Network Resilience and Sustainability: Renewable Energy-based Solutions

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***Abstract*—With the increase in popularity of mobile services, Radio Access Network (RAN) sustainability and resilience to power outages are becoming primary challenges. This article proposes to use power supply solutions based on Renewable Energy Sources (RESs) to jointly increase RANs' resilience and sustainability. We provide an overview of common RAN sustainability practices and present recent data on the increase in communication network failures. We discuss the concept of resilience in RANs, alongside the strategies and challenges of using RESs for power supply. Although RESs integration with RANs has been extensively studied in the literature for sustainability, the operational aspects before, during, and after emergencies remain unexplored. This paper addresses this gap by evaluating the impact of RESs on the RAN sustainability and resilience through the use of real data from Base Station (BS) traffic load, grid power outages, and photovoltaic (PV) power production. Our findings show that integrating small PV panel capacities significantly reduces the carbon footprint of RANs, and it is crucial to maintain network operations during outages, especially during daylight hours when PV production is at its peak.**

***Index Terms*—Renewable Energy, Sustainability, Resilience, Radio Access Network.**

I. Introduction

The Information and Communication Technology (ICT) sector has become a vital part of modern societies. The service demand is growing extremely fast because of the ever-increasing popularity of communication services, the provisioning of new ones, and the pervasive digitalization of other sectors. In this context, two main challenges have emerged and need to be urgently tackled: sustainability and resilience.

Sustainability in the ICT sector is vital, focusing on reducing the environmental footprint through energy efficiency, the use of renewable energy, and the minimization of carbon emissions and electronic waste. Currently, the ICT industry accounts for approximately 2-4% of global CO_2 emissions, and it also accounts for 7-9% of the global electricity consumption, predicted to increase to 13% by 2030 [1]. Within mobile networks, the Radio Access Network (RAN) is the largest energy consumer, responsible for 50-80% of total energy use. To address these challenges, the European Commission has set ambitious targets under the European Green Deal and the Code of Conduct to promote sustainable practices.

Continuity and reliability must also be guaranteed out of the normal operation conditions. This means that the communication infrastructure, in addition to (i) *reliable*, i.e., dependable, performing consistently well, must be (ii) *robust*, i.e., able to sustain full operation without system failures in case of possible challenges, and (iii) *resilient*, i.e., capable of adapting to external changes that may modify the behavior of the system and recover rapidly after an operation interruption.

A fundamental aspect is the power supply, which traditionally relies on the power grid and can present continuity problems. Providing a continuous, high-quality power supply is increasingly challenging for several reasons. Rapid urbanization and population growth place a strain on power grids, leading to frequent outages and diminished quality. Additionally, global economic and political instability, coupled with the transition from fossil fuels, underscores the need for self-sustaining power solutions. The climate crisis further exacerbates this issue by increasing the frequency of natural disasters that disrupt power grids. Moreover, the shift to smart grids with digital systems has heightened vulnerability to cyberattacks. To address these challenges, developing resilient and sustainable communication networks powered by Renewable Energy Sources (RESs) and reducing dependence on unreliable power grids is crucial for maintaining stability in this evolving scenario.

To address sustainability in RANs, there is a growing need to generate energy locally using RESs while interacting with the electrical grid. This work integrates RESs with the dual objectives of mitigating the climate impact of expanding communication infrastructures and enhancing resilience against power supply instabilities caused by cyberattacks, natural disasters, or operational issues. As telecommunication networks become increasingly integral to society, ensuring the resilience and sustainability of RANs is essential. To the best of the authors' knowledge, this is the first study to integrate RESs specifically to enhance both sustainability and resilience in RAN. The approach leverages RESs used for sustainability to also achieve resilience, eliminating the need for dedicated backup energy storage systems, such as batteries, thus avoiding both installation and maintenance costs. Consequently, this dual use of RESs reduces both capital and ongoing maintenance expenses. Furthermore, this study addresses the operational aspects of RESs in RANs management before, during, and after emergencies, an area that, despite extensive research, remains inadequately explored.

We provide an overview of common RAN sustainability practices and present recent data on the increase in communication network failures. We explore the concepts of robustness and resilience in RAN, alongside the strategies and challenges of using RESs for power supply, assessing their impact on RAN sustainability and resilience. Our study offers empirical insights into RESs sizing, with sustainability evaluated by carbon emissions and resilience measured by lost traffic and the average time a BS remains active during power grid interruptions. Data-driven simulations highlight the potential of RESs for enhancing RAN sustainability and resilience. This article is the first to provide insights into resilience and sustainability using real data on BS traffic load, grid power faults, and PV power production. Our goal is to raise awareness and encourage the careful adoption of RESs solutions to avoid compromising operational reliability during emergencies, such as grid power outages.

