Development of an Energy-Sustainable Model for Mobile Communication Base Stations in Ukraine under Conditions of Prolonged Emergency Power Outages

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Abstract

The concept and study in this thesis is the construction of an energy-sustainable service model of mobile communication base stations in Ukraine under a prolonged emergency power outage scenario.
Based on case studies from abroad, industrial lessons learnt, and data-driven analysis, it discusses the applicability of incorporating renewable power, battery storage solutions, and hybrid power systems to ensure the continuous operation of telecommunications infrastructure.
The primary goal is to develop a scalable energy model to enhance the resilience of mobile communication networks in the face of prolonged energy instability, military risks, and other challenges.
The study concluded that resilient power architectures, integrated with solar power, energy storage, and backup generation, can lead to a decline in reliance on traditional, fuel-based systems, greater robustness and efficiency in energy design, and fewer issues with access to the mobile internet or voice calls.

Key words: “urban planning”, “resilience” “telecommunication base stations,” “energy sustainability,” “renewable energy integration,” “solar photovoltaic systems,” “battery energy storage systems,” “hybrid energy systems,” “off-grid base stations,” and “backup power solutions for telecommunications infrastructure.”

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1 INTRODUCTION

1.1 Relevance of the research

With the onset of the full-scale invasion, Ukraine has faced a vast array of security, social, and economic challenges.
Despite the aggressor's attempts to subdue us, Ukraine continues to demonstrate resilience in many areas.

Telecom and the mobile internet are one such area. Despite numerous bombings of power generation and distribution infrastructure, mobile communications and the internet continue to function, providing a vital communications backbone for resilience against enemies.

In addition to the factors mentioned above, the study's value is enhanced by both extensive factors (the economic development of rural areas, the increase in the number of smartphones and subscribers/customers) and intensive factors, such as the development of 4G-5G technologies, which require infrastructure development and more energy consumption.

From a technological point of view, based on the ITU (United Nations specialised agency for information and communication technologies):

- 2G provides the widest coverage area but the lowest data transfer speeds;
- 3G is an intermediate step with moderate speeds and a fairly wide coverage radius;
- 4G combines high speeds with extensive coverage and is the most effective compromise for mass-market mobile internet.
- 5G provides maximum speeds and network capacity, but requires a denser deployment of towers, especially when using high-frequency bands.

Please see Table 1 below, which explains why the number of mobile base stations will increase.

Technology	**Typical User Data Speed**	**Peak Data Rate**	**Typical Cell Radius**	**Approximate Coverage Area**
2G (GSM/EDGE)	Tens to hundreds of kbps	Up to ~384 kbps	2–5 km (urban); up to ~35 km (rural)	12.6–78.5 km²; up to ~3848 km²
3G (UMTS/HSPA+)	1–10+ Mbps	Up to 21–42 Mbps	1–3 km (urban); 5–15 km (rural)	3.1–28.3 km²; 78.5–706.9 km²
4G (LTE/LTE-A)	10–100+ Mbps	100 Mbps–1 Gbps	1–5 km (urban); 10–30 km (rural)	3.1–78.5 km²; 314–2827 km²

5G (Sub-6 GHz)	100–300+ Mbps	Up to 20 Gbps	0.5–2 km (urban); 2–10 km (rural)	0.8–12.6 km²; 12.6–314 km²
5G (mmWave)	Hundreds of Mbps to Gbps	Very high (multi-Gbps)	0.1–0.3 km	0.03–0.28 km²

Table 1. Comparison of Mobile Network Generations by Data Speed and Coverage Area

Note. The coverage area is estimated using the simplified formula S = πr^2. Values are approximate and intended for comparative purposes, as actual coverage depends on frequency bands, terrain, infrastructure density, and environmental conditions.

The comparative table was compiled using a combined approach that integrates normative technical sources with engineering assumptions regarding typical network deployment scenarios.

In the first stage, a data transmission rate was determined for each generation of mobile communications. Official and semi-official technical sources were used for this purpose: for 3G—3GPP materials on HSPA/HSPA+, for 4G—ITU requirements for IMT-Advanced, and for 5G—ITU requirements for IMT-2020. For 2G, the maximum characteristic parameters of EDGE technology were used, as it is the most common option for packet data transmission within 2G. Thus, the table reflects not only "peak" values but also typical user ranges used in the practical evaluation of mobile networks.

In the second stage, the effective coverage radius of a single base station was determined. Usually, communication standards typically do not specify a single universal coverage radius for 2G, 3G, 4G, or 5G, as it depends on the frequency band, antenna height, transmitter power, building density, terrain, network load, and cell type (macro/micro/pico). Therefore, the table uses typical engineering ranges synthesised from regulatory and industry sources. Specifically, for GSM, the timing advance limitation was taken into account, which in a classic scenario supports a practical distance of up to approximately 35 km; for UMTS and LTE, typical macrocell scenarios in urban and rural environments were used; for 5G mmWave—data indicating that typical coverage is usually only a few hundred meters unless special extended-range solutions are employed.

In the third stage, a simplified geometric model of a circular cell was used to estimate coverage by area. This approach is an analytical simplification and is used to compare technologies in a standardised format. It does not account for antenna sectorization, cell overlap, terrain features, building shielding, or radio propagation heterogeneity; therefore, the obtained values should be interpreted as approximate rather than as accurate predictions of actual coverage. The area in the table was specifically presented as an effective theoretical framework for comparing technological generations.

In addition to technological advancements, the past 10 years have seen an increase in both the number of smartphones in use and the number of active subscriptions (SIM cards) among mobile operators.

Specifically, according to the Global Statshot Report, there were 2.2 billion smartphones worldwide as early as 2004; 20 years later, that number has surpassed 7 billion. If we combine this data with the number of active subscriptions, smartphones are currently owned by nearly 60% of the world's population.

At the same time, significant advancements in artificial intelligence will accelerate the growth of the Internet of Things market, which in turn will further increase the number of "active" mobile network users and the volume of data transmitted over mobile networks. Already, in June 2026, 5G technology is available in Lviv with download speeds of up to 1 Gbps; by comparison, my home fibre-optic internet has a speed of only 300 Mbps.

1.2. Research question and hypothesis

Main research question: What role can energy-sustainable power solutions—based on renewable energy sources and hybrid systems—play in ensuring the resilience and uninterrupted operation of mobile communication base stations in Ukraine under conditions of prolonged emergency power outages, and what are the key challenges and opportunities of their implementation?

Research hypothesis:

Renewables (especially solar photovoltaic systems), battery energy storage, and hybrid backup solutions may be central in resilient telecommunications infrastructure to ensure mobile communications service continuity under extended power outages. These systems could help decrease reliance on diesel generators, lower operational costs, and reduce environmental impact. Given the significant decrease in the prices of both solar panels and storage batteries over recent years, the widespread introduction of such a solution is quite economically justified.

The ongoing conflict in Ukraine, along with damage to energy infrastructure, makes power supply stability one of the biggest challenges in today's landscape. Frequent, prolonged power outages affect the performance of mobile communications base stations, which are critical to civilian populations and even life-saving services. The integration of decentralised, energy-sustainable power systems can vastly strengthen network resilience and increase energy sector independence. And modular scalable hybrid energy options let power systems be adjusted for a range of different operational situations—from off-grid to emergency.

Thus, the generation and utilisation of these models can also contribute not only to the sustainability of the telecommunications infrastructure but also to the overall aspiration to strengthen the nation's energy security during post-crisis recovery.

1.3. Research objective

The research objective is to develop and substantiate an energy-sustainable model for mobile communication base stations in Ukraine under conditions of prolonged emergency power outages, based on international experience and techno-economic analysis.

To achieve this objective, the study includes: (1) an analysis of international case studies on energy supply for telecommunication infrastructure, with a focus on implementations in Kuwait and Nigeria; (2) an assessment of current energy consumption patterns of mobile communication base stations, based on an empirical case study of a base station located in the Kirovohrad region; (3) a review of national regulatory requirements concerning the resilience and continuity of mobile communication networks, including obligations imposed on telecommunications operators; (4) the modeling and optimization of alternative energy supply configurations—such as solar photovoltaic systems, battery energy storage, and hybrid solutions—using the HOMER software environment; and (5) the formulation of a generalized model that identifies the most scalable, cost-effective, and operationally feasible solution for ensuring the resilience of base stations under conditions of energy instability in Ukraine.

