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Renewable energy electric sources as a support for multilevel cellular communication networks in various environment conditions – case study

Iñigo Cuiñas[1*], Katarzyna Znajdek[2], Maciej Sibiński[2]

[1] Dept. of Signal Theory and Communications, Universidade de Vigo, atlanTTic Research Center, 36310 Vigo, Spain
[2] Dept. of Semiconductor and Optoelectronic Devices, Lodz University of Technology, Wólczańska 211–215, 90-001 Lodz, Poland

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Abstract

Cellular mobile communication networks are experiencing an important evolution with the emerging deployment of 5G networks and the successive decline in the use of previous generations in the years to come. In parallel, policies promoting ecological transition are gaining social impact and economic interest and this seems to be the trend in the near future. In the telecommunications market, the shift between two dominant generations could be an important opportunity to introduce renewable energy sources to green the sector, reducing the carbon footprint of the world-wide extended activity. This work analyses the current situation and provides an insight into the possibilities to incorporate renewable energy supplies, specifically photovoltaics (as it seems to be the most promising among clean electric sources), perhaps combined with small wind turbines in off-grid systems. Paper also compares the characteristics of standard facilities in Spain and Poland, two different European countries in terms of weather and insolation hours.

1. Introduction

Recently, European Union fixed its activation lines on ecological transition by the European Recovery Plan "Next Generation EU" [1], involving three strategic axes: the development of renewable energies; the rehabilitation and energy efficiency; and the sustainable mobility. This ecological transition in Europe is going in parallel with the deployment of cellular communication networks: now the fifth generation (5G) and, in the future, the sixth generation (6G).

There are some figures that help to focus on the effect of communication networks on the world's energy budget and support the interest of moving them to greenish resources. Information and Communication Technologies (ICTs) use more than 10% of the world's electric energy consumed globally and generate from 8 to 10% of carbon dioxide emissions in 2020. The future could not be better. The subscribers of cellular networks have changed their data traffic requirements over the last decade: from 10 GB to up to 100 GB per year. Albeit the carbon footprint of each subscriber has been reduced, the growing number of users compensates this success with even higher energy demand. The infrastructure energy consumption is far to be controlled: a 4G network (LTE) consumes 60 times more energy than 2G (GSM); and as 5G is intended to provide higher data rates, their designs are denser and thus the energy consumption will be even higher [2].

Energy represents between 18 and 36% of the operational expenses (OPEX) for the operators (and 80% of that is associated to base station (BS) consumption [3]). Any reduction will have a direct economic benefit to the company, and an intangible impact on marketing when associating the corporative image with green environmental initiatives. These reasons support the industry efforts regarding energy reduction [2]. There is therefore an open window of opportunity: these new deployments of 5G and beyond could be a good opportunity to improve the

*Corresponding author at: inhigo@uvigo.es

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energy efficiency of communication systems. Besides, the efficiency improvement, supplying some (or all) elements within a cellular network with renewable energy sources (RES) or even deploying a parallel green energy network would be a critical support in such ecological transition. In fact, the deployment of the emerging radio communication networks would affect all three axes of the European plan [1], thus representing a transversal sector for the ecological horizon. The focus is then on BS consumption: the user terminals have been continuously improved as the energy reduction implies longer battery duration and their total consumption is negligible compared to BS.

At the beginning of cellular communications, the design targets of cellular networks were maximum throughput, spectral efficiency, and meeting quality of service (QoS) requirements [2], rather than energy saving. As mobile phone generations evolve, network complexity grows and, with them, the number of BS: to the macro-cells, micro-, pico- and femto-cells should be added, each of them supported by a BS adapted to the size. Although energy consumption of BS for smaller coverage areas is reduced compared to the larger ones, required supplies increase due to the explosive growth of users and new applications demanding more and more data rates and capacity. Then, operators have upgraded the importance of power consumption to the level of QoS when designing and planning their new cellular networks. Besides, last generations allow the incorporation of different approaches to reduce the power consumption. Namely, 4G can implement BS sleeping, which could be applied to existing infrastructure, avoiding the need to upgrade hardware components or add renewable energy adaptations that require additional and important investments [4]. However, being in the transition period between two dominant cellular generations (4G to 5G), which demands a new network infrastructure, renewable energies could have a chance as a solution for definitively greening the communication networks. 5G networks need to be newly deployed and this ‘blank canvas’ situation is a good opportunity to rethink the full system. Thus, the network capacity would still remain as it is, without the inherent reduction given by the sleeping BS. Specifically, the emerging fifth generation standards put the focus to enhance the energy efficiency in general, and at the network level in particular [5].

