

Sizing and Techno-Economic Analysis of a Photovoltaic–Battery Backup System for a Telecommunication Network Tower Under Grid Outages in Iraq

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ABSTRACT: In areas with a weak electricity grid, telecom towers typically depend on diesel generators when the power goes out, increasing operating costs, the logistics of fuel and emissions. This paper investigates the feasibility of a solar photovoltaic-battery backup system retrofit for a low-power telecommunication tower in Tuz Khurmatu, Iraq, where the daily grid outages are between 4 and 12 hours. The measured tower load, local peak sun-hours, overall system efficiency, charge-current limits and allowable battery depth of discharge are used to provide a clear stepwise sizing procedure. Analysis indicates that for 4-8 hours per day of outage, one 415-watt solar module and one 12-volt 200 ampere-hour tubular lead-acid battery can reliably supply the tower and be completely recharged between outages under the observed site circumstances. A 12-hour outage scenario requires two solar modules and two parallel battery blocks. The baseline configuration costs around 350 US dollars and generates annual savings of around 529–707 US dollars compared to diesel-only operation, corresponding to a simple payback of around 6–8 months, using local 2025 cost data. The novelty of this work is to provide a calculation-ready sizing framework, validated on a low-power weak-grid site, showing that small solar photovoltaic retrofits can offer unusually rapid economic returns compared with many of the larger hybrid base-station studies. These results point to a practical approach to minimize the use of diesel and enhance service continuity for telecommunication infrastructure in Iraq and similar regions.

KEYWORDS: Telecommunication tower; Photovoltaic (PV) system; PV-battery hybrid system; Grid-connected power supply; Diesel generator replacement; Techno-economic analysis; Iraq.

I. INTRODUCTION

The information and communication technologies (ICT) and telecommunication sector is becoming a significant driver of global greenhouse-gas emission. Without corrective action, peer-reviewed assessments suggest that the sector's footprint could trend upwards toward 2040 as traffic growth, device proliferation and network densification outpace efficiency gains [1,2]. In response, policy trajectories are increasingly pointing toward explicit carbon constraints – caps, budgets or disclosure regimes – that place a premium on energy efficiency and low-carbon power across network infrastructure. In mobile networks, the radio access equipment, in particular the cellular base stations, represents the largest share of operational energy consumption. Therefore, site-level actions have a significant impact on decarbonization [3,4].

From an engineering point of view, the power consumption of a base station depends on the efficiency of RF power amplifiers, auxiliary systems (in particular cooling), the variation of the traffic load and the degree of sleep or muting strategies that can be safely adopted without affecting the quality of service [3,4]. Grid supply is prevalent in urban cores, but diesel generation is still common at off-grid and weak-grid sites. Much of the techno-economic work shows that replacing diesel-only operation with renewable-centric alternatives, primarily solar photovoltaics (PV), often combined with batteries and/or small wind, can reduce levelized energy cost and local pollutants as well as CO₂ emissions if systems are properly sized to the load profile and resource of the site [5–7]. These improvements are due to the elimination of long-term fuel logistics, reduction of maintenance due to internal-combustion sets and taking advantage of the predictability of the solar resource during the day.

Meanwhile, the transition from 4G to 5G is a double challenge. This is because 5G's architectural levers such as massive MIMO, virtualization, and finer-grained control can improve energy efficiency per bit, but denser deployments, wider bandwidths, and embodied impacts in new equipment can increase absolute energy and carbon footprints, unless balanced by clean-power integration and robust efficiency strategies [8]. In a national-scale assessment for India, Devela et al. [9] show that although deployment of 5G can lead to increases in emissions, the use of PV-based hybrid systems can strongly reduce the telecom-tower

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carbon footprint. Additionally, Ali et al. [6] quantify the environmental and economic benefits of PV integration in the base transceiver stations, demonstrating both CO₂ reduction and operational cost savings.

These conclusions are further supported by some application-oriented studies. Abdulmula et al. [10] model hybrid micropower systems for telecommunication towers, where optimization approaches that simultaneously reduce costs and environmental impacts are shown when renewable sources are used. In the setting of North Africa, Zegueur et al. [11] provide a techno-economic study of a PV-wind-diesel standalone system for a rural Algerian telecom station. They show that the use of renewables with diesel backup leads to lower cost and better energy sustainability compared to diesel-only supply. Ibrahim et al. [12] propose a bifacial solar-tower configuration for telecom base stations at the module/system level that has the potential to increase energy yield, reduce reliance on fossil fuels and cut carbon emissions through enhanced bifacial harvest and system design choices.