1.4. Research Methodology

A full methodological approach was combined to meet the research goals, using both quantitative and qualitative analytical methods.

The study involves an empirical analysis of energy consumption trends in mobile communication base stations, based on a case study of a base station in the Kirovohrad region. This study was conducted to evaluate the default load profile, power consumption, and energy needs of the station, including the periods of normal and urgent operation, up to and including long-term power loss. The data for this research were provided by Vodafone Ukraine.

Moreover, an international practices review was conducted, considering the application of energy-sustainable solutions to telecom infrastructure in countries such as Kuwait and Nigeria. This made it possible to identify effective actions for sustaining the operation of base stations in off-grid, energy-scarce environments.

An analysis of regulations has also been conducted to examine the existing obligations of telecom operators in Ukraine, including coverage resilience, service continuity, and backup power systems. This laid the groundwork for assessing the feasibility of implementing alternative energy solutions within the existing institutional framework. The following tasks were done based on the data collected:

– Comparative review of international and Ukrainian solutions for ensuring energy-sustainable mobile communication infrastructure;

– Current challenge analysis regarding unstable energy supply and its consequences for the operation of base stations;

– The modelling and simulation of alternative energy supply systems, including solar photovoltaic systems, battery energy storage, and hybrid systems, using the framework provided by the HOMER software environment;

– Evaluation of the techno-economics of modelled scenarios, such as cost-effectiveness, scalability, and operational reliability. In this way, integrating analytical, empirical, and modelling methods led to a comprehensive assessment of energy-sustainable solutions for mobile communication base stations.

The results are used to create a scalable, economically justified model for providing resilience and the uninterrupted operation of telecommunications infrastructure in Ukraine during periods of prolonged energy volatility.

To ensure the correctness of the research, a few semi-structured interviews were conducted (Vodafone Ukraine, Kyivstar, Ministry of Digital Transformation).

The expert survey conducted among representatives of the Ministry of Digital Transformation of Ukraine aimed to identify key regulatory priorities and challenges associated with improving the energy resilience of mobile telecommunications infrastructure. The responses indicate that ensuring uninterrupted operation of telecommunications networks has become a strategic priority since the large-scale disruptions to Ukraine's energy system beginning in 2022.

According to the experts, the primary challenge affecting the energy resilience of mobile networks is the dependence of base stations on the national electricity grid. During prolonged power outages, network operators face difficulties maintaining uninterrupted communication services despite significant investments in backup power systems. Additional challenges include the high cost of energy storage technologies, logistical difficulties associated with maintaining backup generators, and the increasing energy demands of modern telecommunications equipment.

The respondents emphasized that current regulatory requirements focus primarily on ensuring network continuity and operational resilience. Recent regulations have introduced stricter requirements for backup power capacity and autonomous operation of mobile base stations. These measures are intended to improve the ability of telecommunications operators to maintain service availability during emergency situations and large-scale power disruptions.

A significant finding of the survey is the recognition of renewable energy technologies as a promising solution for enhancing infrastructure resilience. Experts identified photovoltaic systems as particularly suitable due to their ability to generate electricity independently of the power grid, reduce operational costs, and decrease reliance on diesel generators. Solar energy systems were viewed not only as a backup power source but also as a strategic component of long-term telecommunications infrastructure modernization.

The respondents also highlighted several government initiatives supporting the development of resilient telecommunications networks. These initiatives include cooperation between government agencies and mobile operators, the development of resilience standards for critical infrastructure, and the exploration of mechanisms to support investments in renewable energy technologies. Although direct subsidy programs remain limited, experts noted increasing policy attention toward sustainable and decentralized energy solutions.

Despite the acknowledged benefits of renewable energy systems, several barriers to implementation were identified. Financial constraints remain one of the most significant obstacles, particularly due to the substantial upfront investment required for photovoltaic installations and battery storage systems. Technical limitations related to available installation space, energy storage capacity, and site-specific infrastructure conditions were also mentioned. Furthermore, respondents noted that the absence of dedicated incentive mechanisms and standardized implementation frameworks may slow the pace of adoption across the telecommunications sector.

To accelerate the deployment of renewable energy technologies, experts recommended the introduction of targeted financial support mechanisms, including tax incentives, preferential financing programs, and public-private partnership initiatives. Additional recommendations included the development of technical standards for renewable energy integration at telecommunications facilities, simplification of permitting procedures, and the inclusion of renewable energy deployment targets within broader national digital infrastructure strategies.

Overall, the survey findings suggest that renewable energy technologies, particularly photovoltaic systems combined with battery storage, are increasingly viewed as an effective means of improving the resilience and sustainability of mobile telecommunications infrastructure. The responses further indicate that regulatory support and targeted investment incentives will play a critical role in facilitating the large-scale adoption of such solutions throughout Ukraine's telecommunications sector.

2 THEORETICAL BASIS DERIVED FROM THE LITERATURE REVIEW

2.1 Literature Review Methodology

For this study, a literature review methodology was employed to evaluate existing academic research on energy sustainability in telecommunications infrastructure, with a particular emphasis on renewable energy integration, hybrid power systems, and backup energy solutions for mobile communication base stations.

Special attention is given to solar photovoltaic systems, battery energy storage, and their role in ensuring operational continuity during prolonged power outages.

The primary focus is on assessing the effectiveness of these energy solutions in enhancing the resilience and sustainability of mobile network infrastructure, while also analysing their technical, economic, and operational advantages and limitations under conditions of energy instability and full-scale war in Ukraine. Additionally, a quick scaling option is preferred.

The study analysed a large body of theoretical data, including publications on the topic over the past decade. Additionally, direct cooperation with Vodafone Ukraine provided access to unique non-public data, enabling a comprehensive and interesting study.

The search process was guided by a list of keywords reflecting the research domain, including “telecommunication base stations,” “energy sustainability,” “renewable energy integration,” “solar photovoltaic systems,” “battery energy storage systems,” “hybrid energy systems,” “off-grid base stations,” and “backup power solutions for telecommunications infrastructure.”

The literature reviewed was not restricted, focusing on studies published between 2013 and 2026, ensuring relevance to current issues in energy resilience and telecommunications infrastructure.

The sources that met the inclusion criteria needed to contain analytical studies, case studies, or technical assessments related to energy-sustainable solutions for mobile communication base stations, including renewable energy integration, battery energy storage systems, hybrid power configurations, and backup energy solutions.

To ensure accuracy and consistency during content analysis, only English- or Ukrainian-language publications were considered. The inclusion criterion was also based on the availability of full-text, allowing for thorough research of methods, data, and conclusions. But then I bought a subscription to Academia Edu, so some of the analysed texts may be in "relatively open access".

I've selected articles that covered energy resilience, the continuous operation of base stations, or alternative power supply systems under grid instability conditions for further examination, and extracted the relevant data.

2.2 Literature Review

The rapid expansion of mobile communication networks has significantly increased the energy demand of telecommunications infrastructure, particularly base transceiver stations (BTSs), which account for the largest share of electricity consumption in cellular networks. As telecommunication operators continue to expand coverage in rural and remote areas, ensuring reliable and sustainable power supply has become a critical challenge. Traditional dependence on diesel generators and unstable electrical grids increases operational costs, carbon emissions, and vulnerability to power disruptions.

The academic literature increasingly emphasizes the role of renewable and hybrid energy systems in addressing these challenges. Early research by Kusakana and Vermaak

(2013) demonstrated that hybrid renewable energy systems integrating solar photovoltaic (PV) generation, battery storage, and conventional backup sources can provide reliable power for mobile telephony base stations in developing countries while reducing fuel consumption and operating expenses. Their work established a foundation for considering renewable-powered BTSs as both technically feasible and economically attractive.