A green network would influence both the mitigation of the environmental problems and the reduction of the OPEX, which is clearly an attractive issue for these companies [6]. For both reasons, research on energy-saving is currently running with multi-angle approaches: innovation in network structure, development of new communication protocols, enhancement of the efficiency of power amplifiers (the most consuming device in the BS), and many others [7].

Renewable energy development and compliant industry transition are currently a major concern of numerous countries, regions, and organizations, including EU policy [8, 9]. Many possible technological solutions may be indicated as the promising candidates for this role, including biomass conversion, wind energy, water flow energy, geothermal energy, solar thermal conversion, or photovoltaics (PVs) [10]. All possible solutions differ in the specific fields of applications, delivering different types of energy with various time and space distribution, power density, reliability, and production costs. Additionally, successive de-carbonization technical aspects of renewable sources with grid cooperation must be successively addressed, as well as the cheap and effective energy storage systems shall be introduced [11]. Expected share of each mentioned energy source in the future global energy market is shown in Fig. 1, with a remarkable expected explosion of PV and wind to increase in the future decades. Add to that percentage increase the total production boost, which draws a future world full of PV and wind generation facilities.

At that point, 5G emerges as the first opportunity to provide a full network design taking into account green policies, which is a positive first step. The network design integrating plenty of layers in the radio sector [from macro to femto-cells but adding also other wireless networks out of the operator’s control: Wi-Fi, wireless sensor networks (WSN)] leads to heterogeneous networks, all operating under the 5G umbrella. This variety of BS (or nodes, if consider all the elements) makes difficult, when not impossible, the definition of a unique greening strategy. Then, this is the force-idea of this paper: the analysis of renewable energies solutions to cope with the variety of situations, considering real-world consumptions of BS. The open question is whether it would be possible to create a full-green cellular network for future mobile generations, perhaps for 5G and surely for 6G.

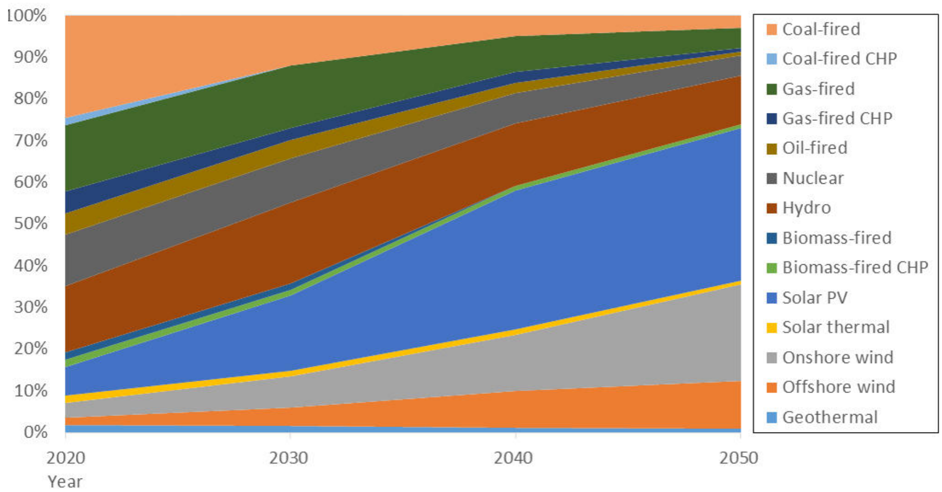

Fig. 1. Predicted transition of global energy-mix until 2050 (data from [12]).