Wider technology and market trends have bolstered the case for PV. Global PV deployment has accelerated and is now the leading source of annual capacity additions in many regions. This growth is underpinned by sustained cost declines and incremental performance improvements in modules, inverters and balance-of-system components [13]. For telecom sites where space is at a premium, the use of bifacial modules combined with low voltage DC architectures can further boost yield and end-to-end efficiency by reducing conversion losses and improving capture in diffuse/albedo-rich conditions [14]. These opportunities at the hardware level supplement radio and network-layer approaches (e.g., multicell cooperation, traffic-aware sleep modes, cell zooming) that reduce energy at the source by adapting radio resources to spatiotemporal demand [3]. Hasan [15] discusses the use of Software-Defined Networking (SDN) in wireless sensor networks on the control plane and how this can improve data aggregation while reducing power consumption, providing transferable design cues for energy-aware operation of solar-powered telecom sites.

Solar photovoltaic supply options for telecommunication towers Solar photovoltaic power generation converts sunlight into electrical energy. It can be integrated into telecommunication sites in various practical ways, depending on the grid reliability and the necessary autonomy level [16]. Weak-grid towers typically use a grid-assisted solar photovoltaic system with battery backup, where solar power during the day powers the load and charges the battery so critical services remain available during outages [17]. In remote areas, fully standalone systems and multi-source hybrids (e.g. solar photovoltaic with wind and diesel backup) are used, but generally require wider optimization, higher capital costs and increased operational complexity [18]. The present study considers a grid-assisted solar photovoltaic–battery retrofit sized for frequent short-duration outages, which mirrors the operational reality of many Iraqi telecommunication sites. There exists a large body of literature on renewable powered telecom systems, but there are some limitations. Firstly, many studies are based on fully off-grid or large hybrid configurations (PV–wind–diesel–battery) using optimization tools such as HOMER [10,11,19,20]. These methods offer detailed techno-economic insights but usually need a specialized simulation knowledge. They do not generate transparent, calculation-ready sizing procedures that practitioners can apply for small weak-grid sites. Second, many case studies published are based on medium or high-power base stations (hundreds of watts to kilowatts), while many field-deployed sites in developing regions operate with much lower DC loads (less than 200 W). These small sites have different sizing constraints and economic drivers that are still underrepresented in the literature. Third, while battery storage is frequently discussed, many studies assume lead-acid technology without a clear techno-economic comparison with advanced chemistries such as lithium-ion in terms of cycle life, efficiency and lifetime cost [21,22]. While some studies report the levelized cost of energy (LCOE) or net present cost (NPC), fewer explicitly address the case of frequent but short daily grid outages such as are typical in Iraq, where modest PV–battery retrofits can pay back quickly at even small scale. Hence, there is a need for practical, field-oriented sizing and evaluation frameworks for low-power, weak-grid telecom towers under frequent short-duration outages. Existing studies provide limited guidance for simple grid-assisted retrofits aiming to minimize diesel generator runtime without requiring full multi-source hybrid optimization. There is also a need to move beyond simple payback in economic evaluation, to include longer term indicators, and to clarify the implications of battery technology choice under local market conditions.

Motivated by this scenario, the current research fills these gaps through a PV–battery solution for a weak grid telecommunication tower in Tuz Khurmatu, Iraq. Specific objectives are to (i) develop a transparent, step-by-step sizing methodology linking measured DC loads and outage statistics to required PV array and battery-bank sizes, (ii) apply this methodology using local peak-sun-hours and component efficiencies, and (iii) quantify the economics of a grid-assisted PV–battery retrofit relative to diesel-only operation using local 2025 cost data, including both simple payback and longer-term indicators. Key contributions include: (1) a calculation-ready PV–battery sizing procedure applicable without dedicated optimization software; (2) a validated field case study of a low-power Iraqi telecom tower under realistic outage conditions, with measured PV and battery performance; and (3) a techno-economic assessment demonstrating that a modest retrofit can provide very short payback (about 6–8 months) and significant annual savings, facilitating practical diesel reduction in Iraq’s telecom infrastructure. The proposed

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sizing and cost-evaluation framework can be extended to other weak-grid regions beyond this specific site to support telecommunication operators and energy planners to reduce their dependence on diesel, improve outage resilience, and reduce their operating emissions with low-cost solar photovoltaic–battery retrofits.

II. CASE STUDY DESCRIPTION

The present study designs a grid-assisted photovoltaic system for a telecommunication tower in Tuz Khurmatu, Iraq. Tuz Khurmatu is a city that suffers from long hours of power outages, especially during the peak seasons of summer and winter. The tower supplies internet connectivity to more than 100 households within its service footprint. Sizing is anchored to the 24-h load inventory summarized in Table I, which enumerates the installed equipment along with their counts and nameplate power ratings. The system operates complementarily with the national grid: when utility power is available, it supports the load and float-charges the batteries via the MPPT charger; during outages, the PV array and battery bank take over automatically to ensure uninterrupted service. Final sizing—PV array capacity, battery storage, and series–parallel configuration—is derived in subsequent sections from the measured outage schedule and site insolation, using 415-W modules and 12-V battery monoblocks as the calculation building units. This work focuses on a grid-assisted PV–battery configuration that displaces diesel generator runtime during grid outages. Unlike many studies that perform full techno-economic optimization of multi-source hybrid systems (PV–wind–diesel–battery) for telecom towers using tools such as HOMER [11], the aim here is to develop a transparent hand-calculation methodology and validate it on a minimum-cost retrofit for a real weak-grid site. The existing diesel generator remains available as a resilience backup but is not included as an optimized component of the design.