Subsequent studies expanded this perspective by focusing on optimization and economic performance. Deevela et al. (2023) investigated solar PV-based hybrid systems for Indian telecommunications infrastructure and found that properly optimized configurations significantly reduce lifecycle costs while maintaining operational reliability. Similar findings were reported by Ebiega, Dugeri, and Irefu (2024), who demonstrated the importance of hybrid renewable-grid systems for enabling mobile network expansion in rural Nigeria, where unreliable grid access remains a major barrier to telecommunications development.

Another stream of research focuses on sustainability and environmental impacts. Syed et al. (2021) examined renewable energy adoption by mobile network operators and highlighted substantial reductions in greenhouse gas emissions associated with hybrid renewable systems. Alsharif, Kim, and Kim (2017) further argued that green cellular base stations represent a necessary direction for future telecommunications development, emphasizing environmental sustainability alongside economic efficiency. More recent studies by Wang et al. (2025) indicate that decarbonization of communication infrastructure can generate not only environmental benefits but also measurable economic and public health advantages.

Recent literature also explores advanced energy management and smart control systems. Cabrera-Tobar et al. (2025) proposed adaptive energy management systems capable of dynamically balancing multiple energy sources to improve both reliability and operational efficiency. Rajendran et al. (2026) and Gupta and Suman (2026) further demonstrated the potential of artificial intelligence and intelligent optimization techniques to improve energy utilization in hybrid telecom power systems. In parallel, Zhong et al. (2025) investigated the integration of distributed photovoltaic generation and energy storage within 5G infrastructure, highlighting the growing importance of renewable-powered telecommunications in supporting emerging digital ecosystems.

Despite the growing body of research, several gaps remain. First, many studies focus primarily on technical optimization or environmental benefits while providing limited analysis of the strategic role of hybrid energy systems in ensuring network resilience under conditions of unstable electricity supply. Second, existing research is concentrated on specific national contexts, such as India, South Korea, Kuwait, Nigeria, and China, limiting the generalizability of findings to other regions facing similar energy security challenges. Third, while recent studies increasingly incorporate artificial intelligence and advanced energy management approaches, there remains insufficient integration of technical, economic, and operational reliability perspectives within a unified analytical framework.

This study adopts the theoretical perspective of sustainable infrastructure development, which considers telecommunications infrastructure as a socio-technical system whose performance depends on the interaction between energy availability, operational reliability, economic efficiency, and environmental sustainability. Within this framework, hybrid renewable energy systems are conceptualized as integrated configurations combining renewable energy sources, energy storage technologies, grid connections, and backup power solutions to ensure continuous BTS operation.

The theoretical framework assumes that the adoption of hybrid renewable energy systems influences telecommunications infrastructure through several interconnected mechanisms. Renewable generation reduces dependence on conventional fuels and electricity grids, battery storage enhances operational continuity during outages, and intelligent energy management systems improve overall system efficiency. Together, these mechanisms contribute to higher network reliability, lower operational costs, reduced carbon emissions, and increased feasibility of telecommunications deployment in underserved regions.

Based on the reviewed literature, the study advances the theoretical expectation that hybrid renewable energy systems significantly improve the reliability and sustainability of mobile communication infrastructure compared with conventional power supply models. Furthermore, it is expected that the effectiveness of such systems depends not only on the selected energy technologies but also on the quality of energy management, local environmental conditions, and the availability of supporting infrastructure. These theoretical expectations provide the foundation for the subsequent empirical analysis of hybrid energy solutions for telecommunications base stations.

3. INTERNATIONAL EXPERIENCE IN ENERGY-SUSTAINABLE POWER SUPPLY FOR TELECOMMUNICATION BASE STATIONS

3.1 Kuwait – implementation of renewable energy solutions for off-grid and rural base stations

The great demand for mobile communications services, especially in arid or sparsely populated regions, has significantly increased the need for sustainable, reliable power supply systems for telecommunications networks.

Kuwait is a suitable case for this reference, owing to its potential for solar energy and the need to ensure mobile communication bases are never interrupted in off-grid and rural areas not on the grid.

In Kuwait, the development of mobile telecommunications has been a long-standing trend, and in areas near the desert and in low-density areas, diesel generators have been used as the main source. But that process has resulted in increased operating expenses, higher fuel transportation costs, and environmental damage. Thus, some research was conducted to explore the feasibility of integrating renewable energy systems into base-station power products.

A key study by Baidas et al. (2022) explores the potential of renewable-based cellular base stations powered by energy sources in the rural Kuwaiti region. Additionally, the availability of more base station development is associated with a big increase in the energy demands (as well as significant environmental effects) and the implementation of these systems requires alternative energy solutions, as described by the authors' study. The study presents hybrid renewable energy systems that use photovoltaic (PV) solar panels, wind turbines, battery storage systems, backup diesel generator, and battery storage systems with configurations optimized with HOMER software.

These results suggest that hybrid system may be able to effectively replace and substitute conventional, diesel-based base station. For example, certain rural areas including Jal-Alayah and Wafra, varied the selected configurations according to local climate. Wind turbine-battery systems were reported in most cost-effective regions with the most wind potential, and PV-battery systems in high-solar irradiance regions were reported to have the best cost effectiveness and environmental effluences.

Crucially, some implementations achieved 100% renewable energy generation with no CO_2 emissions demonstrating the potential for fully autonomous energy systems for primary and control stations. Besides hybrid systems, other studies have also focused in on the large solar energy possibilities in Kuwait. Solar irradiation is particularly prevalent in the country, with about 1900–2100 kWh/m^2 expected per year (and the daily sunshine period being long), hence, photovoltaic applications are highly efficient for telecom infrastructure. These circumstances facilitate the installation of solar-powered off-grid base stations that would decrease dependence on both centralised grid network infrastructure and fossil-fuel energy generation.

Other significant research directions are grid connected photovoltaic systems. The incorporation of PV systems into these existing grid operated base stations has been found by researchers to be advantageous for lowering service fees by offsetting energy demands and providing avenues for selling surplus energy to the grid. Simulation results confirm that these kinds of settings can save the net present cost (NPC) during a base station's period while the carbon emission will at the same time decrease.

The key feature of these solutions is the employment of battery energy storage systems (BESS), which keep stations running autonomously in low solar generation or grid failure scenarios. Battery in place makes it possible for the base stations to operate autonomously for an extended period of time and offers immediate backup power to enhance the availability and reliability of the systems. When coupled with intelligent systems for energy management, these means enable efficient distribution of energy resources, load balancing and the use of natural resources efficiently. The Kuwaiti situation also underlines the necessity of system optimisation and modelling. Tools such as HOMER allow assessment of multiple system configurations with respect to technical and cost parameters – such as CAPEX, OPEX, NPC and emissions.

This method can be used to determine the best and most scalable solutions for some site conditions. Although it has obvious benefits, a few obstacles have been discovered. These are the effects of the extreme environmental factors (e.g., high temperatures and dust-induced accumulations) on the system performance especially for solar panels and battery-storage. Besides, the initial investment cost of renewable energy systems may be a factor against their adoption without proper policy intervention or financial benefits.

Despite this, the findings presented here from Kuwait show that renewable and hybrid energy schemes are technically practical and economically feasible for provisioning off-grid base stations and rural base stations. The shift from diesel-based to energy-saving options lowers overall operation costs, increases energy independence, and lowers the cost of running.

3.2 Nigeria – hybrid energy systems for ensuring the reliability of mobile communication infrastructure

Nigeria provides a relevant case study for analysing how hybrid energy systems can improve the reliability of mobile communication infrastructure in regions with unstable electricity supply. In rural areas, base transceiver stations (BTS) are essential for expanding access to mobile networks, digital services and information infrastructure. However, their operation requires a continuous and reliable power supply, which is often difficult to guarantee because many rural locations are either weakly connected to the national grid or experience frequent power outages.

The Nigerian telecommunications sector has traditionally relied heavily on diesel generators as a backup power source for BTS sites. Although diesel generators can provide short-term reliability, this model creates several long-term problems. First, it increases operational expenditure due to fuel purchase, transportation and maintenance costs. Second, it exposes network operators to fuel price volatility and logistical risks, especially in remote areas. Third, diesel-based power supply increases greenhouse gas emissions and contradicts the global shift toward cleaner and more sustainable infrastructure.

