Towards greener telecom: energy-efficient hybrid solar–grid systems for remote base station operations

Hasanah Putri[1,2,3], Rendy Munadi[4], Sofia Naning Hertiana[4], Alfin Hikmaturokhman[5]
[1]Telecommunication Technology Diploma, Telkom University, Bandung, Indonesia
[2]School of Electrical Engineering, Telkom University, Bandung, Indonesia
[3]Center of Excellence for Green Technology, Research Institute for Intelligent Business and Sustainable Economy, Telkom University, Bandung, Indonesia
[4]School of Electrical Engineering, Telkom University, Bandung, Indonesia
[5]Department of Telecommunication Engineering, Telkom University, Purwokerto, Indonesia

Article Info

Article history:

Received Jul 14, 2025
Revised Feb 23, 2026
Accepted Mar 4, 2026

Keywords:

Base transceiver station
Carbon emissions
Energy efficiency
Hybrid solar–grid system
Operational cost

ABSTRACT

Efficient and environmentally friendly energy use for base transceiver stations (BTS) in remote areas is essential for telecommunication network development. This study simulates and compares two BTS configurations: a conventional grid-powered system and a hybrid solar-grid system, focusing on energy efficiency, operational cost, and carbon emissions. The simulation was conducted over a one-year operational period using Python-based modeling with realistic input parameters. The results indicate that the hybrid system can supply approximately 74% of the annual energy demand using solar power, achieving 24.4% operational cost savings and reducing carbon emissions by 73% compared to the grid-only system. These findings confirm that the hybrid BTS system is a feasible and sustainable solution to support telecommunication expansion in remote areas with lower cost and environmental impact.

Corresponding Author:

Hasanah Putri
School of Electrical Engineering, Telkom University
Bandung, Indonesia
Email: hasanahputri@telkomuniversity.ac.id

1. INTRODUCTION

In recent years, the pursuit of equitable digital connectivity has become a national priority in many countries [1], especially those with vast archipelagic and rural landscapes such as Indonesia. As the government continues to promote digital transformation and economic inclusion [2], the deployment of mobile network infrastructure, particularly base transceiver stations (BTS), in remote and underserved regions plays a central role. However, one of the most fundamental barriers to this expansion is not technological complexity, but rather the accessibility, cost, and reliability of electrical energy to power such infrastructure [3], [4].

Traditional BTS operations in urban and suburban areas benefit from stable grid connections and well-developed utility support systems [5]. In contrast, BTS installations in remote locations such as mountainous regions, outer islands, and frontier zones, often face intermittent grid supply or are entirely off-grid [6]. In these contexts, operators frequently depend on diesel generators as the primary or backup source of power. While diesel gensets offer immediate deployment advantages, they are associated with high fuel costs, logistics challenges in fuel transportation, mechanical maintenance burdens, and substantial environmental impact due to carbon emissions [7].

Moreover, the operational expenditure (OPEX) for maintaining off-grid BTS using conventional power sources is significantly higher than their urban counterparts [8]. Studies have shown that in some locations, energy costs can account for up to 60% of the total OPEX for rural telecom towers. These conditions create a disincentive for operators to expand services in low-income or sparsely populated areas, despite the government's universal service obligation (USO) mandate and increasing demand for basic internet services, particularly for education, health, and disaster response [9]. In light of these challenges, renewable energy solutions have emerged as viable alternatives for powering telecom infrastructure [10]. Among various options, solar photovoltaic (PV) systems are the most mature and adaptable [11], given Indonesia's high solar irradiation levels across most of its regions. When integrated with energy storage systems (lithium-ion or lead-acid batteries) and supported by the grid or a minimal diesel backup, hybrid solar-based systems can reduce long-term costs, ensure operational continuity, and contribute to the national goal of carbon neutrality [12], [13]. Additionally, the declining global cost of solar modules and battery systems further strengthens the business case for such solutions. However, while the theoretical and technological potential of hybrid BTS is well recognized [14], practical implementation requires context-specific analysis [15]. Each remote site presents unique variables such as solar potential, load profiles, fuel costs, infrastructure availability, and regulatory support. Therefore, simulation-based studies that reflect real-world conditions are essential to inform investment decisions, policy formulation, and technical planning. The provision of reliable and energy-efficient power sources for BTS in remote and underserved regions has garnered increasing attention in both academic and industrial domains. A large body of literature identifies energy consumption as a dominant factor contributing to the OPEX of telecom towers, especially in off-grid or semi-grid areas [16]. Aldossary [17] estimate that energy-related costs can represent 60-70% of total OPEX in remote BTS operations. Rajesh and Devi [18] demonstrated the implementation of a micro-hydro and solar PV hybrid system, which successfully reduced diesel fuel dependency and enhanced system sustainability. Likewise, [19] presented evidence showing that solar-battery powered BTS achieved up to 80% savings in fuel consumption and a 60% reduction in net present cost (NPC) [20] demonstrated how replacing conventional high-pressure sodium (HPS) lamps with smart LED streetlights in Iraq led to substantial reductions in energy consumption and operational cost. The study, which used MATLAB-based modeling, reinforces the importance of integrating energy-efficient components in infrastructure projects a principle that aligns closely with the adoption of hybrid energy systems for BTS in remote areas.