Table I. Dc Load Summary for The Telecom Tower.

Units	Number	Max. power cons. (W)	Avg. power (W)	Load (W)
Power Beam M5 400	3	8	6	24
air MAX Rocket M5	5	8	7	40
Air fiber 4x	1	15	12	15
RB4011iGS+RM	1	33	18	33
switch router	1	8	8	8

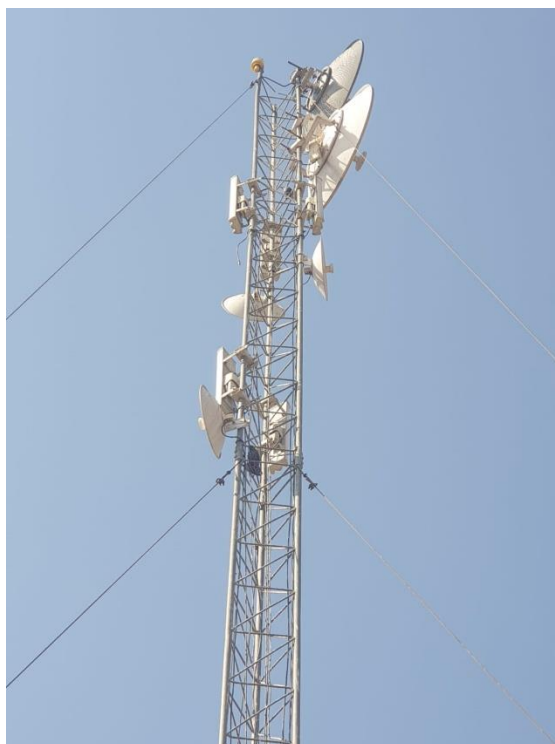


Figure 1. Telecommunication network tower in Tuz Khurmatu, Iraq, used as the case-study site.

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A. LOAD ESTIMATION

Estimating the tower's demand is the first step in sizing the grid-assisted PV system. Table I lists the DC equipment installed at the site, including the number of units, nameplate ratings (W), and operating hours. For sizing, the adopted design value is conservatively computed from the installed equipment ratings as:

$$P_{avg} = \sum_i n_i P_i d_i \quad (1)$$

where n_i is the count of device i , P_i its rating (W), and d_i its duty cycle (fraction of 24 h). For conservative sizing, the maximum listed device powers are used and the duty cycle is $d_i = 1$, giving:

$$P_{avg} = (24 + 40 + 15 + 33 + 8) W = 120 W$$

The reference 24-hour energy is therefore:

$$E_{24h} = P_{avg} \times 24 h \quad (2)$$

$$E_{24h} = 120 W \times 24 h = 2880 Wh = 2.88 kWh$$

Because the system operates complementarily with the national grid, the PV-battery subsystem is sized to cover only the daily outage window t_{out} (hr/day):

$$E_{out} = P_{avg} \times t_{out} \quad (3)$$

B. PV ARRAY SIZING

Instead of sizing the system for full off-grid autonomy, the PV array is sized against the expected daily outage energy derived in section (A). The required array power is computed from the outage energy, the site's Peak Sun Hours (PSH), and the overall balance-of-system efficiency (η).

$$P_{PV,req}[kW] = \frac{E_{out} [kWh/day]}{PSH \times \eta} \times (1 + margin) \quad (4)$$

For Tuz Khurmatu we adopt $PSH_{winter} \approx 3.5$ (design worst case), and $PSH_{summer} \approx 6.0$. Overall efficiency $\eta \approx 0.80$ (temperature, soiling, wiring, MPPT), and a design margin of 10% for cloudy and cold days.

The number of 415-W modules is then:

$$N_{modules} = \frac{P_{PV,req} \times 1000}{415} \quad (5)$$

Table II presents the required PV array power and the resulting 415-W module count as a function of the daily outage duration (grid-assisted operation). Results are shown for winter and summer PSH; detailed assumptions are given in the table note.

Table II. PV array sizing versus daily outage duration

Outage (h/day)	E_{out} (kWh)	Winter $P_{PV,req}$ (kW)	Summer $P_{PV,req}$ (kW)	Winter Panels @415 W	Summer Panels @415 W
4	0.48	0.189	0.110	1	1
6	0.72	0.283	0.165	1	1
8	0.96	0.377	0.220	1	1
12	1.44	0.566	0.330	2	1

C. BATTERY BANK SIZING

The battery bank is sized to ride through the daily outage window determined in section (A). Since all loads are DC, inverter losses are not considered here. Battery-side effects (discharge efficiency and allowable depth of discharge) are accounted for explicitly, and capacity is expressed for 12-V monoblocks (e.g., 200-Ah tubular lead-acid at C10).