The content of the paper is organized into six sections. Section 2 describes the multilevel architecture of cellular and other related networks and introduces some figures on their energy consumption. Section 3 is devoted to the green energy options, providing a general overview of possible solutions. These two sections provided the current overview of cellular communications networks and RES, as a starting point for the proposal in section 4: supplying the communication systems by means of PVs, simulating the performance that could provide considering some real-world situations, and considering some support by other RES options. Section 5 contains a discussion of the results previously presented, and section 6 explains the conclusions of the research.

2. Multilevel architecture and energy consumptions in cellular networks

The growing number of users and the increasing demand of communication resources define the 5G network requirements. Networks for this emerging technology embrace a large number of BS, but also a BS density larger than previous generations, leading to a multilevel architecture to provide services as near as possible to the subscriber: guaranteed fast speed and low latency connectivity promised by 5G networks requires proximity between the user and BS. This means that there are several cell levels (from macro- to pico- and femto-cells), driven by cellular operators, and additional architecture levels out of their control, as private or public local area networks (as Wi-Fi), personal area networks, wireless sensor networks, and so on. On one hand, this provides an efficient solution in terms of QoS. However, on the other hand, resources waste could arise in valley periods, due to the users' fluctuation in both domains: time and space [7].

As the cellular density grows, the energy grid supporting this collection of BS and access nodes of different sizes also expands and not all the time in the organized way that could be expected. The increasing number of BS, and the growing traffic they must carry lead to an increase in the electric energy consumption, which could be reduced or controlled by implementing more efficient components and applying energy saving techniques. In general, the consumption of BS has two main forms: dynamic and static. Whereas static energy consumption refers to the basic power to keep the BS switched on and operative (i.e., the power consumption without traffic load), the dynamic energy consumption is directly related to the BS load [7]. The BS power consumption depends a lot on how it is configured, how it manages the traffic load, or its power reduction measures; then, the long-term average power consumption seems to be a reasonable parameter to assess the power consumption [4, 13].

Taking that into account, a survey on long-term mean power consumption values has been provided by telecommunication companies in Spain, identified for this research effects as "operator A" and "operator B". A summary of those data is given in Tables 1 and 2.

Operator A differentiates between urban and dense urban because of the larger traffic volume, but essentially because of diverse multiple-input and multiple-output (MIMO) configurations. Operator B does not have differences between urban and rural stations.

Observing the data, it can be confirmed that the evolution of the generations brought an increase in power consumption: although new subsystems are more efficient energetically, the amount of traffic they carry and the number of subscribers has grew at a faster rate. Besides, the previous generation systems are not substituted immediately, and some of them endure over time as they are needed for some specific service.

Heterogeneous networks as those supporting 5G operation also include other kinds of wireless networks (or only spots) belonging to other institutions, companies, or citizens. It is also interesting to take into account the consumption of this infrastructure, even lower. Energy consumption of WSN nodes strongly depends on the network architecture and configuration. Table 3 contains data on mean electric consumption computed from simulations along periods of 30 s, in different configurations of WSN [14]. The authors simulated various situations in networks with 10, 20 and 30 nodes under the standard 802.11b [15], considering different node distributions: random, grid, and uniform.

Table 1.
Mean electric power consumption of operator A.

BS typology	Technology	Mean power consumption (W)
Rural (low population)	2G/3G/4G	1 670
Rural	2G/3G/4G	2 274
Semi-urban	2G/3G/4G	3 468
Urban	2G/3G/4G	3 880
Dense urban	2G/3G/4G	5 536

Table 2.
Mean electric power consumption of operator B.

BS typology	Technology	Mean power consumption (W)
Macrocell 1-sector	3G	3 577
	3G/4G	4 560
	3G/4G/5G	5 760
Macrocell 3-sectors	3G	5 243
	3G/4G	7 892
	3G/4G/5G	11 462

Table 3.
Mean electric power consumption of WSN, computed from [14].

WSN deployment	No. of nodes	Mean power consumption (µW)
Random	10	4.83
	20	4.87
	30	5.63
Grid	10	4.43
	20	4.77
	30	5.30
Uniform	10	4.53
	20	5.03
	30	5.40

On the Internet of the Things (IoT) network, based on IEEE 802.11n [16], the data transmission interval (from 10 s to 90 s) seems to make no difference in power consumption, which was estimated to be around 13.518 W for 15 sensor operation and 0.442 W for network operation [17]. Then, the IoT sensor part dominates for small-scale systems. Besides, the number of sensor nodes has a prevailing effect on the total consumption, being the relation between number of nodes and power consumed, approximately linear. From data in Ref. 17, the following relation can be identified

$$P = 0.193 \cdot n + 11.108 , \tag{1}$$

where P is the average power consumed in W and n is the number of sensor nodes of the network.