Several studies have investigated the application of renewable energy systems to power remote telecommunication base stations, particularly hybrid solar-grid and solar-battery configurations. Prior works have demonstrated potential reductions in operational expenditure and carbon emissions by integrating photovoltaic systems into base station power supply architectures. However, many of these studies focus on generalized scenarios or specific geographic contexts, with limited discussion on practical deployment constraints in developing regions. Various configurations of hybrid energy systems have been extensively analyzed. These typically include combinations of solar PV, diesel generators, wind turbines, and energy storage systems. Zebra *et al.* [21] proposed a solar-diesel hybrid model that demonstrated significant improvements in fuel efficiency and operational reliability. Ammari *et al.* [22], researchers used HOMER Pro to simulate PV-wind-diesel-battery setups that achieved over 70% renewable energy penetration with a competitive levelized cost of electricity (LCOE). Similarly, Zhang *et al.* [23] investigated the use of repurposed electric vehicle batteries to support BTS energy storage, while [24] carried out a life-cycle analysis of lithium-ion batteries, highlighting both economic and environmental benefits. Aneesh and Shaikh [25] proposed a novel D2D-driven approach to improve energy efficiency in emerging 6G networks by dynamically enabling device-to-device communication clusters. Their study, which employed K-means clustering and testbed experimentation, demonstrated a 5% improvement in network lifetime per second, indicating that localized communication strategies can substantially reduce energy usage, insights that could be adapted for rural BTS scenarios where minimizing power consumption is critical.

The techno-economic simulation of hybrid systems has become a critical component in evaluating performance across different geographical contexts. Previous study utilized Python and MATLAB to simulate a multi-source energy system (PV, biomass, wind) tailored for remote islands, showing its feasibility both economically and technically. Olaogun *et al.* [26] conducted a similar study using HOMER Pro to optimize the design of hybrid BTS power systems. Additional studies such as the one by [27], [28] emphasized that hybrid models can reduce diesel use by up to 65% while maintaining system reliability, making them highly attractive for developing regions. A study proposed a logical control mechanism for DC–DC converters in swarm-based nano grids to efficiently distribute renewable energy among charging stations in gated communities. The principle of direct DC usage without conventional inverter stages is highly relevant for remote BTS scenarios, where energy losses and equipment costs must be minimized. In terms of environmental sustainability, hybrid BTS configurations have shown a notable reduction in carbon emissions. Goud and Kalpana [29] reported that shifting from diesel-only systems to solar-hybrid BTS can lower CO_2 emissions by more than 90% over the system's lifetime. This aligns with projections by the International Energy Agency, which estimates that over 75% of new telecom towers in emerging markets will be powered, at least partially, by renewable energy systems within the next decade. Policy developments have also shaped the discourse around hybrid BTS deployment. GSMA 2022 highlighted the importance of integrated regulation across the energy and telecom sectors to facilitate renewable adoption in BTS operations [30]. In Indonesia, the Ministry of Communication and Information Technology (KOMINFO) has directed its universal service program (BAKTI) to prioritize energy-resilient and off-grid-compatible BTS deployments in frontier, outermost, and least-developed (3T) regions [31]. Despite these regulatory advancements, many operators still lack standardized frameworks for selecting and deploying energy systems based on site-specific needs, solar resource availability, and long-term operational cost targets. Beyond techno-economic studies, recent research has also explored real-time control strategies, battery degradation models, and remote energy monitoring systems. The researchers [32], [33] review surveyed a range of hybrid renewable energy systems (HRES) with focus on telecom applications, noting the importance of dynamic energy management and predictive algorithms to optimize energy dispatch across varying load conditions [34]. In sum, the literature suggests strong empirical and theoretical support for the adoption of hybrid solar-grid or solar–diesel systems in rural BTS contexts. Nonetheless, most models are either tool-specific or based on idealized assumptions not fully adapted to the Indonesian context. The present study seeks to address this gap by using Python-based simulations, incorporating region-specific solar irradiance data, operational costs, and realistic BTS load profiles to assess the comparative efficiency and sustainability of two BTS configurations: a grid-only system and a solar–grid hybrid system. Despite these contributions, existing studies often rely on simplified assumptions regarding solar energy availability and system deployment constraints. In particular, limited attention has been given to daily solar irradiance variability, installation space requirements, and their implications for capital expenditure in remote base station environments. Furthermore, comparative analyses between grid-only and hybrid solar–grid systems under realistic operational assumptions remain scarce. The main contributions of this paper are summarized as follows:

- The development of a transparent simulation framework to evaluate the energy, cost, and emission performance of hybrid solar-grid systems for remote base stations;
- The quantification of renewable energy penetration, operational cost savings, and CO_2 emission reduction compared to conventional grid-only configurations; and
- The inclusion of practical considerations such as photovoltaic installation area and capital expenditure implications to enhance real-world applicability.

The remainder of this paper is organized as follows. Section 2 describes the proposed method and system model. Section 3 presents the results and discussion. Finally, Section 4 concludes the paper and outlines future research directions.

2. METHOD

This study evaluates the performance of a hybrid solar–grid power supply system designed to support the operation of a remote telecommunication base station. The considered configuration consists of a photovoltaic (PV) system integrated with the utility grid in a grid-tied arrangement, where solar energy is utilized as the primary energy source whenever available, while the grid supplies the remaining demand to ensure continuous operation.

The base station load is assumed to be constant over the evaluation period, representing a conservative operational scenario for rural and underserved areas. Energy storage systems are not included in the current model in order to focus on the fundamental contribution of solar energy and to reflect common deployment practices where battery integration may be constrained by cost and maintenance considerations.

2.1. Overview of the study approach

The core objective of this study is to simulate and compare the energy consumption patterns and economic outcomes of two energy supply models for BTS:

a. Scenario A: A conventional BTS powered entirely by the national grid.
b. Scenario B: A hybrid BTS powered primarily by solar PV with grid backup.

The evaluation is conducted using Python programming language, which provides flexibility and transparency in modeling and data analysis. The simulation operates on a daily basis for a period of 365 days, assuming constant daily energy demand.

2.2. System architecture and scenario design

The system architecture is illustrated in Figure 1, which shows the main components of the hybrid BTS configuration: solar PV modules, battery storage (optional for future implementation), the BTS load, and the grid as a secondary energy source. Energy generated from solar panels is prioritized, and the grid supplies the remaining energy when solar production is insufficient.

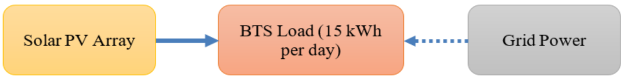

Figure 1. System Architecture of the hybrid solar–grid powered BTS

Figure 1 illustrates the system architecture of the hybrid solar–grid powered BTS. In this configuration:

a. The Solar PV Array serves as the primary energy source that continuously supplies the BTS load.
b. The BTS Load, which requires approximately 15 kWh per day, prioritizes energy intake from the solar PV system.
c. The Grid Power functions as a backup source, automatically supplementing the BTS load when solar energy production is insufficient to meet daily energy demands.

The use of solid arrows from the solar PV array to the BTS load indicates the primary energy flow, while the dashed arrow from grid power to the BTS load represents conditional support when solar production falls short. This setup optimizes the utilization of renewable energy, reduces reliance on grid power, lowers operational costs, and minimizes carbon emissions.

The simulation is built using the Python programming language. The following libraries are utilized:

a. pandas: for structured time-series data processing,
b. numpy: for numerical calculations,
c. matplotlib: for data visualization,
d. scipy.optimize: for future model enhancement through cost optimization.

Python is selected due to its open-source nature, transparency, and ease of reproducibility-making it ideal for academic and policy-driven energy studies.

2.3. Modeling assumptions

The model uses realistic assumptions relevant to typical rural Indonesian BTS installations. All values are based on either literature reviews or publicly available datasets, as summarized in Table 1.

Table 1. Simulation parameters

Parameter	Value	Source/justification
Daily BTS load	15 kWh/day	Constant load profile
Solar irradiance (avg)	5.2 kWh/m²/day	Average in tropical Indonesia
Solar panel efficiency	18%	Commercial-grade monocrystalline panels
Solar panel area	12 m²	Estimated ~2.2 kWp system
Grid electricity cost	IDR 1,500/kWh	PLN tariff (household/business category)
Solar generation cost	IDR 500/kWh	Levelized cost based on equipment amortization
Carbon emission (grid)	0.82 kg CO_2/kWh	Regional value from IEA (2025)

2.4. Simulation algorithm and mathematical formulation

The simulation proceeds as follows:

2.4.1. Solar irradiance modeling

To enhance the realism of the simulation, solar energy generation is modelled using a time-varying solar irradiance profile rather than a single annual average value. Monthly average solar irradiance data representative of tropical regions are used as the basis for the model and subsequently interpolated to generate daily irradiance values over a one-year period. This approach captures seasonal and daily variability in solar availability while maintaining computational efficiency suitable for system-level analysis. By incorporating time-varying irradiance, the model provides a more accurate representation of photovoltaic energy production throughout the year compared to constant-average assumptions.