The energy the battery must deliver to the load during an outage is:

$$E_{bat,del} = E_{out} \quad (6)$$

Accounting for discharge efficiency η_{dis} (typically 0.95):

$$E_{bat,req}(kWh) = \frac{E_{bat,del}}{\eta_{dis}} \quad (7)$$

The required nominal stored energy with allowable depth of discharge DoD, 0.70 for tubular lead-acid, and an aging margin $k_{age} = 1.10$ is:

$$C_{nom,kWh}(kWh) = \frac{E_{bat,req}}{DoD} \times k_{age} \quad (8)$$

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Converted to ampere-hours at 12 V:

$$C_{nom,Ah}(Ah) = \frac{1000 C_{nom,Wh}}{12} \quad (9)$$

For a chosen battery block of Ah_{block} (200 Ah), the number of parallel 12-V blocks is:

$$N_{II} = \frac{C_{nom,Ah}}{Ah_{block}} \quad (10)$$

All adopted inputs, considered outage durations, and the resulting capacities and battery counts are reported in Table III.

Table III. Battery bank sizing with 12-V tubular lead-acid (200 Ah @ C10)

Outage (h/day)	E_{out} (kWh)	$E_{bat,req}$ (kWh)	$C_{nom,Wh}$ (Wh)	$C_{nom,Ah}$ @12 V (Ah)	Reco. 12-V blocks (200 Ah)
4	0.48	0.505	794	66.2	1
6	0.72	0.758	1191	99.2	1
8	0.96	1.011	1588	132.3	1
12	1.44	1.516	2382	198.5	2

D. ECONOMIC EVALUATION METHOD

Component-level CAPEX was estimated for the grid-assisted configuration sized in sections (B and C). Prices are local Q1-2025 retail quotes in Tuz Khurmatu and are expressed in USD. Figure 2 shows the bill of materials of a single tower set consisting of one 415-W PV module, one 12-V 200-Ah tubular battery, one MPPT charge controller, and installation/BOS (mounting, wiring, fuses), with total initial cost ($C_{initial}$) of ≈350 USD. The battery is the major cost item as seen in Figure 2, followed by the controller and the PV module.

For the winter 12-h outage case, the charge-current limit can be met with two 415-W modules, and two parallel 12-V, 200-Ah tubular blocks, for a total of ≈US\$570. Actual values will vary by vendor. Reporting costs on a normalized basis (\$/W for PV and \$/Ah for storage) enables transparent comparison across system sizes and future updates. We quantify the financial benefit of displacing diesel generation during grid-outage hours with the proposed PV–battery system. Let H_{out} be the daily outage duration (h/day). The annual outage hours are:

$$H_{year} = H_{out} \times 365 \text{ (h/year)} \quad (11)$$

The avoided annual diesel fuel cost is

$$C_{fuel} = r_{diesel} \times P_{diesel} \times H_{year} \quad (12)$$

and the avoided diesel O&M (oil, filters, minor service) is modeled as a cost per run hour,

$$C_{O\&M,avoided} = C_{maint.,hr} \times H_{year} \quad (13)$$

Net annual savings and simple payback are,

$$Annual \text{ Savings} = C_{fuel} + C_{O\&M,avoided} - C_{PV,O\&M} \quad (14)$$

$$Payback \text{ (years)} = \frac{C_{initial}}{Annual \text{ Savings}} \quad (15)$$

To account for the time value of money and the evolution of costs and savings beyond the payback period, the Net Present Value (NPV) of the PV–battery investment is evaluated over an analysis horizon N years with discount rate r :

$$NPV = -C_{initial} + \sum_{t=1}^N \frac{S_t - C_t^{O\&M} - C_t^{rep}}{(1+r)^t} \quad (16)$$

where S_t is the annual diesel fuel and O&M cost avoided in year t , $C_t^{O\&M}$ is the PV–battery O&M cost, and C_t^{rep} captures battery replacement and other major component renewals. A positive NPV indicates that the PV–battery system is financially attractive compared with continued diesel-only operation

In addition, the levelized cost of delivered energy $LCOE_{PV-batt}$ is used to compare the PV–battery subsystem with diesel generation on a per-kWh basis:

$$LCOE_{PV-batt} = \frac{\sum_{t=0}^N \frac{C_t^{CAPEX} + C_t^{O\&M} + C_t^{rep}}{(1+r)^t}}{\sum_{t=1}^N \frac{E_t^{PV-batt}}{(1+r)^t}} \quad (17)$$

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where $E_t^{PV-batt}$ is the annual energy supplied by the PV–battery subsystem during grid-outage hours. The same expression is applied to estimate the LCOE of diesel-only operation using fuel and O&M costs. This provides a consistent metric for long-term cost comparison that includes the time value of money.