The study by Ebiega, Dugeri and Irefu (2024) proposes a hybrid renewable/grid power system as a more sustainable solution for BTS energy supply in rural Nigeria. The proposed system combines solar photovoltaic panels, wind energy, battery storage and grid power. This configuration allows BTS equipment to operate more reliably because the system does not depend on a single energy source. During periods of sufficient sunlight, solar panels contribute to the load; when wind resources are available, wind turbines provide additional generation; when renewable output is insufficient, the grid and battery storage support continuity of service.

A key advantage of this hybrid model is improved resilience. For mobile communication infrastructure, even short interruptions in energy supply can reduce service quality, disconnect users and limit access to emergency, financial and educational services. Hybrid systems reduce this risk by diversifying energy sources and providing backup capacity. This is especially important in rural Nigeria, where network expansion is closely linked to broader social and economic inclusion.

The environmental and economic benefits are also significant. According to the analysed case, the hybrid configuration can reduce diesel consumption and lower carbon dioxide emissions. The authors estimate that such a system can save approximately 930.75 kg of diesel and reduce about 1,314 kg of CO_2 emissions annually. This demonstrates that hybrid renewable/grid systems can simultaneously improve network reliability, reduce operating costs and support environmental sustainability.

Overall, the Nigerian case shows that hybrid energy systems are not only a technical solution but also a strategic tool for expanding mobile network coverage in underserved regions. By reducing dependence on diesel generators and improving the stability of BTS power supply, hybrid renewable/grid systems can support deeper penetration of telecommunications infrastructure in rural areas. For countries with similar energy challenges, this model illustrates how renewable energy integration can strengthen digital connectivity and contribute to sustainable infrastructure development.

4. ANALYSIS OF ENERGY SUPPLY CHALLENGES FOR MOBILE COMMUNICATION BASE STATIONS IN UKRAINE

A recent study conducted with the support of the UNDP highlights several systemic challenges in this area, which are exacerbated by security and energy challenges.

Despite the general assessment of mobile communication quality as “good” (average score of 3.6 out of 5), a significant proportion of users note that network quality depends on the type of settlement: in rural areas, satisfaction is significantly lower than in large cities.

This indicates uneven infrastructure development and limited backup power solutions in less urbanised regions, where base stations are more vulnerable to power outages.

Additional confirmation of energy challenges is the behaviour of users during power outages. Although some respondents (37%) noted some improvement in communication quality compared to previous periods, more than half (51%) did not record any changes, and 9% reported deterioration. This indicates a partial adaptation of operators to crisis conditions, but at the same time emphasises the insufficient level of autonomy of the energy supply of base stations. The situation is especially critical during user mobility: communication quality on highways is rated at only 3 out of 5, and a significant proportion of users experience problems making calls, watching videos, and using online services.

In general, the key challenges in the energy supply of mobile base stations in Ukraine are: dependence on centralised power supply, insufficient backup power, and uneven infrastructure development between cities and rural areas. These factors limit network stability, especially during crisis outages, and require the introduction of alternative energy sources and increased energy efficiency of telecommunications infrastructure.

4.1 Case study — Kirovohrad region (with Vodafone Ukraine)

In November 2025, the Ministry of Digital Transformation are launching the "Communication Generator" project to maintain mobile connectivity during blackouts.

Businesses and responsible citizens have been invited to provide power to operators' base stations using their own generators, so that during blackouts, Ukrainians can call an ambulance, receive emergency alerts, and contact their loved ones.

Simplifying — fueling and maintenance are the contractor's responsibility, while connection is handled by the telecom operators.

Based on this, after a few cycles of negotiations, I, as a researcher, signed an agreement with Vodafone Ukraine for a back-up energy supply for a mobile base station located in Mala Vyska city (where I was born), Kirovohrad region.

This collaboration is based on a commercial arrangement and provides for the mobile operator to reimburse the contractor for costs incurred in providing backup power and other payments. The formula takes into account the generating unit's capacity, fuel and maintenance costs, depreciation, and other factors.

In January 2026, a KS 10000 E G power generation unit with a rated capacity of 7.5 kW was purchased and installed.

Following a detailed analysis and several months of operation, a research hypothesis was formulated: the cost of backup options using diesel or gasoline-powered generators is less advantageous for all parties (contractor, customer) than the use of a small solar power plant with an energy storage system to achieve the same goal (backup power for the station in case of a power outage).

Following this conclusion, I immediately contacted the mobile operator with a proposal to supplement the backup system with a solar power station.

Without going into details, thanks to this request, I, as a researcher, stumbled upon the main barrier to providing backup power for base stations. And it has nothing to do with financial resources; rather, it concerns the organisational structure and certain organisational peculiarities of the telecommunications business.

Typically, the land on which the base station is located has already been allocated to another legal entity (specialised in telecommunications towers), while the mobile operator focuses on customer service. Please see Image 2.

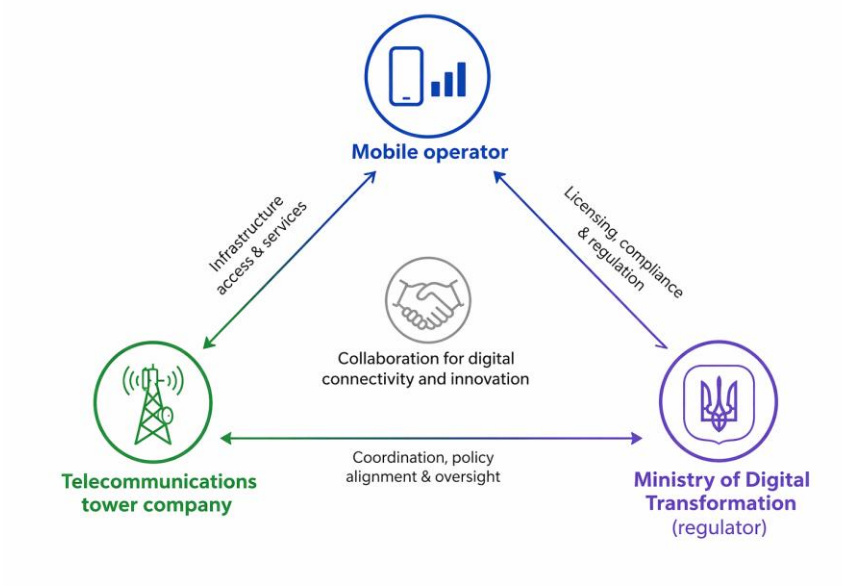

Image 2. Nature of relationships between parties

4.2 Analysis of energy consumption patterns and load profiles

A typical mobile communication tower contains two main components that consume energy.

First, the communication equipment, which by its nature does not consume much electricity.

Then there is auxiliary equipment, such as: energy storage units, signal lights, and air conditioners for heating or cooling the space. Proper heating and cooling are critical for the stable and long-term operation of the system. At the same time, this part is the most resource-intensive; typical "containers" near base stations are entirely made of metal, which heats up very quickly and loses heat just as easily in winter, while modern battery systems have a recommended operating temperature range (often from +5 to no more than +26 degrees, etc.). The total power rating of installed equipment and appliances is shown in Table 2.

Applying a diversity factor of 0.7, the average power consumption or total individual peak consumption in watts is — 1827W.

Equipment	Power rating	Hours of service	Average daily consumption
Communication equipment	24 W, 48 V	24h/24	0.65 kWh

Heat extractor	1000 W	24h/24	24.00 kWh
Seven lighting lamps	4 W × 7	24h/24	0.67 kWh
Telecommunication receiver	1500 W	24h/24	36.00 kWh
5 security lamps 220 V, 50 Hz	12 W × 5	8h/24	0.48 kWh
Total	**2610 W**	—	**61.80 kWh**

Table 2. Load summary profile

Additionally, each mobile base station is equipped with battery storage. Please see Table 3 with the analysis.

Equipment	Power rating	Hours of service	Average daily consumption
Battery storage	30000k Wh, 48V	24h/24	30.0 kWh
Total	**2000 W**	—	**30.00 kWh**

Table 3. Battery storage systems in a mobile base station.