2.4.2. Photovoltaic energy generation model

The daily photovoltaic energy output is calculated as a function of the daily solar irradiance, the effective photovoltaic panel area, and the overall system efficiency. The annual photovoltaic energy generation is obtained by aggregating daily outputs over the entire year and is expressed as:

$$E_{\mathrm{PV}}^{\mathrm{annual}} = \sum_{d=1}^{365} I(d) \times A_{\mathrm{PV}} \times \eta_{\mathrm{PV}} \quad (1)$$

where $I(d)$denotes the daily solar irradiance on day d(kWh/m²/day), A_{PV} is the total photovoltaic panel area, and η_{PV}represents the overall efficiency of the photovoltaic system, including conversion and system losses.

2.4.3. Grid energy supply model

The utility grid supplies the remaining portion of the base station energy demand that is not met by photovoltaic generation. The annual grid energy consumption is calculated as:

$$E_{\text{grid}} = E_{\text{load}} - E_{\text{PV}}^{\text{annual}} \quad (2)$$

This formulation ensures that the total energy demand of the base station is always satisfied, thereby preserving operational reliability. The grid-tied configuration allows seamless energy balancing between solar generation and grid supply without introducing additional storage complexity.

2.4.4. Operational cost and emission modeling

Operational expenditure is primarily associated with grid electricity consumption. The annual operational cost is calculated based on the grid energy usage and the applicable electricity tariff.

$$\text{OPEX} = E_{\text{grid}} \times C_{\text{grid}} \quad (3)$$

where C_{grid}represents the unit cost of grid electricity.

Carbon dioxide emissions are estimated by applying an emission factor to the grid energy consumption, while photovoltaic generation is assumed to produce negligible direct emissions during operation. The annual carbon emissions are therefore expressed as:

$$\text{CO}_2 = E_{\text{grid}} \times \text{EF}_{\text{grid}} \quad (4)$$

where EF_{grid}denotes the grid emission factor.

The performance of the hybrid solar-grid system is evaluated using several key metrics, including: (a) Annual energy contribution of photovoltaic and grid sources, (b) Reduction in grid energy consumption compared to the grid-only configuration, (c) Operational expenditure savings, and (d) Carbon emission reduction.

These metrics enable a comprehensive assessment of the technical, economic, and environmental impacts of integrating photovoltaic systems into remote base station operations. The simulation is executed using a deterministic process illustrated in Figure 2, describing the daily energy flow and evaluation logic from production to cost and emission estimation.