The hourly O&M rate $C_{maint,hr}$ is derived from service intervals and unit costs:

$$C_{maint,hr} = \frac{V_{oil}P_{oil} + C_{oilFiltr} + C_{labor}}{H_{oil}} + \frac{C_{fuelFiltr}}{H_{fuelFiltr}} + \frac{C_{airFiltr}}{H_{airFiltr}} + \frac{C_{minor}}{H_{minor}} \quad (18)$$

In this study we use typical small-genset intervals (oil every 250 h; fuel filter 300 h; air filter 500 h; minor service 1000 h) and field-typical unit costs, yielding $C_{maint,hr} \approx 0.153$ \$/h. PV O&M is estimated to be about 1 % of CAPEX. Robustness is assessed using one-way sensitivity analysis (diesel price, fuel rate and O&M rate).

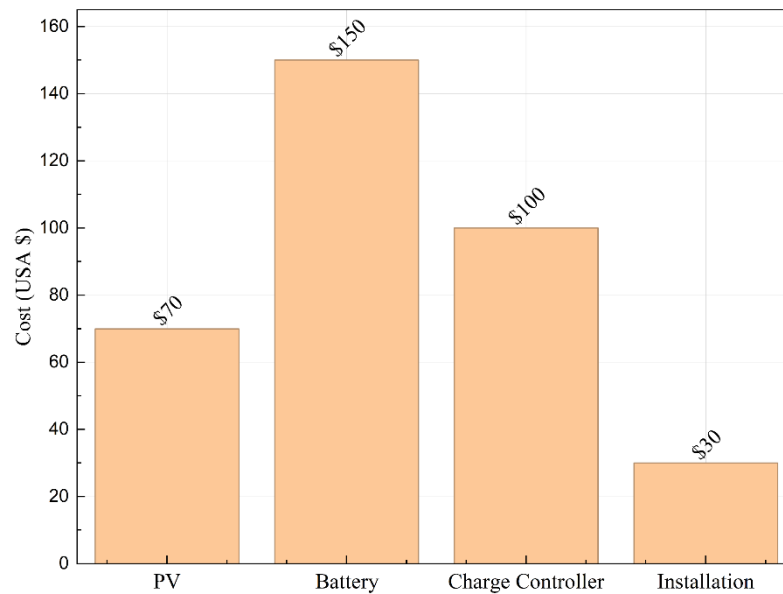


Figure 2. Estimated cost of PV system components

III. RESULTS AND DISCUSSION

A. PV SYSTEM IMPLEMENTATION

The as-built system was deployed at Tuz Khurmatu telecom tower to provide reliable service even during frequent grid interruptions. It operates in a grid-assisted mode and supports 120-W DC load, float-charges the battery when utility power is available and the PV–battery subsystem feeds the tower seamlessly during outages.

Hardware and topology: The installation consists of a single 415-W mono-Si PV module, an MPPT charge controller on a 12-V DC bus, and a single 12-V, 200-Ah tubular (C10) lead-acid battery. All tower equipments listed in Table I are DC so no inverter losses are involved. The PV module is roof-mounted south-facing with a tilt close to the site latitude to improve winter yield, and wired to the MPPT through outdoor-rated PV cable and DC fusing; the controller output is wired to the battery with short, upsized conductors to limit I^2R losses. On the controller side there is earth and a DC surge protective device.

Controller set-points and charging: The MPPT was set following the tubular battery datasheet with temperature compensation (typical values: absorption ≈ 14.4 V, float ≈ 13.6 V). The maximum charge current from one 415-W module is about $415 \times 0.95 / 14 \approx 28$ A, which is within the recommended ≤ 0.2 C (≤ 40 A) for a 200-Ah tubular block. Therefore, one battery is sufficient in terms of capacity and current limitations.

Operating window of site: Interruptions to national-grid at this location are intermittent based on tower logs and operator records and can be up to 8 consecutive hours per day in the worst case. The sizing calculations use a conservative 120-W design load, while measured operation is typically 85–100 W (about 90 W in the daily profiles). Battery alone supplies the load during the night when grid is off (typical window within 4–8 h). Using the adopted efficiency and DoD = 0.70 the usable energy is ≈ 1.68 kWh; an 8 h outage requires $E_{out} = 0.96$ kWh (section A) i.e. ≈ 1.01 kWh drawn from the battery after discharge efficiency – well within the planned DoD window. PV power begins to rise after sunrise and the per module daily PV energy aligns with Section 2: ~ 1.16 kWh/day (winter, PSH ≈ 3.5 , $\eta \approx 0.80$) and ~ 2.0 kWh/day (summer, PSH ≈ 6.0). Thus, the single 415 W module will easily satisfy the 4–8 h outage energy and will recover the battery before the next night in normal conditions.

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Operation & maintenance: Tubular battery is maintained according to manufacturer recommendations (checking electrolyte levels, cleaning terminals, equalization as recommended). Due to the dusty environment, PV glass cleaning is scheduled periodically to reduce soiling losses discussed in Section 2. MPPT log checked monthly to monitor charge stages, peak current and energy balance against measured outage window.

