥25 years, efficiency 20.7%, 10-year warranty, 1530 × 760 × 35 mm	-	15
13	3 × 2.5 mm ² VVGng-LS power cable	300 m	3
14	20 mm corrugated protective conduit	3 m	3
15	Delta Battery GEL, 100 Ah, 12 V	-	32
16	Fumagalli Ricu/G300 G30.157.000.AXE27 outdoor garden luminaire	-	6
17	SRNE SR-MC48100H, 100 A solar charge controller	-	2
18	Heavy-duty conductors for battery bank interconnections	1 m	1
19	12 V DC / 220 V AC, 2 kW power inverter	-	2

Table 1. Equipment and Construction Materials Required for the Installation of the Perimeter and Main Entrance Lighting System

To determine the required capacity of a photovoltaic (PV) power generation system, the electrical energy demand of the lighting network must first be evaluated. Photovoltaic modules generate electricity exclusively during daylight hours, while their rated output power can only be achieved under standard operating conditions, namely clear-sky irradiance and solar rays incident perpendicular to the module surface. Under practical operating conditions, however, the angle of solar incidence continuously varies throughout the day, resulting in a reduction in the generated electrical power. The greater the deviation from the optimal incidence angle, the more pronounced the decrease in energy production.

Weather conditions have an equally significant influence on photovoltaic performance. Under overcast conditions, the output power of PV modules may decrease by a factor of 15–20 compared with clear-sky conditions. Even partial cloud cover or light atmospheric haze can reduce the generated power by approximately two to three times. Consequently, these environmental factors must be incorporated into the system design to ensure reliable operation.

For engineering calculations, it is generally assumed that photovoltaic modules operate close to their rated capacity for approximately 7 effective sunshine hours per day, corresponding to the period from 09:00 to 16:00. Although electricity generation begins shortly after sunrise and continues until sunset, the energy produced during the early morning and late afternoon contributes only 20–30% of the daily output. Approximately 70% of the total daily energy is therefore generated during the peak solar irradiation period.

Accordingly, a photovoltaic array with a nominal capacity of 1 kW is capable of producing approximately 7 kWh of electrical energy during the effective operating period (09:00–16:00) on a typical summer day, corresponding to nearly 210 kWh per month. An additional 3 kWh may be generated during the morning and evening hours, providing an operational reserve to compensate for intermittent cloud cover and fluctuations in solar irradiance. Because the PV modules are installed in a fixed position, the continuously changing solar incidence angle prevents the system from maintaining rated power throughout the day. Increasing the installed PV capacity proportionally increases the expected energy yield. For example, a 2-kW photovoltaic array can generate approximately 420 kWh of electrical energy per month, whereas a single 100-W photovoltaic module typically produces around 700 Wh per day, or approximately 21 kWh per month.

The battery energy storage system (BESS) must be sized to ensure continuous power supply during periods without solar generation. The required battery capacity can be estimated using the following relationship:

$$C = \frac{P}{U} \quad (1)$$

where:

C — required battery capacity (Ah);

P — hourly electrical energy consumption of the load (Wh);

U — battery system voltage (V).

For the case study considered in this research, assuming a 12-V battery system, the required battery capacity is calculated as follows:

$$C = \frac{600}{12} = 50 \text{ Ah} \quad (2)$$

The next stage of the design procedure involves determining the solar irradiance coefficient, also referred to as the monthly solar radiation level. This parameter is location-dependent and varies according to the geographical region and local climatic conditions. Reliable solar radiation data are publicly available and can be obtained from meteorological databases and engineering reference sources [Kuvshinov 2017].

For example, the average annual solar irradiance in Sevastopol is 3.49 kWh/m²/day, with a minimum value of 0.93 kWh/m²/day recorded in December and a maximum value of 5.89 kWh/m²/day observed in June. In Simferopol, the corresponding average annual solar irradiance is 3.41 kWh/m²/day, while the minimum and maximum values are 0.87 kWh/m²/day in December and 6.39 kWh/m²/day in July, respectively.

To estimate the daily energy output of the selected photovoltaic (PV) system, the energy production of an individual PV module must first be determined. This can be calculated using the following equation:

$$P = K \times S \times \eta \quad (3)$$

where:

P — daily energy output of a single photovoltaic module (kWh/day);

K — solar irradiance coefficient (solar radiation level) (kWh/m²/day);

S — effective surface area of the photovoltaic module (m²);

η — photovoltaic module conversion efficiency (%).