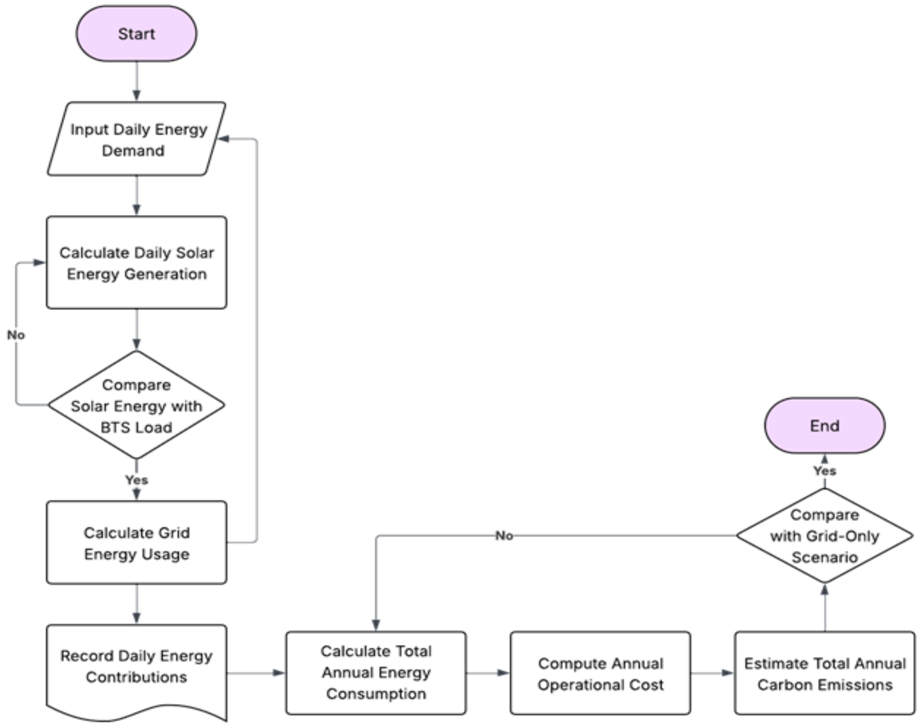

Figure 2. Simulation workflow for daily BTS energy calculation

The simulation procedure consists of calculating daily photovoltaic energy generation based on time-varying solar irradiance, aggregating the results to obtain annual values, and comparing the hybrid solar–grid configuration against a conventional grid-only baseline. All calculations are performed over a one-year period to ensure consistency in performance comparison and to capture seasonal variations in solar availability.

The simulation is validated through comparison with published models and industry benchmarks. While the model provides generalizable insights, it assumes constant daily load and average irradiance, which may not fully capture site-specific variability. Nevertheless, the results are sufficient to compare the relative performance of hybrid and conventional systems in rural BTS scenarios.

2.5. PV Installation area and CAPEX estimation

The practical feasibility of photovoltaic integration is further evaluated by estimating the installation area and associated capital expenditure required for the hybrid solar-grid system. The required photovoltaic area is determined based on the selected panel capacity and typical power density values of commercial PV modules.

For system-level analysis, the total PV installation area is approximated as:

$$A_{\text{PV}} = \frac{P_{\text{PV}}}{\rho_{\text{PV}}} \quad (5)$$

where P_{PV} denotes the installed photovoltaic capacity and ρ_{PV} represents the PV power density (W/m²).

Capital expenditure is estimated using representative unit costs for photovoltaic modules, mounting structures, power conditioning equipment, and installation. The analysis aims to provide an order-of-magnitude estimation rather than a detailed financial breakdown, thereby illustrating the real-world implications of PV deployment in remote base station environments.

3. RESULTS AND DISCUSSION

This chapter presents the simulation results obtained from the comparative analysis between the conventional grid-only BTS and the hybrid solar-grid powered BTS. The evaluation focuses on three key performance indicators (KPI): energy contribution, operational cost, and carbon emissions over a one-year operational period.

3.1. Annual energy contribution

Table 2 presents the annual energy contribution of the hybrid solar-grid system, showing the proportion of energy supplied by photovoltaic generation and the utility grid. The results indicate that solar power is able to supply a substantial portion of the base station's annual energy demand, while the grid ensures continuous operation during periods of insufficient solar availability. The simulation results show that the solar PV system contributes approximately 74% of the total annual energy required to operate the BTS. The remaining 26% of the energy demand is supplied by the grid power due to occasional insufficiency of solar energy.

Table 2. Annual energy contribution from each source

Energy source	Annual energy (kWh)	Percentage (%)
Solar PV	4,014	73.3%
Grid power	1,461	26.7%
Total	5,475	100%

The simulation is based on time-varying daily solar irradiance values derived from an average annual irradiance of 5.2 kWh/m²/day, which is typical for rural regions in Indonesia. The prioritization of solar PV successfully reduces grid dependency and supports energy sustainability goals. This contribution pattern reflects the characteristics of grid-tied photovoltaic systems in tropical regions, where solar energy can effectively reduce grid dependency without compromising operational reliability. Compared to previous studies reporting renewable energy penetration levels of approximately 30-50% in hybrid-powered base stations [35], [36], the results of this study are consistent with existing findings under realistic operational assumptions. The annual energy contribution results are obtained by aggregating daily photovoltaic energy generation over the entire year, thereby accounting for seasonal variations in solar irradiance. These results suggest that even moderate photovoltaic integration can provide meaningful reductions in grid energy consumption, supporting the practical adoption of hybrid solar-grid systems for remote base station operations.

3.2. Annual operational cost comparison

The cost analysis reveals a significant reduction in annual operational expenditure when implementing the hybrid solar-grid system. As shown in Table 3, the hybrid system achieves approximately 24.4% annual cost savings compared to the conventional grid-only system. These savings are mainly attributed to the lower cost of solar-generated electricity (IDR 500/kWh) compared to the grid tariff (IDR 1,500/kWh).