5. ANALYSIS OF REGULATORY AND LEGAL FRAMEWORK FOR TELECOMMUNICATION NETWORK RESILIENCE IN UKRAINE AND THE EU

5.1 European Union approaches to ensuring energy resilience of telecommunications infrastructure

The European Union has established a holistic, layered approach to enhancing the resilience of telecommunications infrastructure, particularly in the current scenario characterised by growing threats to its safety and resilience from energy uncertainties, climate change and geopolitical disruptions.

A key element of the EU's strategy is integrating resilience into broader digital and energy policies. The European Commission has emphasised the importance of secure and uninterrupted communication networks as part of critical infrastructure protection. Telecommunications networks are formally recognised as critical infrastructure under the European Union framework, which obligates member states to ensure their robustness and continuity.

One of the central policy instruments in this area is the European Electronic Communications Code (EECC), which establishes requirements for the availability and resilience of communication networks. The EECC requires operators to take appropriate measures to ensure the integrity and availability of public communications networks, including preparedness for power outages and other emergencies. This includes implementing backup power systems, redundancy mechanisms, and risk management strategies.

In parallel, the EU has significantly expanded its focus on energy resilience through initiatives such as the "Clean Energy for All Europeans" package and the "European Green Deal." These frameworks encourage the transition toward decentralised and renewable energy systems, which directly impacts the telecommunications sector. Increasingly, mobile network operators are expected to integrate renewable energy sources—particularly solar photovoltaic systems—into their infrastructure to reduce dependency on centralised power grids.

A notable trend across EU member states is the adoption of hybrid energy systems for base stations, combining grid electricity, battery energy storage systems (BESS), and renewable energy sources. These systems enable base stations to remain operational during grid failures while optimising energy efficiency and reducing operational costs. The integration of battery storage is particularly critical, as it enables short- to medium-term autonomy during outages and supports load balancing.

In addition, the EU promotes the development of microgrids and distributed energy resources (DERs), which enhance the resilience of localised infrastructure. Microgrids can operate independently of the main grid in "island mode," ensuring uninterrupted power supply to critical facilities, including telecommunications sites. This approach is especially relevant in rural and remote areas, where grid reliability may be limited.

Regulatory authorities in EU countries also impose specific requirements on telecom operators regarding backup power capacity. In many member states, operators are required to ensure a minimum autonomous operation time for base stations, typically 2 to 24 hours, depending on the site's criticality. This is achieved by deploying batteries, diesel generators, or hybrid systems. However, there is a growing shift away from diesel-based solutions due to environmental concerns and high operational costs.

Environmental sustainability has become a core component of EU telecommunications policy. Operators are increasingly required to reduce carbon emissions and improve energy efficiency. This has led to the adoption of energy management systems (EMS), intelligent monitoring tools, and optimisation algorithms that minimise energy consumption while maintaining network performance. Advanced solutions include AI-based energy optimisation and dynamic load management, which adjust power usage in response to traffic demand.

Another important aspect of the EU approach is resilience planning and risk assessment. Operators are required to conduct regular risk analyses, including scenarios involving large-scale power outages, natural disasters, and cyber-physical threats. These assessments inform the design of contingency plans and emergency response strategies, ensuring rapid recovery and minimal service disruption.

The EU also emphasises cross-sector collaboration, particularly between the energy and telecommunications sectors. This includes coordination between telecom operators, energy providers, and government agencies to ensure priority access to power supply during crises. In some cases, telecommunications infrastructure is granted priority status for energy restoration, reflecting its critical role in emergency response and public safety.

Recent geopolitical developments also strengthen the need for energy resilience — consider the energy crisis caused by supply chain disruptions. This response has prompted a wave of EU investments in renewables, energy storage, and infrastructure modernisation. And by doing so, it indirectly helps the telecom industry by delivering a more stable power supply. The EU is taking a multidimensional perspective to realise regulatory requirements, technological innovation, and strategic policy integration to ensure energy resilience in Telecom infrastructure. The integration of renewable energy sources, battery storage, and sophisticated energy management solutions, along with the deployment of hybrid energy systems, is key to enabling these changes. Together, these measures strengthen the reliable operation of mobile communication networks under energy instability, laying the groundwork for a model applicable to other contexts, including Ukraine.

5.2 Analysis of Ukrainian regulatory requirements for mobile network stability and continuity of services

In Ukraine, it is vital to ensure the stability and continuity of mobile communication networks, especially amid the ongoing military intervention and the large-scale disruption of the energy system.

A blackout isn’t so bad when you have a mobile network. At the same time, following the ongoing shelling of energy infrastructure, the operators’ backup equipment can't be charged in time. As reports of temporary disruptions to mobile network access began pouring in from across Ukraine, the situation reached alarming proportions. At the same time, the Ukrainian government took the necessary steps to respond to the challenges we all faced.

Since 2022, the requirements for mobile base stations and their backup power systems have evolved significantly.

2022–2023: Backup power for base stations was considered more of a technical necessity than a strict regulatory requirement. Typical autonomy ranged from **2 to 4 hours**, with some sites capable of operating for up to 6 hours. Following large-scale attacks on Ukraine’s energy infrastructure, mobile operators began investing heavily in batteries, uninterruptible power supplies (UPS), and diesel generators.

2024: The Ukrainian government substantially increased resilience requirements. The National Center for Operational and Technical Management of Telecommunications Networks (NCTM) required operators to ensure **10 hours of autonomous operation** for base stations, compared to the previous target of 4 hours. The implementation schedule required 60% of base stations to meet the standard by October 2024, 70% by November, 80% by December, and 100% by January 2025.

2024–2025: It became evident that achieving 10 hours of battery-powered operation for all base stations was technically and economically challenging. Significant investments were required in battery capacity, charging infrastructure, generators, fuel supply, and maintenance. Operators widely deployed lithium-ion battery systems and backup generators; however, actual operating times often varied between 2–6 hours depending on network load and site conditions.

2025: The focus shifted from a universal "10-hour battery autonomy" requirement to a more flexible resilience model combining batteries, generators, and prioritization of critical network sites. During this period, Ukraine also introduced regulations simplifying the deployment of low-power base stations (small cells), supporting improvements in network coverage and capacity.

Late 2025–2026: Regulatory approaches became more pragmatic. While some battery autonomy requirements were adjusted, greater emphasis was placed on generator-supported operation and extended resilience of critical telecommunications infrastructure. Certain categories of strategically important base stations were expected to maintain service for up to **72 hours** during prolonged power outages. Local governments and municipal authorities were also authorized to assist operators by providing generator power to maintain communications services.

Overall, since 2022, mobile base stations have evolved from facilities relying on short-duration UPS systems into energy-resilient infrastructure. Modern requirements increasingly emphasize a combination of high-capacity batteries, backup generators, fuel reserves, and operational strategies designed to maintain network availability during extended disruptions to the power grid.

Period	Regulatory Environment	Backup Power Requirement	Technical Measures Implemented	Challenges and Outcomes
2022–2023	No unified nationwide resilience standard; focus on emergency response to wartime energy disruptions.	Typically 2–4 hours of backup operation, occasionally up to 6 hours.	Deployment of UPS systems, lead-acid and lithium batteries, and mobile generators.	Network performance strongly depended on local power availability and equipment condition.

2024	Government and telecom regulator introduced stricter resilience requirements.	Target of 10 hours autonomous operation for base stations.	Large-scale installation of lithium-ion battery systems and fixed backup generators.	Significant capital expenditures required to meet regulatory deadlines.
2024–2025	Progressive implementation of resilience requirements across national operators.	10-hour target remained the benchmark.	Expansion of battery capacity, fuel logistics, remote monitoring, and energy management systems.	Performance varied due to site-specific energy consumption and network traffic.
2025	Transition toward risk-based resilience planning and prioritization of critical infrastructure.	Combination of battery autonomy and generator support rather than battery-only operation.	Deployment of hybrid backup architectures and low-power small-cell infrastructure.	Improved operational flexibility and network sustainability during prolonged outages.
Late 2025–2026	More pragmatic regulatory approach emphasizing service continuity.	Critical telecommunications sites expected to maintain operation for up to 72 hours under emergency conditions.	Integration of batteries, generators, fuel reserves, and local authority support.	Enhanced resilience of telecommunications infrastructure against extended blackouts.