Figure 7 illustrates the proposed installation site for the low-capacity photovoltaic power plant. This configuration was used to evaluate the practical electricity generation performance of the proposed PV system.

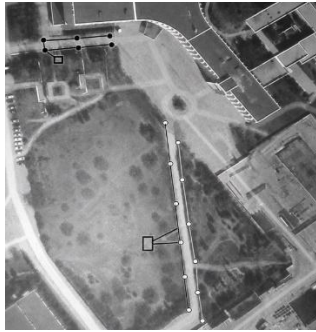


Figure 7. Proposed location of the mini photovoltaic power plant (PVPP) designed to provide electricity for perimeter lighting and the main entrance of the facility

For a photovoltaic module with a rated power of 250 W, an active surface area of 2 m², and a conversion efficiency of 15%, the expected daily energy production can be determined as follows.

Average Daily Energy Production for Sevastopol

Average annual solar irradiance

$$P = 3.49 \times 2 \times 0.15 = 1.047 \text{ kWh/day} \quad (4)$$

Maximum solar irradiance (June)

$$P_{max} = 5.89 \times 2 \times 0.15 = 1.767 \text{ kWh/day} \quad (5)$$

Minimum solar irradiance (December)

$$P_{min} = 0.93 \times 2 \times 0.15 = 0.279 \text{ kWh/day} \quad (6)$$

Average Daily Energy Production for Simferopol

Average annual solar irradiance

$$P = 3.41 \times 2 \times 0.15 = 1.023 \text{ kWh/day} \quad (7)$$

Maximum solar irradiance (July)

$$P_{max} = 6.39 \times 2 \times 0.15 = 1.917 \text{ kWh/day} \quad (8)$$

Minimum solar irradiance (December)

$$P_{min} = 0.87 \times 2 \times 0.15 = 0.261 \text{ kWh/day} \quad (9)$$

The required number of photovoltaic (PV) modules can be determined using the following equation:

$$N = \frac{P}{P_{PV}} \quad (10)$$

where:

N — required number of photovoltaic modules;

P — total daily electrical energy demand of the load (kWh/day);

P_{PV} — daily energy output of a single photovoltaic module (kWh/day).

Based on the calculated daily energy production of an individual PV module, the required number of modules for the proposed system can be estimated as follows.

Sevastopol Maximum solar irradiance

$$N = \frac{6}{1.767} = 3.40 \approx 3 \text{ modules} \quad (11)$$

Minimum solar irradiance

$$N = \frac{6}{0.279} = 21.51 \approx 22 \text{ modules} \quad (12)$$

Simferopol Maximum solar irradiance

$$N = \frac{6}{1.917} = 3.13 \approx 3 \text{ modules} \quad (13)$$

Minimum solar irradiance

$$N = \frac{6}{0.261} = 22.99 \approx 23 \text{ modules} \quad (14)$$

The electrical energy storage system of the photovoltaic mini power plant is illustrated in Fig. 8. The required capacity of the battery bank for the photovoltaic array is subsequently determined through the corresponding design calculations. An example of a battery bank comprising four batteries connected in series to provide a 48 V DC supply, together with a universal solar charge controller, is presented in Fig. 9.



Figure 8. Battery bank configuration for the electrical installation

The minimum required battery capacity should be sufficient to ensure that an adequate state of charge is maintained throughout the nighttime period. For example, if the electrical energy consumption between evening and morning is 3 kWh, the battery bank must provide at least this amount of usable stored energy. For a battery rated at 12 V with a capacity of 200 Ah, the total stored energy is:

$$12 \times 200 = 2400 \text{ Wh} = 2.4 \text{ kWh} \quad (15)$$

However, batteries should not be discharged to 100% of their nominal capacity. Specialized deep-cycle batteries are typically designed to withstand a maximum depth of discharge of approximately 70%. Exceeding this limit significantly accelerates battery degradation and reduces service life. The battery interconnection configuration is illustrated in Fig. 9.