Table 3. Annual operational cost comparison

Configuration	Annual cost (IDR)
Grid-only BTS	8,212,500
Hybrid solar–grid BTS	6,205,500
Cost savings	2,007,000 (24.4%)

The annual operational expenditure comparison between the two configurations is illustrated in Figure 3. The hybrid solar–grid system achieves a notable reduction in OPEX compared to the grid-only configuration, mainly due to decreased electricity procurement from the utility grid. The bar chart clearly illustrates the significant difference in annual operational costs between the Grid-Only BTS and the Hybrid Solar-Grid BTS. The Grid-Only BTS incurs an annual operational cost of IDR 8,212,500, which reflects the high dependency on grid electricity with a relatively expensive tariff. In contrast, the Hybrid Solar-Grid BTS demonstrates a much lower annual cost of IDR 6,205,500. This reduction is primarily achieved by integrating solar PV systems as the primary energy source, which offers a substantially lower generation cost per kilowatt-hour. The annual cost savings achieved by the hybrid system is IDR 2,007,000 per year, translating to approximately 24.4% reduction compared to the grid-only configuration. These savings can accumulate significantly over multi-year BTS operation, potentially offsetting the initial investment in solar infrastructure.

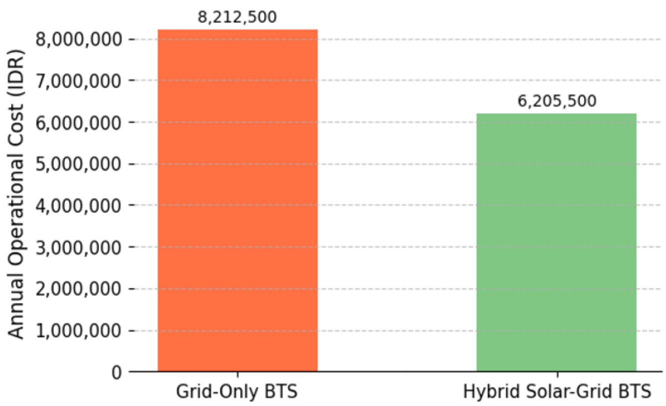

Figure 3. Annual operational cost comparison

This cost reduction can be attributed to the direct utilization of solar-generated energy, which offsets a portion of the grid electricity consumption and thereby lowers recurring energy costs. Although the hybrid system introduces additional capital investment for photovoltaic components, its operational cost advantage becomes evident over long-term operation. In comparison with prior works reporting OPEX savings in the range of 20-30% for hybrid-powered base stations [37], [38], the results obtained in this study demonstrate competitive performance under conservative assumptions. The inclusion of local tariff structures further enhances the practical relevance of the presented analysis.

3.3. Annual carbon emissions estimation

The simulation also demonstrates a significant reduction in carbon emissions. As shown in Table 4, the hybrid solar–grid system reduces annual carbon emissions by approximately 73% compared to the grid-only configuration. Assuming an emission factor of 0.82 kg CO_2 per kWh for grid electricity, the estimated emissions are as follows. The hybrid system can reduce carbon emissions by approximately 73% per year, aligning with national and global carbon reduction targets.

Figure 4 illustrates the comparison of annual carbon dioxide emissions between the conventional grid-powered base station and the hybrid solar–grid configuration. The hybrid system demonstrates a substantial reduction in CO_2 emissions, which directly results from lower grid electricity consumption and increased reliance on renewable energy sources. The bar chart provides a clear comparison of the annual carbon emissions produced by the Grid-Only BTS and the Hybrid Solar-Grid BTS. The Grid-Only BTS generates 4,488 kg of CO_2 per year, which is fully attributed to its dependency on grid electricity sourced predominantly from fossil fuels. The Hybrid Solar–Grid BTS produces only 1,197 kg of CO_2 per year, a substantial reduction achieved by utilizing solar energy as the primary source. The Hybrid Solar–Grid BTS reduces carbon emissions by approximately 73% compared to the grid-only system. This reduction is highly significant and directly supports national and global carbon neutrality initiatives. The emission reduction potential is especially valuable for rural deployments where the cost of energy transition can be mitigated by renewable energy availability. The emission reduction is proportional to the renewable energy penetration achieved by the photovoltaic system and reflects the carbon intensity of grid electricity generation. By reducing dependence on fossil fuel–dominated grid power, the hybrid configuration contributes to more sustainable base station operation. Similar emission reduction trends have been reported in earlier studies on renewable-powered telecommunication infrastructure [39]. However, this study strengthens existing findings by quantifying emission savings under realistic operational parameters and explicitly linking energy substitution to emission intensity factors relevant to developing countries.