The telecommunications infrastructure in Ukraine is considered a crucial element of national security and public safety. The government has placed increasing emphasis on the need for uninterrupted communication services, particularly during emergencies. Operators are primarily regulated by the State Service of Special Communications and Information Protection of Ukraine and the Ministry of Digital Transformation, which sets requirements for network performance, availability, and resilience.

A core regulatory principle in Ukraine is the obligation for telecommunications operators to ensure service continuity. This obligation encompasses maintaining network availability under adverse conditions, including power outages, physical damage, or increased network load. However, in contrast to the EU, specific technical standards for energy resilience, such as minimum backup power duration, have historically been less formalised.

This context has changed dramatically since the start of the escalating conflict. When energy infrastructure is destroyed, it creates a new vulnerability for mobile networks to power grid disruptions. Ukrainian authorities have responded with a tighter policy on operators to install backup power solutions at base stations. Such measures include the use of battery facilities, diesel generators, and, increasingly, alternative energy sources. Government initiatives have encouraged operators to improve base-station autonomy. In reality, this has meant that large numbers of batteries have been added to extend operating periods during outages. Yet the efficacy of such measures also varies by site location and other factors, including energy use and maintenance capabilities.

The lack of a unified, detailed regulatory framework for energy resilience in telecommunications remains a significant obstacle for Ukraine. Although general requirements for service continuity are in place, there are no standardised procedures for the technical deployment of backup systems. It leads to variation in resilience levels among operators and between regions. At the same time, the Ukrainian Government is working to align the regional regulatory framework with that of Europe. These involve implementing harmonisation to EU standards, and in particular the progressive convergence of telecommunications legislation towards EU directives, particularly vis-à-vis Ukraine's entry into the European digital market. This alignment is expected to yield more clearly defined requirements for network resilience and energy sustainability.

The role of emergency response regulations is also significant. Communications service providers must prioritise restoring service and ensuring the functionality of critical communication channels during a crisis. This requires coordination with energy providers and government agencies to secure access to power supplies. In certain cases, mobile operators receive priority in fuel allocation for generators, emphasising the strategic role of communication networks. Economic constraints constitute a major barrier to the implementation of advanced energy solutions. The deployment of hybrid systems, renewable energy installations, and large-scale battery storage demands substantial investment. Without targeted financial incentives or regulatory mandates, operators may prioritise short-term solutions like diesel generators, despite their long-term inefficiency and environmental impact.

However, there is increasing recognition of the necessity for more sustainable and resilient approaches. In remote or high-risk areas, solar photovoltaic systems and hybrid energy models are gradually being adopted. These solutions have the potential to reduce operational costs, improve reliability, and decrease dependence on fuel logistics, which are vulnerable to disruption during conflict.

From a regulatory perspective, it is evident that a standardised energy resilience framework is required in telecommunications. Recommended actions include establishing minimum standards for backup power duration, providing incentives for renewable energy uptake, and mandating the use of energy management systems. These would benefit network stability and align Ukraine with European best practices.

Also, the use of modelling tools, such as HOMER, for planning and decision-making can help develop optimised energy solutions tailored to specific site conditions. This strategy is especially pertinent in Ukraine, where energy supply conditions vary significantly. As in many other regions, Ukraine's regulatory framework for maintaining mobile network stability and continuity reflects a rapidly evolving landscape responding to ongoing challenges.

Whilst substantial progress has been made on this front, especially in terms of enhanced backup power capabilities, there is no established, standardised, and comprehensive framework for energy resilience. Hybrid and renewable energy solutions will be necessary, supported by clear regulatory guidelines and economic incentives, to modernise Ukraine's telecommunications infrastructure and make it more sustainable and reliable.

From a public policy perspective, I would like to see government measures better aligned with the UN Sustainable Development Goals. In particular, the current focus on equipping mobile communication towers with diesel generators, while providing a temporary solution, has proven insufficient.

Among the risks, the operation of diesel generators during the extreme cold spells that occurred in the winter of 2026 is significantly hampered, and there are not enough repair crews among either mobile operators or contractors.

At the same time, the current technical capabilities of mobile base stations allow for a more flexible, resilient, and environmentally friendly alternative in the form of promoting power generation primarily from renewable sources and its subsequent storage at generation-consumption sites, i.e., directly near mobile base stations, etc.

Given the low power consumption of base stations and the availability of energy storage equipment, it is possible to implement both AC solutions using inverters and DC solutions using solar panels directly connected to energy storage systems. At the same time, while DC solutions are technologically effective, they are organizationally complex, primarily due to the difficulty of accounting for electricity from DC sources. Simply put, it is difficult to distinguish between energy from the grid and energy from solar panels; while formulas exist, they are not ideal for commercial metering.

To complement the regulatory perspective, an expert survey was conducted among representatives of major mobile network operators in Ukraine, including Vodafone Ukraine, Kyivstar, and lifecell. The purpose of the survey was to assess industry views regarding the feasibility, effectiveness, and implementation challenges of photovoltaic energy systems for mobile base stations. The findings provide valuable insights into the practical considerations associated with improving the energy resilience of telecommunications infrastructure.

The survey results indicate that ensuring uninterrupted power supply has become one of the most significant operational challenges faced by mobile network operators since 2022. Respondents identified prolonged power outages, increasing energy costs, fuel supply logistics, and the growing energy consumption of telecommunications equipment as key factors affecting network reliability. Maintaining continuous operation of thousands of geographically dispersed base stations requires substantial investments in backup power infrastructure and ongoing operational support.

A common observation among all respondents was that the approach to backup power systems has changed significantly since 2022. Prior to the energy crisis, backup systems were primarily designed to support short-term interruptions lasting several hours. However, the increased frequency and duration of power outages necessitated a shift toward more robust energy resilience strategies. Operators reported large-scale deployment of lithium-ion battery systems, expansion of generator fleets, implementation of remote monitoring technologies, and the development of contingency plans aimed at maintaining network availability during extended disruptions.

Regarding the adoption of photovoltaic technologies, respondents generally viewed solar energy systems as a promising long-term solution for improving the resilience of mobile telecommunications infrastructure. Photovoltaic systems were recognized for their ability to reduce dependence on the electrical grid, lower operational costs, and provide an additional layer of energy security. Industry representatives emphasized that solar energy is particularly attractive for rural and remote base station locations where grid reliability is limited and fuel logistics can be challenging.

The survey revealed that investment decisions concerning renewable energy technologies are influenced by several interconnected factors. Economic considerations remain the primary determinant, with respondents highlighting capital investment requirements, expected return on investment, lifecycle costs, and maintenance expenses. Reliability was identified as an equally important factor, as telecommunications operators must ensure uninterrupted service regardless of weather conditions or seasonal variations in solar generation. Regulatory requirements and future resilience standards were also cited as important drivers encouraging investment in alternative energy systems.

Despite the positive perception of photovoltaic solutions, respondents identified several technical and operational challenges associated with implementation. One frequently mentioned issue is the limited physical space available at many base station sites, particularly in urban environments. Additional concerns include battery storage sizing, equipment security, maintenance requirements, and variability in solar energy production throughout the year. Operators also noted that the integration of renewable energy systems into existing telecommunications infrastructure requires careful engineering design and advanced energy management solutions.

When asked about measures that could accelerate the adoption of renewable energy technologies within the telecommunications sector, respondents emphasized the importance of supportive government policies and financial incentives. Recommended measures included tax benefits for renewable energy investments, preferential financing programs, simplified permitting procedures, and public support for pilot projects demonstrating the effectiveness of photovoltaic-powered telecommunications infrastructure. Industry representatives also highlighted the need for clearer technical guidelines and best-practice frameworks to support large-scale deployment.

Overall, the survey findings demonstrate strong industry interest in renewable energy solutions, particularly photovoltaic systems combined with battery storage. While operators acknowledge the technical and financial challenges associated with implementation, they generally view solar energy as an effective tool for improving network resilience, reducing long-term operating costs, and supporting sustainability objectives.