II. Review on Radio Access Network Sustainability

The recent works towards future communication networks have the objectives of RAN efficiency and sustainability. Various techniques have been investigated, such as Sleep Mode, Cell Zooming, the integration of RESs and Coordinated Multi-Point (CoMP). Sleep Mode allows BSs to gradually deactivate components during periods of low traffic, reducing energy demand [2]. Cell Zooming adapts the transmission power to decrease cell coverage in lightly loaded cells, thereby reducing the overall energy demand [3].

The integration of energy locally produced by RESs, such as PV panels and battery storage systems, contributes to CO_2 reduction and enables BSs to become *prosumers* capable of producing renewable energy and self-sustainable [2], [4].

Another approach to enhance RAN energy efficiency is through Coordinated Multi-Point (CoMP), which dynamically coordinates transmission/reception at multiple geographically separated sites, improving system performance and end-user Quality of Service (QoS) [5].

Moreover, deploying energy-efficient telecommunication equipment is crucial in limiting RAN energy demand. For example, the transition from 3G to 4G brought a significant reduction in peak power consumption, passing from approximately 3.5 kW to less than 1 kW [2]. Lastly, optimizing cooling systems and introducing advanced cooling solutions address the substantial portion of energy consumption attributed to cooling, which can account for more than 17% of the total BS energy demand [5].

III. Communication Network Failures

ENISA (European Union Agency for Cybersecurity), in [6], identifies four root causes of communication network failures: system failures, human errors, malicious activity, and natural phenomena.

System failures occur when the number of requests exceeds the normal capacity, such as during overcrowded events or emergencies. These failures can propagate from low levels to higher ones, affecting the overall network, including the RAN. For instance, while submarine cable cuts are common and typically unnoticed, significant events like the Taiwan earthquake and Mediterranean cable cuts have caused major service outages, impacting RAN availability indirectly.

Malicious attacks can occur due to terrorism, political reasons, or competitive business interests. These attacks can destroy or damage critical components in the network infrastructure to disrupt services or cause collateral damage. For instance, on the 11^{th} September 2001, the attack on the Twin Towers in New York City also damaged the network infrastructure, affecting both core networks and RAN [7]. Natural phenomena can cause failures over large areas due to hardware devastation, making remediation actions almost impossible. For example, after Hurricane Katrina, the main causes of power outages in a BS were flooding, security issues, and reduced fuel supply [7].

According to ENISA's online reporting tool, [6], system failures were responsible for 78% of incidents in 2012 and for more than 61% in 2023. Interruptions due to malicious actions have increased from 5% in 2019 to 14% in 2023. Between 2013 and 2017, the interruptions caused by natural phenomena increased from 14% to 17% of the total interruptions. However, in 2023, it has been attributed to only 7% of the total interruptions. Human errors have caused at least 18% of the total incidents from 2017 up to 2023, except for 2022, which reduced up to 13%.

Power interruptions are a major cause of incidents in telecommunication networks, significantly impacting RAN stability. In 2017, power cuts accounted for 22% of all incidents, with a similar figure in 2019 at 21%. Notably, at least 61% of these incidents in 2017 were attributed to natural phenomena. These power outages had a substantial impact on critical RAN assets: in the same year, 29% of power-related incidents affected BSs, and 16% impacted network nodes. As BSs and nodes are essential RAN components, these disruptions directly compromised the RAN's ability to maintain stable connectivity and ensure uninterrupted service for users [6]. These data underscore the need to enhance the resilience of BS power supplies. One potential solution is adopting green, ad hoc systems that interact with the main power grid and act as reliable, sustainable power sources during grid outages.

IV. Review on RAN robustness and resilience

A well-designed system should maintain or recover its performance and operation despite the challenges and disruptions it may face. Specifically, two desirable features can be identified: *robustness* and *resilience*.

As anticipated above, robustness is the ability of the system to maintain its performance and operations despite various challenges; resilience refers to the ability to adjust to external changes, possibly altering system behaviors and quickly restoring following a disruption in operations. In communication networks, these characteristics are crucial because of the increasing dependence on reliable connectivity.