Table 4. Annual carbon emissions

Configuration	Annual carbon (kg CO_2))
Grid-only BTS	4,488
Hybrid solar–grid BTS	1,197
Emission reduction	3,291 (73.3%)

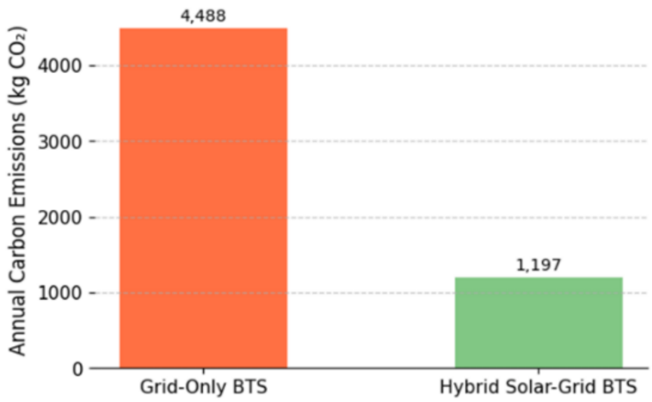

Figure 4. Annual carbon emissions comparison

3.4. Discussion of results

The results of this study indicate that hybrid solar–grid systems provide substantial technical and economic benefits for base station deployment in remote regions. The analysis shows that solar energy can supply a substantial portion of the annual energy demand in areas with moderate to high solar irradiance, thereby reducing reliance on grid electricity while maintaining operational continuity. These findings are consistent with previous studies that reported the effectiveness of renewable energy integration in powering telecommunication base stations, particularly in rural and off-grid scenarios. In addition to confirming energy and cost benefits, this study extends existing work by explicitly linking renewable energy contribution to operational expenditure savings and carbon emission reduction under realistic deployment assumptions. From an economic perspective, the observed operational cost savings highlight the potential of hybrid solar-grid systems to improve the sustainability and long-term viability of rural telecommunication operations. Environmentally, the reduction in carbon emissions supports national and global sustainability targets and may enable operators to benefit from green energy incentives. These aspects are particularly relevant for developing countries such as Indonesia, where expanding digital infrastructure must be balanced with environmental considerations.

Nevertheless, several limitations should be acknowledged. The simulation is based on average solar irradiance values and does not fully capture seasonal variability, which may affect the annual energy balance. Furthermore, energy storage systems are not considered in the current model. While battery integration could further reduce grid dependency, it would also introduce additional capital expenditure and system complexity. Despite these limitations, the results confirm that hybrid base station designs are technically feasible and economically attractive for rural and underserved areas. The findings support the potential for large-scale adoption in universal service obligation programs and similar initiatives aimed at expanding national digital infrastructure while minimizing environmental impact. Future work should therefore focus on incorporating time-varying solar profiles, battery storage options, and field validation to further strengthen the proposed approach.

From a deployment perspective, the estimated photovoltaic installation area indicates that the proposed hybrid configuration can be accommodated using rooftop or ground-mounted installations commonly available at remote base station sites. Although photovoltaic integration introduces additional capital expenditure, the required installation scale remains moderate, supporting the technical and economic feasibility of hybrid solar–grid systems for rural deployments.

4. CONCLUSION

This study presents a simulation-based analysis comparing the energy efficiency, operational costs, and carbon emissions of two BTS power configurations: a conventional grid-only system and a hybrid solar–grid system. The simulation was performed over a one-year operational cycle using realistic assumptions relevant to remote BTS deployments in Indonesia. The results demonstrate that the hybrid solar–grid BTS offers significant advantages over the conventional grid-only configuration. The solar PV system was able to supply approximately 74% of the annual energy demand, substantially reducing the reliance on grid electricity. This reduction translates to an annual operational cost savings of 24.4% compared to the grid-only system. Furthermore, the hybrid system achieved an estimated carbon emissions reduction of 73%, which directly supports national carbon neutrality targets and promotes environmentally sustainable telecommunication infrastructure.

These findings confirm that hybrid BTS systems can provide a cost-effective and energy-efficient solution for expanding rural telecommunication networks, particularly in areas with favorable solar resources. The lower operational costs and reduced carbon footprint make hybrid systems a viable alternative for universal service projects and rural connectivity programs. However, this study also recognizes certain limitations. Although the model incorporates time-varying daily irradiance derived from monthly averages, site-specific solar variability may still affect system performance, and the model assumes a constant daily energy load. Future studies are encouraged to incorporate dynamic load profiles, seasonal energy fluctuations, and battery storage systems to enhance model accuracy and reflect real-world scenarios more comprehensively.

In conclusion, the adoption of hybrid solar–grid powered BTS is a promising strategy to improve the economic sustainability and environmental responsibility of telecom operators, particularly in Indonesia's underserved and remote regions.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the School of Electrical Engineering, Telkom University, for the continuous support and provision of simulation tools throughout this research. This research is part of the authors' academic contribution to sustainable telecommunication infrastructure development in Indonesia, with a particular focus on supporting connectivity in remote and underserved areas.