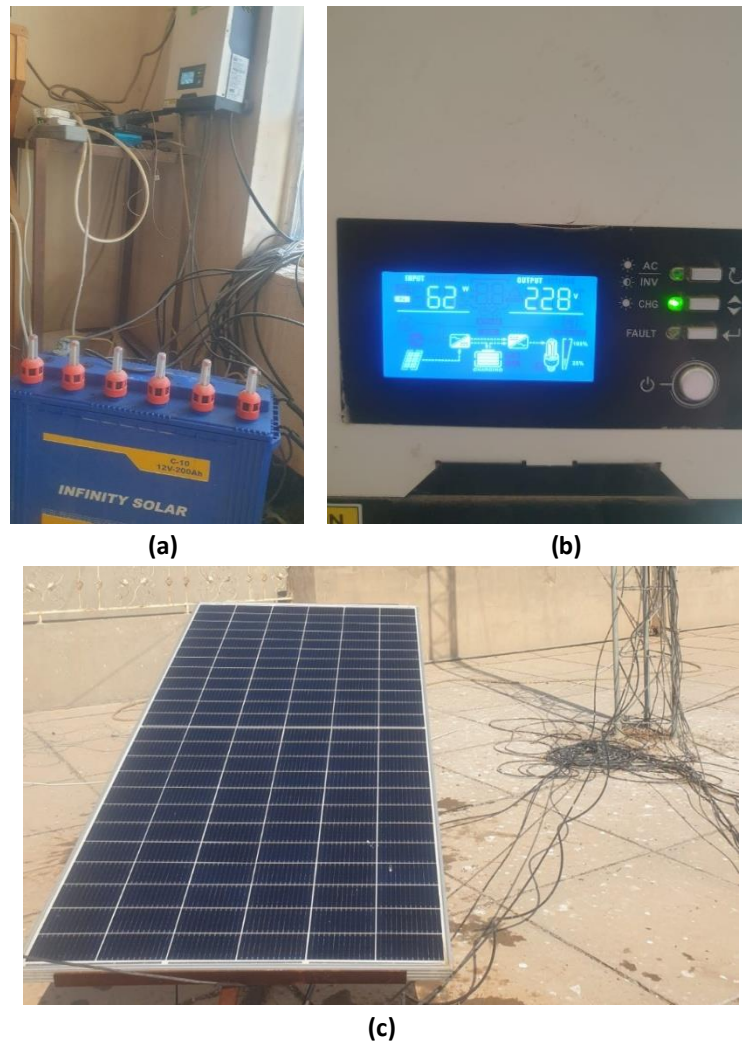


Figure 3. The implemented PV system includes (a) battery bank and inverter unit, (b) inverter front panel and operating display, and (c) PV module installed at the site.

B. ENERGY PERFORMANCE

As shown in Figure 4, PV generation follows a typical bell-shaped profile between sunrise and sunset. Power output increases after about 5.5 h, reaches a maximum of approximately 320 W around midday, and then decreases to zero close to 19 h. In contrast, the electrical demand is almost constant at about 90 W over the full 24 h period. As a result, there is a deficit during the night, while for most of the daytime the PV array produces more power than the load, creating a surplus that can be used to charge the battery.

As indicated in Figure 5, battery power is positive during discharge and negative during charging. The results show three daily grid-outage windows, located in the early morning, around midday, and in the evening. During the early-morning and evening outages, when PV production is low or zero, the battery discharges and supplies up to about 90 W to maintain the load. During the midday outage, PV generation coincides with the interruption, so the load is covered directly by the PV array and the battery remains almost idle. Outside the outage periods, the battery operates in charging mode or stays near zero, which confirms that the coordinated PV-battery operation can sustain the load and mitigate the impact of scheduled outages.

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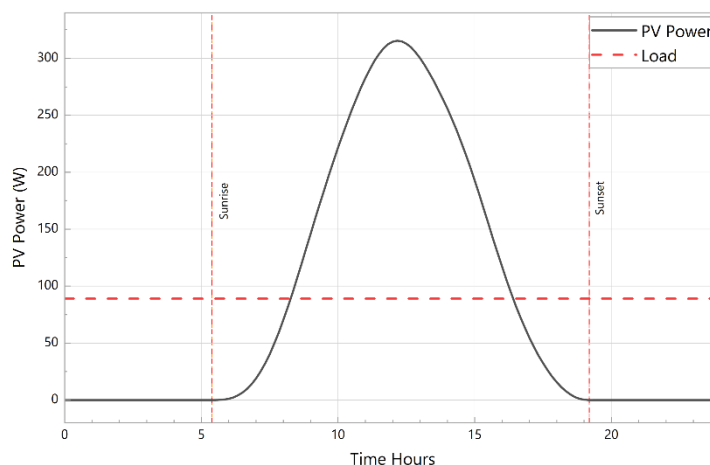