Regarding Wi-Fi routers, their estimated consumption is between 2 and 20 W, with an average of 6 W. This low power consumption allows for the continuous operation for such solid-state devices [18].

In this regard, it can be stated that the range of a possible power consumption is very wide, from a few µW requested by WSN with few nodes to various kW demanded by urban BSs serving large amounts of data traffic.

3. Renewable energy sources

To understand the potential of specific RES application in 5G, and subsequently 6G, network development, it is necessary to take a closer look at the specifics of each generation type. In the following short survey, only electricity generation methods, suitable for small scale off-grid systems will be described, since the whole potential of the RES is much above the scope and the volume of this publication.

3.1. Wind generation

Fast and effective wind turbines development is currently the main source of RES generation in many countries including Germany (75%) [19], Spain (57%) [20], and USA (26%) [21]. Also, China recently put a great effort in a wind turbine sector development as a serious element of green energy system [22, 23].

Among two most popular wind generator constructions, high efficiency Horizontal Axis Wind Turbine (HAWT) is mostly used for grid power generators, whereas single-rotation axis Vertical Axis Wind Turbines (VAWTs) are frequently used for small off-grid installations because of their wind direction independence and high efficiency at low wind velocity.

HAWT constructions are nowadays characterised by high efficiency exceeding 50%, large, generated power (with values up to 12 MW/turbine), low ground space occupation, and long-term stable production up to 30 years with the option of on-shore and off-shore construction [24]. As all renewable generators, they have no primary CO_2 emission, but their secondary emission, connected with the waste during the production and utilization processes, is also relatively low. According to the recent investigations [25], the biggest impact on secondary emission (73.5%) is derived from the use of raw materials during the extracting and manufacturing phase, 24.9% during the installation phase, 1.41% in the transportation phase, and only 0.1% during the operation phase.

Nevertheless, high power HAWT turbines are also connected with some drawbacks, which may cause problems during their practical implementations. These main sources are related to blades vibrations and infrasound emission, undesired landscape modification, bird migrations disturbances, and occasional accidents [26]. Also, it should be remembered that the successful application of these generators is always related to proper position planning, wind rose distribution measurement, and wind speed estimation, since the nominal operation power is typically achieved at the wind speed of 12–15m/s. Thus, the application of smaller HAWT generators, placed at lower altitudes in urbanized area, is often problematic, which is clearly visible in the typical Weibull dissipation graph, presented in Fig. 2.

Contrarily, VAWT generators are almost immune to the frequent wind direction shifts and may effectively operate at the wide range of wind speeds. Their main drawbacks are related to high wind pressure on both opposing blades, which significantly limits the possibility of dimensions up-scaling. Also, high constructions of these types are in danger of high contorted force since the wind speeds at different altitudes may vary significantly. Some experiments