5.3 Comparison of Diesel Generators and Renewable Energy-Based Backup Systems

A key consideration in improving the energy resilience of mobile telecommunications infrastructure is the selection of an appropriate backup power solution. Traditionally, diesel generators have been the primary technology used to maintain the operation of mobile base stations during power outages. However, recent advances in renewable energy technologies, particularly photovoltaic (PV) systems combined with battery storage, have created a viable alternative that offers both economic and operational advantages.

From an investment perspective, the total capital expenditure required for a photovoltaic system with battery storage can be comparable to that of a high-capacity diesel generator installation. While the renewable energy solution requires the purchase of solar panels, batteries, inverters, and associated equipment, diesel-based systems also involve significant costs related to generator acquisition, installation, fuel storage infrastructure, and safety requirements.

The primary advantage of photovoltaic systems lies in their substantially lower operating and maintenance costs. Unlike diesel generators, solar panels do not consume fuel and contain no moving mechanical components that require frequent servicing. Once installed, photovoltaic modules can operate for more than 25 years with minimal maintenance, while battery systems typically require replacement only after several years of operation depending on usage conditions.

In contrast, diesel generators require continuous fuel supply, periodic maintenance, oil changes, filter replacements, and regular testing to ensure operational readiness. During extended power outages, fuel consumption becomes a significant operational expense. Furthermore, logistical challenges associated with fuel delivery may reduce the effectiveness of generator-based backup systems, particularly in remote locations or during emergency situations.

Photovoltaic systems combined with battery storage also provide environmental benefits by reducing greenhouse gas emissions and minimizing dependence on fossil fuels. The ability to generate electricity directly on-site increases energy independence and enhances the resilience of telecommunications infrastructure against disruptions in fuel supply chains.

Another important advantage is the scalability of renewable energy systems. Additional photovoltaic modules and battery capacity can be integrated into existing installations as energy demand increases. This modular approach allows telecommunications operators to expand system capacity gradually without replacing the entire infrastructure.

Consequently, while diesel generators remain an effective short-term emergency power solution, photovoltaic systems with battery storage represent a more sustainable and economically attractive long-term strategy. Given that the overall investment cost can be comparable to that of generator-based solutions, but operational and maintenance expenses are significantly lower, renewable energy systems offer a superior balance between reliability, cost efficiency, and environmental sustainability for modern mobile telecommunications networks.

6. DEVELOPMENT OF AN ENERGY-SUSTAINABLE MODEL FOR BASE STATIONS IN UKRAINE

6.1 Modelling of alternative energy supply systems (PV, battery storage, hybrid systems) using HOMER software

To evaluate the feasibility of renewable energy solutions for powering mobile telecommunication base stations, a simulation-based approach was employed using the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software developed by the National Renewable Energy Laboratory (NREL). HOMER is widely used for the design, optimization, and economic assessment of hybrid energy systems integrating renewable energy sources, battery storage technologies, conventional generators, and grid connections.

The software enables the simulation of multiple system configurations under varying technical and economic conditions. In this study, HOMER was used to model and compare three alternative energy supply scenarios for mobile base stations: a photovoltaic (PV) system with battery storage, a battery-supported grid-connected system, and a hybrid system combining photovoltaic generation, battery storage, and backup generation. The objective was to determine the most reliable and cost-effective solution capable of maintaining uninterrupted operation during grid outages while reducing dependence on conventional energy sources.

The modelling process began with the definition of the electrical load profile representing the energy consumption of a typical mobile base station. The load demand was assumed to remain relatively stable throughout the day, reflecting the continuous operation of telecommunications equipment, cooling systems, and auxiliary devices. Seasonal variations and network traffic fluctuations were incorporated where applicable.

Solar resource data were obtained from meteorological databases integrated within HOMER. The photovoltaic subsystem was characterized by installed capacity, module efficiency, derating factors, and expected lifetime. Battery storage systems were modelled using parameters such as nominal capacity, depth of discharge, round-trip efficiency, replacement cost, and operational lifetime. For hybrid configurations, a backup generator was included to provide additional reliability during extended periods of low solar irradiation or prolonged power outages.

HOMER performed hourly simulations over an annual operating period, calculating energy production, storage utilization, unmet load, excess electricity generation, and system reliability indicators. Furthermore, the software evaluated the economic performance of each configuration using metrics such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), operating costs, fuel consumption, and payback period.

The optimization algorithm embedded in HOMER generated multiple feasible system architectures and ranked them according to predefined technical and economic criteria. Particular attention was given to system reliability, renewable energy penetration, battery autonomy, and lifecycle costs. These indicators provide a comprehensive basis for assessing the suitability of alternative energy supply systems for mobile telecommunications infrastructure operating under increasingly stringent resilience requirements.

The results of the simulations are presented in the following sections, where the technical performance and economic viability of each system configuration are compared and discussed.

6.2 Techno-economic analysis and comparison of modelled scenarios

The techno-economic analysis was conducted to evaluate the performance, reliability, and economic viability of the alternative power supply configurations modelled in HOMER Pro. The assessment focused on three scenarios: a conventional grid-supported system with battery backup, a photovoltaic (PV) system integrated with battery storage, and a hybrid PV-battery-generator configuration. Particular attention was given to the role of solar photovoltaic technology as a sustainable solution for improving the resilience of mobile telecommunications infrastructure.

From a technical perspective, the photovoltaic-based scenarios demonstrated a significant ability to reduce dependence on the electrical grid while maintaining continuous operation of the base station. During periods of normal solar irradiation, the PV system supplied a substantial portion of the energy demand, reducing both grid electricity consumption and battery cycling frequency. As a result, the operational lifetime of battery storage systems can be extended, contributing to lower long-term replacement costs.

The simulation results indicate that the PV-battery configuration achieved a high level of renewable energy penetration while maintaining acceptable reliability indicators. However, system performance remained dependent on local solar resources and seasonal variations. During periods of reduced solar generation, stored energy in the battery system ensured continuity of operation, although extended outages could require supplementary energy sources.

The hybrid PV-battery-generator scenario provided the highest level of reliability among the modelled alternatives. The addition of a backup generator effectively eliminated unmet load and ensured uninterrupted operation during prolonged periods of low solar production or extended grid failures. Nevertheless, this increased reliability was associated with higher capital investment, fuel consumption, maintenance requirements, and greenhouse gas emissions compared with purely renewable configurations.

From an economic perspective, photovoltaic technology offers substantial long-term benefits despite requiring higher initial investment. The installation of solar panels represents the largest share of the capital expenditure in renewable energy systems; however, the absence of fuel costs and the reduction in electricity purchases contribute to significant operational savings over the project lifetime. As electricity prices continue to increase and energy security becomes a critical concern, the economic attractiveness of PV-based solutions improves further.

The Net Present Cost (NPC) analysis revealed that systems incorporating photovoltaic generation generally achieved lower lifecycle costs than solutions relying primarily on conventional energy sources. Similarly, the Levelized Cost of Energy (LCOE) was reduced through the utilization of solar energy, particularly in regions with high annual solar irradiation. The economic benefits become even more pronounced when considering the rising costs associated with diesel fuel, generator maintenance, and grid instability.

In addition to economic advantages, photovoltaic systems provide important environmental benefits. By replacing a portion of grid electricity and diesel-generated energy with renewable generation, carbon dioxide emissions can be significantly reduced. This contributes to both corporate sustainability objectives and broader environmental policies promoting decarbonization of critical infrastructure sectors.

The comparative analysis suggests that photovoltaic-based energy systems represent the most promising solution for enhancing the resilience and sustainability of mobile telecommunications networks. While battery storage remains essential for ensuring uninterrupted operation during non-generating periods, solar photovoltaic generation substantially reduces operating costs and dependence on external energy supplies. Consequently, the PV-battery configuration emerges as a highly attractive option for mobile base stations located in regions with sufficient solar resources, whereas hybrid PV-battery-generator systems may be preferred where maximum reliability is required under extreme operating conditions.

Overall, the results demonstrate that integrating solar photovoltaic technology into the power supply architecture of mobile base stations can provide an effective balance between economic efficiency, operational reliability, and environmental sustainability. These findings support the growing adoption of renewable energy systems within the telecommunications sector as operators seek to improve network resilience and reduce lifecycle energy costs.