Robustness extends beyond mere reliability, as it requires performance under both normal and challenging conditions. Resilience, on the other hand, encompasses the ability to recover and adjust following unexpected events that violate initial design assumptions. According to [8], robustness and resilience are evaluated through features such as *anticipation*, *absorption*, *adaptation*, and *rapid recovery*. Anticipation involves forecasting potential adverse events and assessing the components prone to failure, while absorption aims to mitigate the impact of hazards. Adaptation uses available resources to improve system operation during disruptions, and rapid recovery focuses on restoring normal operations promptly. These elements contribute to the robustness and resilience of the network. Further evolution in evaluating resilience includes two additional phases. First, the *resilience by design phase*, which includes the planning and building of a resilient system based on the insights from past failures of similar systems. Second, the *posterior analysis phase* investigates failures to improve the system accordingly.

The authors in [9] introduce a different definition of resilience from the one given above. According to their perspective, it does not include the ability to adapt the system behavior or to restore normal operation after potential interruptions due to unexpected events. Instead, it primarily encompasses the implementation of measures and protocols to guarantee network reliability, availability, and robustness. To cope with these three communication network aspects, operators usually leverage hardware redundancy and diversity to minimize the single points of failure. The network must be designed to be scalable to avoid network overloads generated by possible future growth in traffic demand. In addition, traffic rerouting and failed components restoring address the detection, recovery, and avoidance of faults, and load balancing and interference management prevent congestion, while security measures are needed to prevent and detect malicious attacks. Usually, a device in the network infrastructure is equipped with an energy battery backup system used as an alternative power supply during temporary electrical grid interruptions to avoid out-of-service network [7]. However, to properly design this system, battery location and lifetime analysis are necessary to minimize communication service interruptions. These backup batteries are designed to sustain operations for 2 to 4 hours during a power outage and are recharged only when grid power is available [7]. However, as the frequency and duration of grid outages continue to rise, leveraging RES installed for network sustainability could significantly enhance backup capabilities. On one hand, Energy Storage Systems (ESSs) can be recharged even during grid failures; on the other, RES can provide a continuous power supply to BSs, thereby extending operational hours during outages. Additionally, due to the large number of BSs, especially with the recent increase from BS densification, relying on backup batteries for power in RAN BSs leads to high capital and maintenance costs. However, using RES to mitigate outages reduces the need for batteries, potentially lowering both installation and maintenance expenses.

If properly designed, RESs makes the network less power grid-dependent, preventing the cascade effects of power grid outages [10]. The approach used in its design is similar to that used for BSs located in remote areas, where the connection to the power grid is not feasible or cost-effective. Their supply system is typically hybrid, including solar, wind, and hydrogen energy sources, and with some energy storage.

Besides RESs employment, infrastructure virtualization has emerged with the new generation of networks. It allows (i) dynamically migrating network functionalities, which is fundamental for network recovery and fault isolation, and (ii) the creation of virtual access points on mobile devices to provide multi-hop radio access to users in case the RAN is not accessible. Furthermore, mounting BS hardware on Unmanned Aerial Vehicles or High Altitude Platform Stations, turned out to be a promising solution to bring communication capacity where the terrestrial RAN fails [11]. However, the challenges of backhaul network implementation and scarcity of on-board energy availability must be addressed.

V. Energy Resilience for RAN

Telecommunication networks face significant energy resilience challenges, particularly concerning power outages due to the connection to the electric grid. Various threats can jeopardize the regular operation of the power system. Natural disasters require lengthy recovery times that range from 1 to 4 days for earthquakes and last up to 3 weeks for outages due to floods [7]. System failures like operational faults, equipment failures, and poor maintenance can cause short outages ranging from 1 to 200 minutes [10].

The power system resilience can be improved using RESs, usually located near the load. Distributed RES (DES) are small-scale power generators comprising photovoltaic generators, wind energy generators, fuel cells, and batteries. In 2022, 167 GW from distributed PVs were added globally, out of which 50 GW were for residential purposes [12]. The advantages of using DES for the BSs of the RAN include the use of more affordable energy and the reduction of the electricity drained from the grid, which could come from a source based on fossil fuels.