Figure 4. Daily PV power profile compared with the constant system load

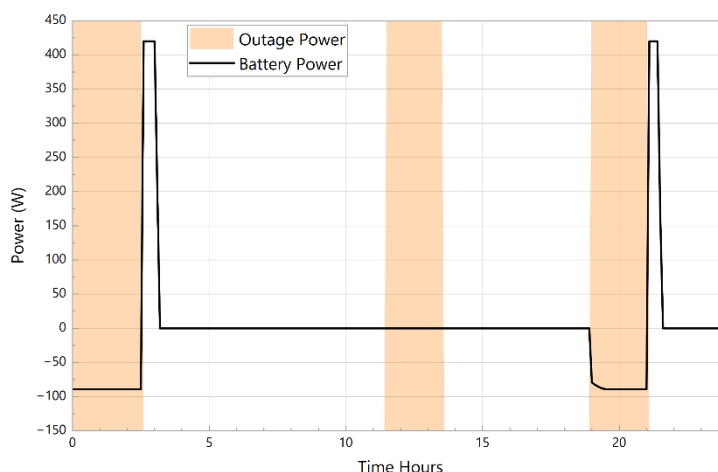


Figure 5. Battery charge–discharge power during daily grid-outage intervals.

C. ECONOMIC RESULTS

Using the Tuz Khurmatu site parameters (complementary operation), we adopt assumptions for economic evaluation in Table IV:

Table IV. Assumptions for Economic Evaluation

Symbol	Value	Notes
P_{diesel}	0.30 USD/L	Local baseline adopted
r_{diesel}	0.3 L/h	Light-load genset consumption
$C_{\text{maint,hr}}$	0.153 USD/h	Oil, filters, minor service (hourly equivalent)
C_{initial}	350 USD	Panels + battery + controller + installation
$C_{\text{PV,O\&M}}$	3.5 USD/year	$\approx 1\%$ of CAPEX
H_{out}	6–8 h/day	Complementary operation (grid-tied site)

Figure 6 compares the annual economic benefits of the proposed PV–battery retrofit under two representative outage scenarios: 6 hours per day and 8 hours per day. For each scenario, the total annual savings are decomposed into avoided diesel fuel cost and avoided diesel operation-and-maintenance cost. As expected, increasing outage duration increases the diesel energy displaced and therefore raises all components of savings. Total annual savings rise from approximately 529 US dollars (6 hours per day) to approximately 707 US dollars (8 hours per day). Consequently, the simple payback period decreases from about eight months to about six months, indicating that the proposed retrofit becomes more economically attractive as outage severity increases.

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The simple payback of 6–8 months reported here is substantially shorter than the 18–36 months commonly reported for hybrid PV–diesel telecom systems in the literature [5,10,11]. This difference is mainly attributed to: (i) the low-power direct-current nature of the studied site, (ii) relatively high diesel cost when fuel logistics and servicing are considered, and (iii) the minimal capital cost of the retrofit configuration. Overall, the results indicate that low-power weak-grid telecom towers can achieve faster economic returns than higher-power base-station systems evaluated in many prior studies.

To provide a long-term financial perspective beyond simple payback, additional metrics such as net present value and levelized cost of delivered energy can be evaluated over a defined project lifetime and discount rate. Over a 10-year horizon and an 8% discount rate, the PV–battery retrofit yields an NPV of approximately 3,200 USD (6 h/day outage) and 4,394 USD (8 h/day outage) relative to diesel-only operation. The corresponding levelized cost of energy supplied during outage hours is approximately 0.212 USD/kWh (6 h/day) and 0.159 USD/kWh (8 h/day), which is about 89.5%–92.2% lower than the diesel-only supply cost under the same operating assumptions.

Validation of results: The PV energy yield and battery charge–discharge behavior were cross-checked against reference irradiance and peak-sun-hour values for Salahaddin governorate derived from global solar datasets (PVGIS and NASA POWER). The estimated daily PV production (approximately 0.9–1.1 kilowatt-hour per day from a 415-watt-peak array) is consistent with these datasets. In addition, the load model was validated using measured tower power consumption (85–100 watts direct-current) averaged over multiple operating days. These cross-checks support the technical reliability of the sizing method and the resulting performance estimates for weak-grid telecom applications.