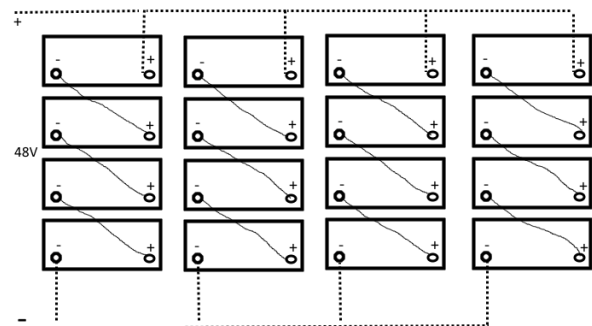


Figure 9. Series-parallel configuration of 12 V batteries forming a 48 V battery bank

If conventional lead-acid automotive batteries are used, their maximum permissible depth of discharge should not exceed 50% [Arbuzov 2007].

3 RESULTS OF THE PERFORMANCE EVALUATION OF THE SMALL-SCALE PHOTOVOLTAIC POWER PLANT

The optimal battery bank capacity corresponds to the amount of energy required to satisfy the daily electrical demand. For instance, if the daily energy consumption is 10 kWh, the battery bank should provide an equivalent usable capacity. Under these conditions, the system can operate reliably for 1–2 consecutive overcast days without interruption. During normal operating conditions, the batteries are discharged by only 20–30% of their rated capacity each day, thereby extending their operational lifetime.

The round-trip efficiency of lead–acid batteries is approximately 80%; however, it strongly depends on the charging and discharging currents. As these currents increase, the battery efficiency decreases. For example, a 200 Ah battery supplying a 2 kW load experiences a discharge current of approximately 250 A, resulting in a significant voltage drop and a reduction in energy delivery efficiency to approximately 40–50%. Likewise, charging at excessively high currents substantially decreases charging efficiency. In addition, DC/AC inverters that convert 12/24/48 V DC to 220 V AC typically exhibit efficiencies in the range of 70–80%.

Considering the energy losses associated with battery storage and DC-to-AC power conversion, the total system losses are approximately 40%. Therefore, both the battery bank capacity and the installed photovoltaic array should be oversized by approximately 40% to compensate for these losses and ensure reliable system operation.

Two principal types of solar charge controllers are commonly employed in photovoltaic systems. Pulse Width Modulation (PWM) controllers are relatively simple and inexpensive; however, they are incapable of performing voltage conversion, limiting the effective utilization of the photovoltaic array to approximately 80% of its rated power. In contrast, Maximum Power Point Tracking (MPPT) controllers continuously track the maximum power point of the photovoltaic modules and optimize energy conversion by reducing the output voltage while increasing the charging current. As a result, MPPT controllers can increase the effective energy utilization of photovoltaic panels to approximately 99%.

Consequently, when a lower-cost PWM controller is selected, the photovoltaic array should be enlarged by an additional 20% to compensate for the reduced energy harvesting efficiency. Accordingly, a direct proportional relationship exists between the electrical power delivered to the load, the operating duration of the system, the capacity of the battery bank, the inverter power rating, and, ultimately, the total cost of the photovoltaic installation.

Based on the design calculations, the required numbers of battery units and photovoltaic modules were determined. For the local lighting system, 23 independent lighting poles are required, each equipped with a 200 Ah battery, a 250 W photovoltaic module, and a 12 V DC LED luminaire operating directly from the battery without the need for an inverter [Kuvshinov 2009].

To illuminate the perimeter of the pedestrian alley and the main entrance of the healthcare facility, a mini photovoltaic power plant (mini-PVPP) is proposed. The system consists of a steel-framed structure housing 16 batteries connected in a series–parallel configuration to provide a 48 V DC output. This battery bank supplies a combined charge controller–inverter unit with a rated power of 3 kW and a peak power capability of 6 kW.

The lighting system includes 12 lighting poles installed along the perimeter of the alley, each equipped with two 20 W LED floodlights operating from a 220 V AC supply, providing a cost-effective lighting solution. In addition, the supporting steel

structure accommodates at least 14 photovoltaic modules, each rated at 200 W, together with six decorative LED luminaires installed on the main entrance staircase, each having a rated power of 10 W.

Consequently, the total installed lighting capacity supplied exclusively by renewable energy sources for the 900 m illuminated area is 1.8 kW. The complete list of the required components for the proposed photovoltaic electricity generation system designed to provide outdoor lighting for the healthcare facility is presented in Table 2.