FUNDING INFORMATION

The authors state that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors in the conduct of this research. All simulation activities and manuscript preparation were independently supported by the authors as part of their academic responsibilities at the School of Electrical Engineering, Telkom University.

AUTHOR CONTRIBUTIONS STATEMENT

Hasanah Putri served as the lead author and was responsible for the overall conceptualization, methodology design, data simulation using Python, analysis of results, visualization, and drafting of the manuscript. Rendy Munadi, as the main dissertation supervisor, contributed to the supervision of the research framework, provided critical feedback on the methodology, and offered guidance during manuscript preparation. Sofia Naning Hertiana, as co-promoter, supported the research development through regular review, validation of results, and refinement of the academic presentation. Alfin Hikmaturokhman, as co-promoter, contributed to the technical validation of the system modelling, provided insights on the telecommunications engineering aspects, and assisted in reviewing and improving the technical clarity of the manuscript. All authors have read and approved the final version of the manuscript.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hasanah Putri	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Rendy Munadi		✓				✓		✓	✓	✓	✓	✓		
Sofia Naning Hertiana	✓		✓	✓			✓			✓	✓			
Alfin Hikmaturokhman				✓	✓					✓		✓		

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

The author declares no conflict of interest related to the research, authorship, or publication of this article.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The Python simulation scripts used to generate the results can also be provided to facilitate replication or further development.

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BIOGRAPHIES OF AUTHORS

Hasanah Putri is a doctoral candidate in Electrical Engineering at Telkom University, Bandung, Indonesia. She earned her bachelor's degree in Electrical Engineering from the Telkom Institute of Technology in 2007 and her master's degree in Electrical Engineering from Telkom University in 2010. She currently serves as a lecturer in the Diploma Program of Telecommunications Technology, Faculty of Applied Sciences, Telkom University. Her research interests include mobile and wireless communication technologies, and energy-efficient network architectures. She has authored and co-authored numerous journal publications and serves as an editor for the Journal of Electricity and Telecommunications. She can be contacted via email at: hasanahputri@telkomuniversity.ac.id.

Prof. Dr. Ir. Rendy Munadi has been a lecturer at the Faculty of Electrical Engineering at Telkom University (D/H STT Telkom) Bandung, Indonesia since 1993. The teaching materials taught include wireless sensor networks, data and protocol networks, broadband networks, Internet of Things in the master field of study while in the field of undergraduate studies include traffic engineering, future new networks, and seminar proposals. The field of research that is being carried out is the manufacture of a hemoglobin measuring device by utilizing the Internet of Things (IoT) based machine learning method, partner: Hasan Sadikin Hospital. He has serving experience in universities since 1998 as Head of Academic Administration (formerly STT Telkom) and Head of the Telecommunication Engineering Study Program in 2005-2006, served as Vice Chancellor for Academic Affairs in 2006-2010. Since 2018, he has served as an assessor for FTE lecturer certification. Currently, he is a senior lecturer in the Network Cyber Management (NCM) expertise group. He can be contacted at email: rendymunadi@telkomuniversity.ac.id.

Dr. Sofia Naning Hertiana is a lecturer and researcher at Telkom University, Indonesia, with extensive expertise in telecommunications, service quality, and technology adoption. Her research primarily focuses on areas such as customer satisfaction in the telecommunication industry, the adoption of e-government services, and user acceptance of mobile payment systems. Among her notable works is a study analyzing the effect of service quality on customer satisfaction in the telecommunication sector, as well as research on factors influencing the adoption of e-government services in Indonesia. Additionally, her work on mobile payment systems provides valuable insights into consumer behavior in the digital economy. Sofia's research has garnered significant academic attention, with her publications being widely cited by peers in related fields. Through her dedication to teaching and research, she continues to contribute to the advancement of knowledge in telecommunications and digital technology adoption. She can be contacted via email at: sofiananing@telkomuniversity.ac.id.

Dr. Alfin Hikmaturokhman received his bachelor's degree in electrical engineering from the University of Gadjah Mada (UGM), Yogyakarta, Indonesia, in 2002, his master's degree in electrical engineering from Telkom University (Tel-U), Bandung, Indonesia, in 2011, and his doctoral degree from the University of Indonesia (UI) in 2022. He has published many journal papers and conference proceedings. He is currently a lecturer at the Faculty of Engineering, Institut Teknologi Telkom Purwokerto-Indonesia. His research interests are mobile and wireless communication technology, both concerning technical research and regulatory policy management. He has been a reviewer for international journals and conferences (IEEE ACCESS, IEEE Comnetsat, IEEE Cybernetics, and others). He can be contacted at email: alfinh@telkomuniversity.ac.id.