DESs can also help to supply RAN BSs to reduce the impact of threats in the power system. For instance, floods and extreme temperatures are expected to increase in the next years, affecting the power system resilience. Therefore, installing DES has become popular, in combination with microgrids that can operate off-grid and provide an uninterrupted electricity supply. Moreover, the electrical grid could use DES to restore the power supply in the event of a fault in remote areas [13]. However, providing resilience in hazardous situations could mean oversizing DES. Thus, a compromise between cost and resilience should encompass an improved telecommunication network and the power system.

The growth of DES in the power system imposes the challenge of matching the demand with the power generation, which is variable and weather dependent. Therefore, flexible energy and load management are necessary. A smart local load management considering these energy variations helps improve the power system resilience when a hazard occurs.

The control of these DESs is commonly developed by Virtual Power Plant (VPP)s that operate the DES according to the constraints of the Power Transmission System Operator (PTSO) and comply with the user's needs (Fig. 1). A VPP relies on advanced software and control systems to coordinate

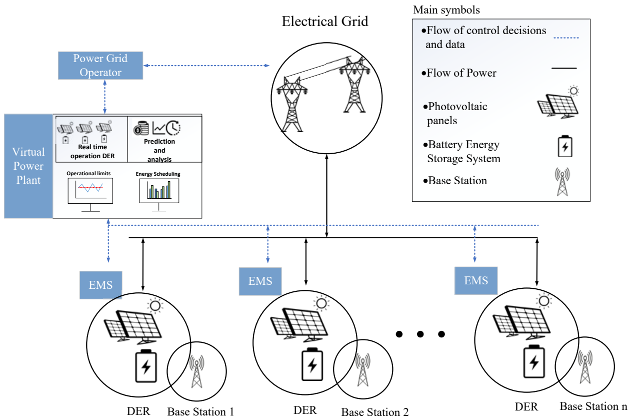

Fig. 1: An example of a VPP architecture considering the interaction with every DES and BS and their individual Energy Management System.

TABLE I: Simulation configuration.

Parameter	Value
Technology	5G
Operating Frequency	2 100 MHz
Bandwidth per BS	120 MHz
PV Panel Capacity	0 - 20 kW (in steps of 2 kW)
PV Module Efficiency	19%
Grid Outage Duration	Minimum: 1 min Maximum: 564 min Average: 46 min
Traffic Bitrate per BS	Minimum: 0.8 kb/s; Maximum: 110 Mb/s
Time step duration	1 min

and manage energy generation and load. It can also manage various microgrids installed on every BS. These VPPs and energy-efficient techniques in the RAN can be an excellent solution to improve resilience in dense urban areas during a power grid blackout [14].

VI. Evaluation of RESs for RAN Resilience and Sustainability

In this section, we quantify the impact of RESs on the RAN sustainability and resilience. The simulations are performed using HPC@POLITO, a High Performance Platform, composed of 29 computational nodes, each equipped with 24 Intel XEON v3 cores and 128 GB of RAM, interconnected by an InfiniBand QDR and an Ethernet networks.

In this work, we consider a portion of a RAN, composed of more than 1 400 5G macro BSs, operating for one year, that operates at 2 100 MHz, using 120 MHz bandwidth. Their energy consumption is modeled as in [3], which states that when idle, a BS consumes 62% of the energy required when fully loaded. We assume that each BS uses the power provided by a PV panel system. Additionally, a connection to the power grid is available, through which the needed energy can be purchased to survive periods of insufficient RESs production to power the BSs. Table I summarizes the simulation set up.

Considering this scenario, the sustainability is assessed under a business-as-usual (BAU) situation; the resilience is instead evaluated during power grid outages, which are considered emergency events in this study. When a power grid outage occurs, a BS cannot drain electricity from the grid, but can use only the energy produced by the PV panel. If that amount of energy is insufficient for the BS supply, the BS shuts down, and the service it provides is interrupted.

Input Data: We use traffic data confidentially provided by a large Italian Mobile Network Operator (MNO). The data report the hourly traffic load of more than 1 400 BSs in Milan, Italy, and a wide area around it for two months. The BSs in the dataset collectively represent heterogeneous zones that coexist in an urban environment, including touristic, business, residential, suburban, and rural areas. The traffic demand ranges from a minimum of 0.8 kb/s to a maximum of 110 Mb/s. Further details of the dataset (traffic characteristics and the covered areas) can be found in [2]. For the evaluation, we associate each BS traffic trace in the dataset with a BS of our scenario and use the typical daily traffic pattern for each BS as described in [10]. We compute the traffic demand for a typical day at each BS using a minute-level granularity, which we consider a suitable trade-off between computational time and the level of detail that this granularity allows us to achieve. We report an example of traffic demand in the following.