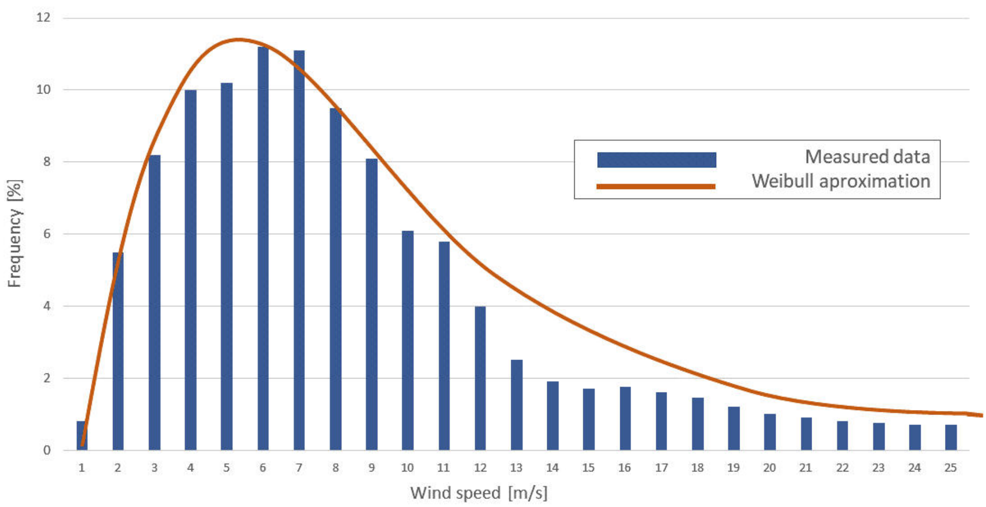

Fig. 2. Typical wind speeds measured in an urbanized area at low altitude and their Weibull statistical modelling.

leading to the solution of these problems were undertaken in Poland [27], by application of the modular construction with adjustable blades and clutch-coupled axis, which allowed for the experimental construction of 3 VAWT turbines, each 30-meter high with a nominal power of 500 kW. However, main field of application for this turbine type relates to household micro-installations and small off-grid DC systems [28]. Typical power of these turbines varies from several watts to a few kilowatts. What is important for individual 5G and 6G applications, they may be effectively used with a floating wind at an average speed of 4–6 m/s and in the normal conditions do not require any special construction permission since the height of their masts is below 5 m.

3.2. *Photovoltaic generators*

PV technology, being now the second RES type, has been growing rapidly since the beginning of the current century and is expected to be dominant among energy sources in the next decades. Over the last 5 years, PV installations represented on average around 40% of the newly installed renewable generators [29]. This tendency is strongly driven by a constant price drop of the generated PV power, caused by mass production and dynamic technology development (Fig. 3). It may be expected that this trend will be continued within forthcoming period, which, accompanied by constant rise of combustion-based electricity generation prices, will lead inevitably to great commercial success of PV installations.

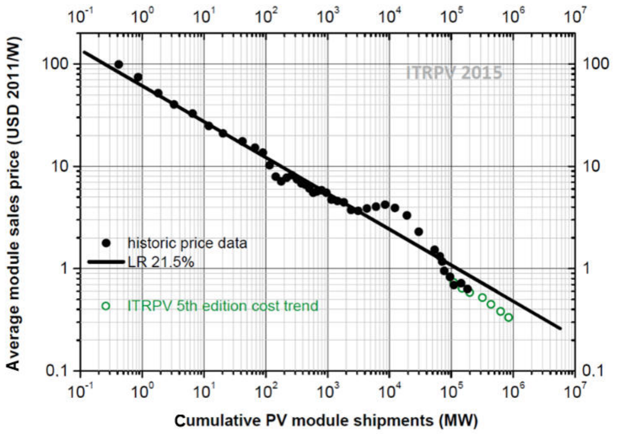

Fig. 3. Historic prices and current trend of the PV generators price reduction dependent on the global production volume [30].

The main technical advantages of PV generators are direct energy conversion, robust construction, long lifespan (up to 30 years of operation [31]), easy re-scaling of installation size, and, what is important for small off-grid installation, production of direct current with adjustable voltage and current. The productivity of PV installation varies significantly depending on localization, orientation, and tilt angle. Thus, specific calculation of the installation parameters is the key factor for a successful designing and operating of the setup.

The most significant drawback of PV-based power supply system is the energy production instability throughout the day and year period. Though strongly based on the localization, weather conditions and modules position, PV production estimation is reliably possible within longer time of operation. Additionally, the battery and/or additional auxiliary supply system is frequently needed for off-grid systems. Figure 4 shows the variation of a PV system electric energy production within the year period at two different localizations in Europe.

Nowadays, several materials and technologies of production are successfully used for the commercial PV module production. The most important of them are monocrystalline silicon (efficiency up to 22%), polycrystalline silicon (efficiency up to 20%), inorganic thin film materials (efficiency up to 18%), hybrid cells and organic cells (both technologies efficiency up to 12–14%) [32]. Moreover, some emerging technologies including perovskites, copper oxides, tandem cells and many more are constantly developing towards further technical and economical optimization.