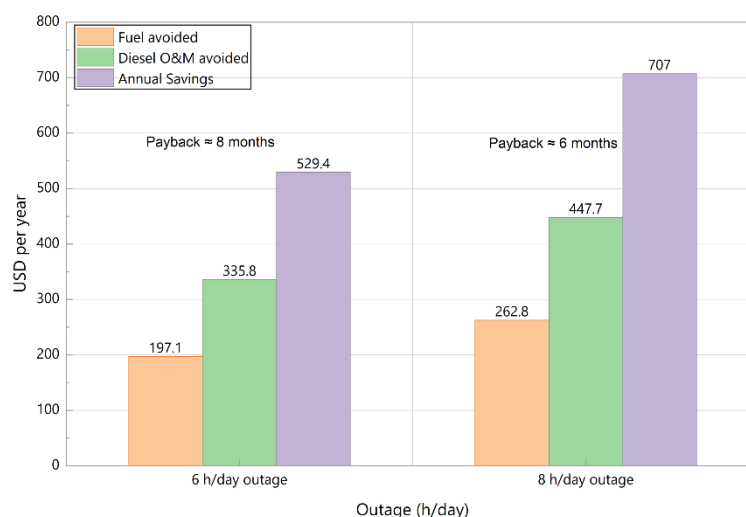


Figure 6. Annual fuel and O&M savings, and resulting payback time of the PV system for 6 and 8 h/day grid outage

IV. CONCLUSION

This paper presented the design and techno-economic assessment of a grid-assisted solar photovoltaic–battery system for a telecommunication network tower in Tuz Khurmatu, Iraq. Starting from measured direct-current loads at the site, a stepwise sizing procedure was developed to determine the required solar array and battery storage as a function of daily grid-outage duration. The method explicitly accounts for local peak-sun-hours, balance-of-system efficiency, battery discharge efficiency, allowable depth of discharge, and an aging margin, making it directly applicable to similar towers in other Iraqi locations.

For the studied tower, the analysis shows that one 415-watt solar module combined with one 12-volt, 200 ampere-hour tubular lead-acid battery is sufficient to support typical 4–8 hours per day outage scenarios, while a 12-hour outage requires two 415-watt modules and two parallel 200 ampere-hour battery blocks. Simulated daily power flows show that coordinated solar photovoltaic–battery operation can power the tower load during planned outages and recharge the battery during grid-available hours.

The baseline configuration has an initial investment of about 350 US dollars at local 2025 prices, and annual savings of about 529–707 US dollars when diesel fuel and maintenance costs are displaced during 6–8 hours per day of outages, resulting in a simple payback of about 6–8 months. The very short payback (≈ 6 –8 months) together with significant annual savings demonstrates that retrofitting PV–battery is not only technically feasible, but also financially attractive at current Iraqi diesel and equipment prices. The 6–8-month payback period reported here is significantly lower than the one or more-year payback periods reported in many hybrid telecom power studies (depending on the load level, diesel price and storage sizing). This is mainly due to the low constant

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power load of the studied site and the low-cost minimal retrofit configuration which provides fast diesel displacement during frequent daily outages. The novelty of this work is a transparent, calculation-ready sizing method validated on a low power weak grid telecom site, showing that modest solar PV-battery retrofits can provide extremely rapid cost recovery and meaningful diesel reduction for real world telecom deployments.

This study explores a simple grid-assisted PV-battery retrofit without full multi-source optimization (e.g. diesel/wind). Detailed cycle-life curves are not modeled but battery aging is approximated. The results are for a low power tower and will vary for higher power sites. Moreover, inputs of irradiance and temperature are based on satellite-derived datasets that may differ slightly from long-term ground measurements. Future work will involve hybrid optimization, detailed degradation modeling and validation on multiple sites.

V. NOMENCLATURE

A. Abbreviations

PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
PSH	Peak Sun Hours
margin	Design safety margin
DoD	Depth of Discharge
MPPT	Maximum Power Point Tracking
BOS	Balance of System
CAPEX	Capital Expenditure
O&M	Operation and Maintenance
C10	10 h discharge rate
USD	US Dollar
C	Cost
Maint.	Maintenance
PVGIS	PV Geographical Information System

B. Symbols

n_i	Number of units of device i
P_i	Power rating of device i, W
d_i	Duty cycle of device i
P_{avg}	Average DC load of the tower, W
E_{24h}	Daily energy demand, kWh
t_{out}	Grid-outage duration, h/day
E_{out}	Energy supplied during outage, kWh/day
$P_{PV,req}$	Required PV array power, kW
$N_{modules}$	Number of PV modules
$E_{bat,del}$	Battery energy to the load, kWh
$E_{bat,req}$	Required battery energy after discharge efficiency, kWh
$C_{nom,kWh}$	Nominal battery energy, kWh
$C_{nom,Ah}$	Nominal battery capacity at 12 V, Ah
k_{age}	Battery aging factor
Ah_{block}	Nominal battery capacity at 12 V, Ah
N_{II}	Number of parallel 12 V blocks
H_{out}	Daily outage hours, h/day
H_{year}	Annual outage hours, h/year
C_{fuel}	Avoided diesel fuel cost, USD/year
P_{diesel}	Diesel fuel price, USD/L
r_{diesel}	Diesel fuel consumption rate, L/h
$C_{maint.,hr}$	Diesel O&M cost per hour, USD/h

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$C_{O\&M,avoided}$ Avoided diesel O&M cost, USD/year
 $C_{PV,O\&M}$ PV–battery O&M cost, USD/year

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