Similarly, the data for PV panel production in Milan are taken from the PVWATT tool. The data it provides are derived based on realistic solar irradiation patterns, corresponding to a typical meteorological year for the selected area. The PV system we consider is a fixed rooftop PV array, featuring a module efficiency of 19%, system losses of 14%, a tilt angle of 30°, and an azimuth of 120°. The data accounts for losses due to power conversion, with the DC-to-AC ratio and the efficiency of the electronic components equal to 1.2 and 96%, respectively. These data report the hourly PV panel electricity production in Milan (Italy) over a year, and we process them to obtain a one-minute-level granularity.

The power grid outage data are real power outages in Turin, Italy, between 2014 and 2018, collected using an API confidentially provided by an Italian Distribution System Operator. They account for more than 3 300 events (at low voltage distribution level), with the majority occurring between May and August and peaking in June. Outages tend to happen most frequently around 4:00 a.m. and 1:00 p.m. Additionally, outage durations range from 1 to 564 minutes, with half lasting less than 40 minutes. An exponential distribution provides a good approximation of the fault duration. For further details, see [10]. For the study, we consider that all the BS were affected at the same time by the outage.

Key Performance Indicators (KPIs): To evaluate the impact of PV panel integration on both sustainability and resilience, we selected specific KPIs that capture environmental benefits and network resilience during outages. In this study, the KPI for sustainability is:

- *CO_2 emissions intensity* (gCO_2/Wh) – This metric quantifies the environmental impact of each BS by measuring the mass of CO_2 emitted per watt-hour of energy consumed. We use technology-specific reference values, with grid energy contributing 0.26 gCO_2/Wh and PV-generated energy contributing 0.00 gCO_2/Wh, as reported in [15]. This KPI demonstrates the emissions reduction potential of PV integration.

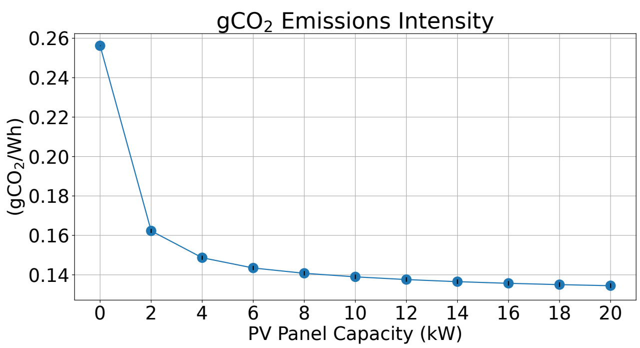

Fig. 2: Average yearly CO_2 emission intensity, in gCO_2/Wh, varying the PV Panel capacity.

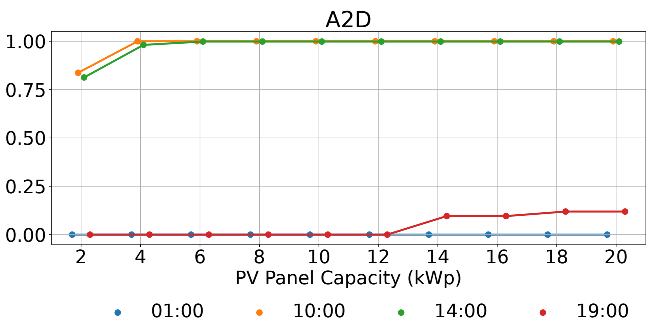

Fig. 3: Average A2D Ratio, in %, varying the PV Panel capacity, at 1:00 a.m. (blue), 10:00 a.m. (orange), 2:00 p.m. (green) and 7:00 p.m. (red).

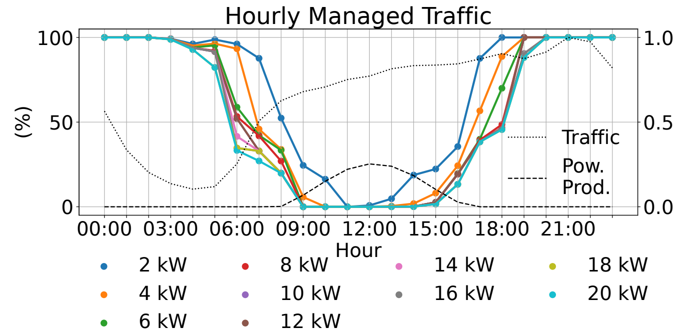

Fig. 4: Hourly average lost load (%) in different colors (left y-axis), along with hourly average BS traffic load, dotted, and energy production in January, dashed (right y-axis).