No.	Equipment and Construction Materials	Quantity
1	Pole (Steel pipe $\varnothing 127 \times 3.5$ mm, length 6 m (5 m above ground))	140 m
2	Yeger 4 (200+) mounting bracket for photovoltaic panels on poles	23 pcs
3	Low-voltage outdoor luminaire for photovoltaic systems, PLI-09-3600-30W-DC12V-U	23 pcs
4	Weatherproof enclosure, IP54, $400 \times 400 \times 200$ mm, with pole mounting bracket	23 pcs
5	Delta Battery GEL, 100 Ah, 12 V	24 pcs
6	Pole mounting bracket for luminaire	23 pcs
7	MPPT solar charge controller	23 pcs
8	Cement M400, 25 kg	25 pcs
9	Unscreened sea sand, 50 kg	25 pcs
10	Polycrystalline photovoltaic panel, 200 W	25 pcs
11	3-in-1 black gloss paint and brush	23 sets
12	Fastening elements (banding tape and clips)	100 m
13	6 mm ² cable and connectors	100 m
14	Heat-shrink tubing	10 m

Table 2. Equipment required for the proposed photovoltaic lighting system

To improve electricity generation efficiency, the photovoltaic system can be equipped with a solar tracking mechanism (solar tracker). Photovoltaic power plants are characterized by significant fluctuations in power generation due to variations in solar irradiance, time of day, and weather conditions. Consequently, the power generation profile of a photovoltaic power plant (PVPP) generally does not coincide with the load demand profile of consumers. Therefore, the integration of a Battery Energy Storage System (BESS) is a technically justified solution for balancing energy production and consumption, as illustrated in Fig. 10 [E-VETEROK 2013].

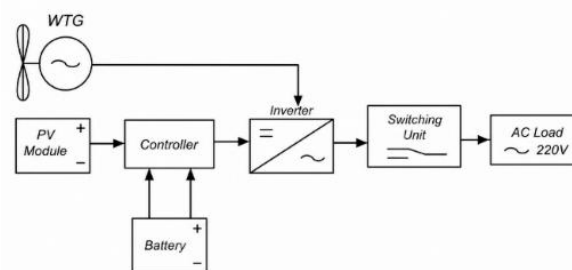


Figure 10. Block diagram of the hybrid power supply system: wind turbine generator (WTG) + photovoltaic (PV) array + battery energy storage system (BESS) supplying a 220 V AC load

Integration of photovoltaic generation into an existing AC auxiliary power supply system (SAPS) can be implemented by replacing the auxiliary-transformer supply to one section of the auxiliary distribution board with power generated by the renewable energy system. When the installed capacity of the

renewable energy system is comparable to that of the auxiliary transformer, renewable generation can completely replace the auxiliary-transformer supply to that section.

To ensure uninterrupted operation and maintain system reliability, the renewable energy generation system integrated into the AC auxiliary power supply system (SAPS) must be fully backed up by an alternative power source, such as the utility grid, a conventional fuel-based generator, or an additional energy storage system. The proposed integration scheme is illustrated in Fig. 11.

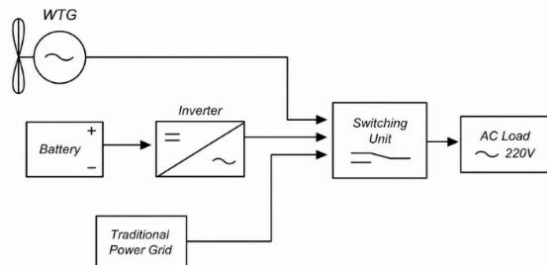


Figure 11. Block diagram of the hybrid power supply system: wind turbine generator (WTG), photovoltaic (PV) array, and conventional power plants supplying a 220 V AC load

The integration of renewable energy sources (RESs) into an existing AC auxiliary power supply system (SAPS) can also be implemented by supplementing the power supply of one section of the auxiliary distribution board with electricity generated by a renewable energy system. In this configuration, the selected section of the auxiliary distribution board is supplied simultaneously by both the auxiliary transformer (AT) and the renewable energy generation system, thereby enhancing supply reliability and operational flexibility.