6.3 Selection of the most scalable and cost-effective solution

Based on the results of the techno-economic assessment, the photovoltaic (PV) system combined with battery storage was identified as the most scalable and cost-effective solution for powering mobile telecommunication base stations. This configuration provides a balance between operational reliability, economic efficiency, and long-term sustainability while minimizing dependence on conventional energy sources.

The analysed mobile base station consumes approximately 72 kWh of electricity per day. To satisfy this demand while maintaining sufficient reserve capacity during periods of reduced solar irradiation, a photovoltaic array with a minimum installed capacity of 15 kW was selected. Such a system is capable of generating the required energy under typical solar conditions while simultaneously charging the battery storage system for nighttime operation and emergency backup.

The proposed design utilizes photovoltaic modules with a rated capacity of 670 W each. To achieve the target installed capacity of 15 kW, approximately 23 solar panels are required:

$$15\ \text{kW} \div 0.67\ \text{kW} \approx 22.4\ \text{panels}$$

Therefore, a practical configuration consists of 23 photovoltaic modules with a total installed capacity of approximately 15.41 kW.

Assuming a market price of USD 100 per 670 W solar panel, the total investment in photovoltaic modules is estimated at:

23 × USD 100 = USD 2,300

Although additional expenditures are required for battery storage systems, inverters, charge controllers, structural supports, installation, and maintenance, the photovoltaic subsystem remains the primary contributor to long-term operating cost reductions. Unlike diesel generator solutions, solar energy systems do not require fuel purchases and have relatively low maintenance requirements throughout their operational lifetime.

From a scalability perspective, the PV-battery configuration offers significant advantages. Additional photovoltaic modules can be installed as network traffic and energy consumption increase, allowing operators to expand system capacity without substantial modifications to the existing infrastructure. This modular architecture is particularly valuable for telecommunications operators managing large numbers of geographically distributed base stations.

Compared with generator-based backup systems, photovoltaic installations provide lower lifecycle costs and reduced exposure to fuel price fluctuations. Furthermore, solar-powered systems contribute to environmental sustainability by decreasing greenhouse gas emissions and reducing reliance on fossil-fuel-based electricity generation.

The analysis indicates that a 15 kW photovoltaic system integrated with battery storage provides the most favourable balance between investment cost, energy production, operational reliability, and future scalability. Consequently, this solution is recommended as the preferred energy supply architecture for mobile base stations operating in regions with adequate solar resources and increasing requirements for network resilience.

6.4 Implementation roadmap and practical recommendations

The successful deployment of photovoltaic-based energy systems for mobile telecommunication base stations requires a structured implementation strategy that addresses technical, economic, and operational factors. Based on the results of the modelling and techno-economic analysis, a phased implementation roadmap is proposed to facilitate the transition from conventional power supply systems to renewable energy-supported infrastructure.

Phase 1: Infrastructure Assessment and Site Selection

The first stage involves the evaluation of existing base station infrastructure and the identification of suitable deployment locations. Key assessment criteria include average daily energy consumption, frequency of grid outages, available installation area, solar irradiation levels, and accessibility for maintenance activities. Priority should be given to base stations located in regions experiencing frequent power interruptions or high electricity costs, as these sites offer the greatest potential economic and operational benefits.

A detailed energy audit should be conducted to verify the average daily consumption of approximately 72 kWh and to identify opportunities for improving energy efficiency before renewable energy integration.

Phase 2: System Design and Technical Planning

Following site selection, the technical design of the photovoltaic energy system should be completed. Based on the analysis conducted in this study, a photovoltaic array with a minimum installed capacity of 15 kW is recommended. This configuration consists of approximately 23 photovoltaic modules rated at 670 W each, providing a total installed capacity of approximately 15.4 kW.

The system design should also include appropriately sized battery storage to ensure uninterrupted operation during nighttime hours and grid outages. Additional components such as hybrid inverters, charge controllers, monitoring systems, and protection equipment must be integrated into the overall system architecture.

Phase 3: Pilot Deployment

Before large-scale implementation, a pilot project should be conducted at a limited number of representative base station sites. The objective of the pilot phase is to validate the assumptions used in the HOMER simulations, evaluate actual energy generation performance, and identify potential operational challenges.

Performance indicators should include:

- Renewable energy contribution (%);
- Battery autonomy duration;
- Reduction in grid electricity consumption;
- System reliability during outages;
- Operating and maintenance costs.

The pilot phase should operate for a minimum of six to twelve months to capture seasonal variations in solar energy production.

Phase 4: Large-Scale Rollout

Following successful pilot validation, the photovoltaic solution can be gradually deployed across the operator's network. A phased rollout approach allows investment costs to be distributed over multiple budget cycles while enabling continuous optimization based on operational experience.

Priority should be assigned to strategically important base stations, rural sites with limited grid reliability, and locations where diesel generator operation currently results in significant fuel expenditures.

The modular nature of photovoltaic systems allows capacity expansion without major modifications to the existing infrastructure, making the solution highly scalable for nationwide implementation.

Phase 5: Monitoring and Continuous Optimization

Long-term success depends on continuous monitoring and performance management. Advanced monitoring platforms should be used to track solar energy generation, battery state of charge, system efficiency, and maintenance requirements in real time.

Collected operational data can support predictive maintenance strategies and facilitate future optimization of system sizing, battery capacity, and energy management algorithms.

Practical Recommendations:

Based on the findings of this research, the following recommendations are proposed for mobile network operators and policymakers:

1. Prioritize the deployment of photovoltaic systems at base stations located in regions with high solar potential and frequent power outages.
2. Adopt a minimum photovoltaic capacity of 15 kW for base stations with an average daily consumption of approximately 72 kWh.
3. Integrate battery storage systems to ensure continuous operation during nighttime periods and emergency grid failures.
4. Reduce reliance on diesel generators by utilizing renewable energy as the primary backup power source wherever technically feasible.
5. Implement centralized monitoring platforms to improve operational visibility and optimize maintenance activities.

6. Encourage governmental support mechanisms, including tax incentives, grants, and green financing programs, to accelerate the adoption of renewable energy technologies in the telecommunications sector.
7. Incorporate renewable energy solutions into long-term network resilience strategies to comply with evolving regulatory requirements and sustainability objectives.

The implementation of photovoltaic-powered base stations offers a practical pathway toward enhancing energy resilience, reducing operating costs, and improving the environmental sustainability of telecommunications infrastructure. The proposed roadmap provides a scalable framework that can support both individual pilot projects and nationwide deployment programs.

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9. APPENDIX

Appendix A. Questionnaire for Representatives of the Ministry of Digital Transformation of Ukraine

Purpose: To identify regulatory priorities and challenges related to improving the energy resilience of mobile telecommunications infrastructure.

1. In your opinion, what are the main challenges affecting the energy resilience of mobile telecommunications networks in Ukraine?
2. How do current regulatory requirements address backup power and energy security for mobile base stations?
3. What role can renewable energy sources, particularly photovoltaic systems, play in strengthening telecommunications infrastructure resilience?
4. Are there any existing or planned government initiatives aimed at encouraging the deployment of renewable energy systems at telecommunications facilities?
5. What barriers (regulatory, financial, technical, or organizational) currently limit the wider adoption of renewable energy solutions by mobile network operators?
6. What policy measures would you recommend to accelerate the implementation of renewable energy technologies in the telecommunications sector?

Appendix B. Questionnaire for Representatives of Mobile Network Operators (Vodafone Ukraine, Kyivstar, lifecell)

Purpose: To assess industry perspectives on the feasibility and effectiveness of photovoltaic energy systems for mobile base stations.

1. What are the primary challenges your company faces in ensuring uninterrupted power supply to mobile base stations?
2. How has your company's approach to backup power systems changed since 2022?

3. To what extent do you consider photovoltaic systems a viable solution for improving the resilience of mobile base stations?
4. What are the most important factors influencing investment decisions regarding renewable energy technologies (e.g., cost, reliability, regulatory requirements, return on investment)?
5. What technical or operational challenges do you anticipate when deploying photovoltaic systems and battery storage at base station sites?
6. In your opinion, what measures could facilitate wider adoption of renewable energy solutions within the telecommunications industry?