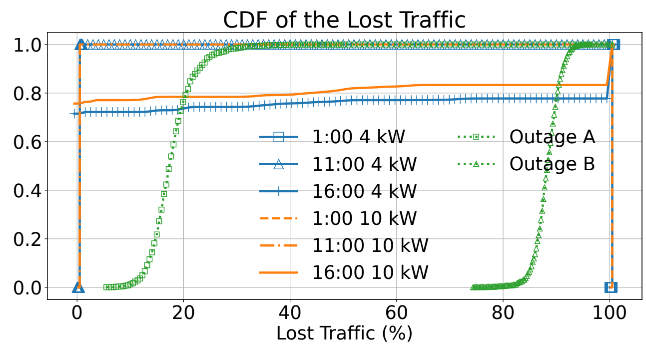

Fig. 5: CDF of the Lost Load, in %, for different hours of the day and PV Panel capacity.

To assess resilience, we use KPIs that measure the network's ability to maintain service continuity and quality during power disruptions:

- *Lost Traffic* (%) – The average percentage of traffic demand that cannot be served during a grid outage, representing the reduction in QoS in the RAN. Lost Traffic is calculated by estimating the proportion of unmet traffic demand due to inactive BSs during an outage. This metric reflects the immediate impact of outages on service availability.
- *A2D*(Active-to-Downtime Ratio) –The average proportion of time each BS remains active during a grid outage. It is calculated as the ratio of the time each BS can provide service (powered by PV panels) to the total duration of the outage. A BS is considered active when its PV system produces sufficient energy to meet traffic demand; otherwise, it is off and unable to serve users.

These KPIs are essential as they indicate the effectiveness of PV integration in supporting service continuity during outages.

Performance Evaluation: We now discuss the numerical evaluations of the simulated scenarios. We start analyzing the BAU, reporting in Fig. 2 the average *CO_2 emissions intensity* for the BS supply, varying the PV panel capacity between 0 kW, i.e., when the BS drains energy only from the power grid, to 20 kW. The figure evidences that the *CO_2 emissions* are 0.26 gCO_2/Wh in case there is no PV panel, but when installed, it reduces them by up to 47%. However, this growth is not constant: increasing the PV panel up to 4 kW means reducing the *gCO_2 emissions intensity* by 42%, not significantly lower than the drop previously reported, achieved with 10 kW. This indicates that, when produced during the daily hours, a 4 kW PV panel is almost sufficient to fully supply the BS and emissions are mainly due to the energy drained from the power grid, when it does not produce, during the night.

Now, we investigate the scenario, where a power grid outage occurs. To do this, we evaluate the system performance, simulating the occurrences of each power grid outage of our dataset. Fig. 3 shows the *A2D*, varying the PV panel capacity, from 0 kW, i.e. no PV panel, to 20 kW, for the outages that occur at 1:00 a.m., 10:00 a.m., 2:00 p.m. and 7:00 p.m., in blue, orange, green and red, respectively. These figures reveal that the *A2D* strictly depends on the hour of the day, because of the variation in solar energy production during the day, and on the PV panel capacity. At 1:00 a.m. (blue curve in Fig. 3), the *A2D* is always equal to zero. This means that each power outage interrupts the communication service and BSs are off for the whole duration of the outage. Because of the lack of energy production, the PV panel capacity has no impact on the *A2D*. The situation at 7:00 p.m. is similar, as shown by the red curve in Fig. 3. The situation significantly differs at 10 a.m. and 2 p.m., see orange and green curves in Fig 3. In these cases, PV panel systems with a capacity of 2 kW can power a BS for 80% of the outage duration, while BSs remain active for nearly the entire duration with a PV panel capacity of at least 4 kW.