The objective of analyzing methods for integrating photovoltaic power plants (PVPPs) into the electrical power supply system is to evaluate the system performance and efficiency as a function of the technological interconnections among its individual components, as well as the structural, operational, and design parameters governing the overall energy system. The principal technical characteristics of the proposed renewable energy-based power generation system are summarized in Table 3.

Item	Component	Quantity
1	PV power plant (fixed mounting structure), complete set	1 set
1.1	Bifacial heterojunction photovoltaic modules, 380 Wp	60 pcs
1.2	Ground-mounted support structure for PV modules	1 pc
1.3	Grid-connected inverter, 20 kW rated power	1 pc
2	PV power plant with single-axis solar tracker, complete set	1 set
2.1	Bifacial heterojunction photovoltaic modules, 380 Wp	40 pcs
2.2	Single-axis solar tracking support structure with sensor package	1 pc
2.3	Grid-connected inverter, 12.5 kW rated power	1 pc
3	PV power plant with dual-axis solar tracker, complete set	1 set
3.1	Bifacial heterojunction photovoltaic modules, 380 Wp	35 pcs
3.2	Dual-axis solar tracking support structure with sensor package	1 pc
3.3	Grid-connected inverter, 12.5 kW rated power	1 pc
4	Battery Energy Storage System (BESS), complete set	1 set
4.1	Bidirectional power converter, 5 kW rated power	3 pcs

4.2	Lithium iron phosphate batteries (12.8 V, 200 Ah) with BMS and interconnection kit	4 pcs
4.3	Battery rack	1 pc
4.4	DC distribution cabinet with protection and switching equipment	1 pc
5	Wind turbine generation system, complete set	1 pc
5.1	Wind turbine generator, 5 kW rated power	1 pc
5.2	Tower	1 pc
5.3	Grid-connected inverter, 5 kW rated power	1 pc
6	Monitoring system and weather station, complete set	1 set
6.1	Visualization and monitoring panel	1 pc
6.2	Meteorological data acquisition controller	1 pc
6.3	Anemometer	1 pc
6.4	Ambient temperature sensor	1 pc
6.5	PV module temperature sensor	1 pc
6.6	Solar irradiance sensor	1 pc
7	Renewable Energy Monitoring and Control System	1 set
7.1	Operator workstation (MASTER SCADA, CMT Viewer software)	1 pc
7.2	Modicon M241 controller	1 pc
7.3	Weintek MT8150XE operator panel	1 pc
7.4	Weintek cMT-SVR-102 HMI server	1 pc
7.5	TM4 communication module	1 pc
7.6	MKON-24 Modbus protocol converter	1 pc
7.7	ENKM-3 data acquisition unit	1 pc
7.8	ENKS-2 time synchronization unit	1 pc
7.9	DIS-100E-8W managed Ethernet switch	1 pc
7.10	NDR-240-24 power supply	1 pc
7.11	DR-UPS40 battery charge controller	1 pc
7.12	DTM12045 batteries	2 pcs
7.13	Two-pole load switch BA47-60 2P 10A 6kA	1 pc
7.14	Single-pole circuit breaker BA47-29 1P 6A 4.5kA	1 pc
7.15	PLC-RPT-24DC/21-21 relay modules	24 pcs
8	Auxiliary power monitoring system	1 set

Table 3. Components of the Proposed Renewable Energy System

The principal design parameters include the number of photovoltaic (PV) modules, the installation configuration (fixed or solar tracking), and the specifications of the Battery Energy Storage System (BESS). The operating parameters of the system comprise the solar irradiance level, the installation angle (tilt angle) of the photovoltaic modules, and the daily auxiliary energy consumption of the substation.

The primary objective of evaluating the integration of renewable energy sources (RESs) is to establish a mathematical relationship between the system performance, represented by the amount of electrical energy generated, and the operating characteristics and state variables of the Battery Energy Storage System (BESS). This relationship is analyzed as a function of the technological interconnections among the system components within the overall energy system architecture [Beckman 1988].

4 RESULTS OF THE STUDY

The primary power generation components of renewable energy-based power systems are photovoltaic (PV) modules and wind turbine generators (WTGs) (Fig. 12). These sources generate direct current (DC), which is converted into alternating current (AC) by grid-connected inverters to provide priority power supply to the electrical loads.