Each curve in Fig. 4 is the *Lost Traffic*, on the left y-axis, with different PV panel capacities installed on each BS, grouping the power grid outages by the hour of the day they begin. On the right y-axis, the dashed and dotted lines are the hourly traffic load of one of the considered BSs and the energy production in January, normalized with respect to its maximum and the yearly maximum, respectively. In case of power grid outages, which start before 4 a.m. and from 8:00 p.m., the communication service is completely interrupted, i.e., the load is completely lost, due to the lack of PV panel production. In this case, the increase in the PV panel capacity does not affect the QoS. In addition, the figure reveals that during the PV panel production hours, from 9 a.m. to 3 p.m., the *Lost Traffic* is almost zero when the PV Panel capacity is larger than 2 kW, meaning that the BSs are able to remain active and provide the service. Between 6:00 a.m. and 9:00 a.m. and from 4 p.m. to 8 p.m., the *Lost Traffic* is strictly dependent on the PV Panel capacity. For instance, the *Lost Traffic* ranges between 42% and 27%, if the PV Panel capacity increases from 6 kW to 20 kW, in case the power grid outage starts at 7 a.m.

The orange and blue curves in Fig. 5 show the Cumulative Density Function (CDF) of the *Lost Traffic*, measured on each BS, for PV panel capacities of 4 kW and 10 kW, respectively, simulating the outages starting at 1 a.m., 11 a.m., and 4 p.m. The figure confirms that for all outages starting at 11 a.m., both PV panel capacities generate sufficient power to keep the BSs active. In contrast, during outages starting at 1 a.m., BSs remain inactive due to insufficient energy production, resulting in a complete loss of traffic, regardless of the PV panel capacity. For outages starting at 4 p.m., the CDF of the *Lost Traffic* varies depending on the PV panel capacity. Specifically, with PV panel capacities of 4 kW and 10 kW, no traffic is lost in 72% and 76% of simulated outages, respectively. Notably, between February and September, the PV panels can fully power the BSs in 88% and 90% of the outages, respectively, preventing any traffic loss. However, from October to January, the energy produced is typically insufficient, resulting in complete communication service interruption. This is the case of 22% and 17% of outages that start at that hour. These results indicate that the performance for power outages starting at 4 p.m. is more variable than for the other considered starting hours, depending strictly on the time of year.

Now, we analyze the heterogeneity of performance among BSs during the same outage, considering the case where each BS is equipped with a 4 kW PV panel. For this analysis, given each outage in our dataset, we measure the *Lost Traffic* for each BS and select the two outages that exhibit the highest variance among the BSs. For each of these two outages, we build the corresponding CDFs of the *Lost Traffic* measured for each BS and plot them in Fig. 5 (green curves). We observe that, even though these outages, *Outage A* and *Outage B* in the figure, provide the highest variance among the available outages, the variability of the *Lost Traffic* is bounded between 6% and 50% for one outage and between 74% and 96% for the other. The lowest values of *Lost Traffic* are observed for BSs located outside urban areas, where traffic demand is typically low. However, notice that for more than 90% of the outages, the variance of the *Lost Traffic* is null, hence the outage impact mostly results homogeneous over all BSs.

In conclusion, our results indicate that for regions with PV panel production similar to that of the studied location (Northern Italy), PV panel integration significantly enhances RAN sustainability by halving emissions intensity, even with low PV capacity (4 kW). Additionally, PV panels improve RAN resilience with a marginal impact from traffic demand profiles, but with performance highly dependent on factors such as the time of day, seasonality of power outages, and the capacity of the installed PV systems.

VII. Challenges

Several challenges must be addressed to deploy resilient communication infrastructures. First, it is crucial to identify the most sensitive services that require high reliability and resilience. Second, the variability of solar energy production necessitates the inclusion of EESs, optimal energy management, and hybrid energy solutions. These solutions should combine multiple renewable sources, such as solar, wind, and geothermal, with traditional power grids, and they should be optimized for different geographical locations and urban, suburban, and rural contexts. Additionally, initial installation costs and space requirements for RESs with ESSs must be considered, as these factors make widespread adoption challenging. Finally, incorporating smart algorithms to predict daily failures could enhance energy management and increase installation resilience.

VIII. Conclusion

This paper analyses communication network failures due to power grid outages and presents solutions for the RAN sustainability and resilience. Our findings show that, for regions with PV panel production characteristics similar to those in Northern Italy, integrating even small PV systems (4 kW) substantially reduces the carbon footprint of RANs. Their integration is also crucial for maintaining network operation during power outages (in a power grid similar to Northern Italy), especially during daylight hours when PV generation is high. The traffic demand profile has a marginal impact on the effectiveness of this approach, which instead depends on (i) the time of day and year when a power outage occurs and (ii) the generation capacity of the installed PV systems.

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