The Battery Energy Storage System (BESS) stores a portion of the electrical energy generated by the PV modules and WTGs, ensuring a continuous power supply during periods of insufficient renewable energy generation, particularly during nighttime when photovoltaic power production is unavailable.



Figure 12. Photovoltaic (PV)-based renewable energy systems

Figure 13 presents the single-line diagram of a renewable energy-based power generation system. The proposed power plant is equipped with a Battery Energy Storage System (BESS), which enables the connected facility to maintain a reliable power supply and operate independently during interruptions or outages of the centralized electrical grid.

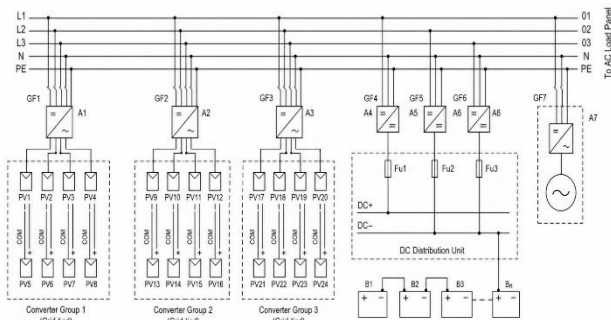


Figure 13. Single-line diagram of the renewable energy-based power generation system

The performance of the proposed system was evaluated over a five-month monitoring period. Electrical energy generated by the individual RES components and the total auxiliary energy consumption of the substation were recorded using the monitoring and control system described in Table 3. The recorded data were used to evaluate the contribution of the individual sources and the share of the auxiliary load covered by the RES system. To evaluate the necessity of deploying renewable energy-based power generation systems for supplying electricity to critical infrastructure, a comprehensive assessment of existing renewable energy installations was conducted. The monitoring results of the electrical energy generated by the renewable energy system prototype are presented in Figs. 14 and 15. These figures also include the total recorded auxiliary energy consumption of the electrical substation, enabling a direct comparison between renewable energy generation and the substation's internal power demand.

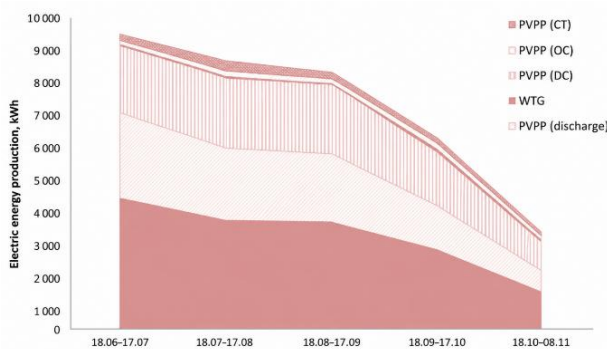


Figure 14. Electrical energy generated by the individual components of the renewable energy system

Overall, depending on the operating period and seasonal conditions, the proposed renewable energy system is capable of compensating for approximately 5–20% of the total electrical energy demand. During periods of high solar irradiance, particularly during daylight hours in July, when the facility's electricity consumption is relatively low, the renewable energy system is capable of fully satisfying the instantaneous load demand, thereby eliminating the need for electricity supplied from the centralized grid during those periods [Polukhin 2026].

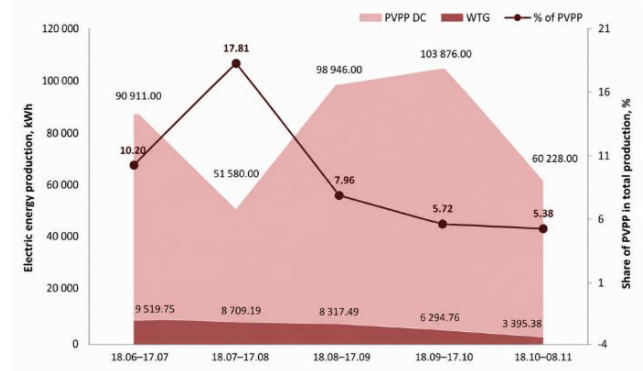


Figure 15. Temporal comparison between renewable energy generation and the recorded electrical energy consumption

To evaluate the performance of the photovoltaic installation, a detailed analysis was conducted on an individual photovoltaic (PV) module. According to the proposed system configuration, the fixed-mounted photovoltaic array exhibited the highest power output among the renewable energy generation components. Throughout the entire operational monitoring period, this subsystem produced the largest amount of electrical energy, accounting for 47% of the total energy generated, as illustrated in Fig. 16.

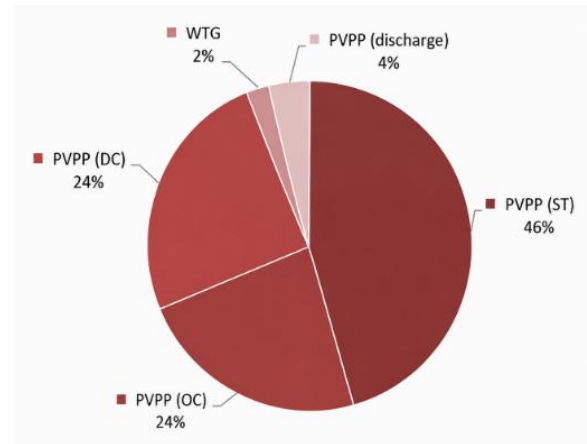


Figure 16. Distribution of electrical energy generated by the renewable energy system components

Figure 17 presents an assessment of the specific energy yield of the photovoltaic system, expressed as the electrical energy generated per individual photovoltaic module. This metric enables a comparative evaluation of the performance of different PV installation configurations independently of the total number of installed modules. As shown in Fig. 17, despite the solar-tracking capability of the single-axis and dual-axis PV arrays, the fixed-mounted PV array achieved the highest specific electrical energy yield in every observation period.

Overall, depending on the operating period, the experimental prototype compensated for approximately 5–20% of the electrical energy consumed by the auxiliary power system of the 330 kV substation. During certain sunny hours in July, when the

electricity demand of the electrical loads was relatively low, the experimental prototype completely satisfied the required load demand [Arbuzov 2007]. The proposed renewable energy system (RES) is intended to supply the auxiliary power requirements of a typical 330 kV AC substation by utilizing photovoltaic (PV) modules, grid-connected inverter equipment, a wind turbine generator (WTG), and a Battery Energy Storage System (BESS) based on lithium-ion batteries. Its implementation makes it possible to reduce the electrical energy consumed by the substation's auxiliary power system.



Figure 17. Specific electrical energy yield per photovoltaic module (thousand kWh/module)

The advantages of the proposed configuration include a significant reduction in dependence on weather conditions through the utilization of multiple renewable energy resources and the incorporation of an energy storage system; the capability for autonomous operation; the ability to serve as a reliable backup power source for a limited period (up to one day); and the possibility of operating as an uninterruptible power supply (UPS) while providing connection to a DC electrical network.

Despite the relatively low installed capacity of the proposed power generation system, during the summer months, when solar irradiance is high and the auxiliary power consumption of the substation decreases, the contribution of the generated electrical energy becomes significant. During the five-month observation period, the renewable energy system supplied 8.87% of the substation's total auxiliary energy demand. During the first two observation periods, the energy coverage reached 10.2% and 17.8%, respectively.

During certain hours of operation, the renewable energy system (RES) completely satisfied the electrical load demand of the 330 kV substation auxiliary power system.

5 CONCLUSIONS

The proposed renewable energy system demonstrates the technical feasibility of combining photovoltaic generation, wind generation and battery energy storage to support the power supply of critical infrastructure. During the five-month observation period, the experimental system supplied 8.87% of the total auxiliary energy demand of the investigated substation, while the contribution varied with operating and seasonal conditions. During selected periods of high solar irradiance and relatively low load demand, the renewable energy system was able to fully cover the instantaneous auxiliary load.

The proposed photovoltaic power supply system enables consumers to operate independently of the centralized electricity supply while significantly reducing the consumption of conventional fossil fuels. The use of a combined charge

controller and inverter integrated into a single unit and employing Maximum Power Point Tracking (MPPT) technology increases the overall efficiency of the mini photovoltaic power plant by approximately 13% compared with a system utilizing a Pulse Width Modulation (PWM) charge controller. The proposed configuration of the photovoltaic power supply system not only improves its overall efficiency but also significantly extends the duration of uninterrupted operation in the absence of electricity supplied from the utility grid [Tutak 2024].

Furthermore, the integration of renewable energy sources (RESs) substantially reduces harmful pollutant emissions, thereby improving the environmental sustainability of the power supply system.

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