Owing to developed PV market, a wide range of types and parameters of PV modules is available with the power ranging from 10 Wp (Watt peak) until 500 Wp for a single module. Average productivity in the conditions of mid-Europe is 1 MWh/year from 1 kWp installation. Current costs of the final installation may vary depending on type and size but are typically close to1 € per Wp. The current range of applications is extremely broad, from small off-grid DC installations (telemetric, road control stations, lamps, etc.), through vehicles (electric cars, planes, and spacecraft), house off-grid and on-grid installations to big power plants with several MWp. As it was mentioned, a constant development of these products is observed,

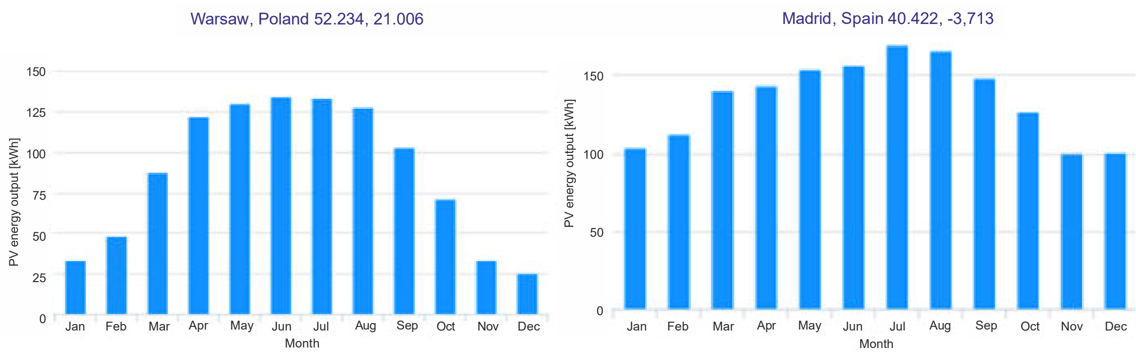

Fig. 4. Standard silicon 1 kWp PV installation productivity throughout the year (simulation performed in a PVGIS software) in (a) Warsaw, Poland, and (b) Madrid, Spain.

which is a good prognostic for future applications in communication networks.

3.3. *Water flow generators*

Water flow generators have been popular since the beginning of 20th century and operate on the basis of water mass potential and kinetic energy, according to

$$N = \eta \cdot 9.81 \cdot Q \cdot H \quad [\mathrm{kW}], \tag{2}$$

where N is the raw power of the water generator [kW], η is the efficiency [%], Q is the water flow volume [m^3/s], and H is the waterfall height [m].

Their practical use is connected with series of advantages like high efficiency (up to 80%), high power generation, easy and fast start of the generation; but, also, with inevitable drawbacks including necessity of a direct access to the water stream. Nevertheless, some small portable generators are being investigated and manufactured as a back-up energy source for convenience in rural areas [34]. Unfortunately, their inherited drawback is a complicated structure and a very limited efficiency [35]. Some of these generators may be also potentially used as the energy accumulation systems in the pumped storage power plant cycle, but their low efficiency and complicated construction makes their use in 5G and 6G communication systems hardly possible.

3.4. *Energy harvesting systems*

Apart from mentioned energy generation methods, there is still a big group of emerging technologies, which in the near future may achieve the level of successful commercialization. Amongst them one may certainly distinguish the following technologies:

- radio frequency generators,
- vibration based generators,
- thermal effect generators.

Practical potential of these solutions is still widely unknown, but their general estimation is given in Fig 5. The most technically advanced methods of energy harvesting are based on piezo-electric effect in flexible elements (including yarns), Seebeck thermo-generators, thermo-PVs and inductive generation; however, new innovative methods like micro spin effects are also investigated [36]. Nevertheless, one may estimate that presently all listed methods are not commercially available and either of low effectivity or not technically suitable for cellular network communication applications.

3.5. *Mixed systems*

Among many solutions for small-scale off-grid power generation, mixed systems of renewable energy generators seem particularly attractive [37]. The application of complementary RES generators leads typically to much more convenient generation dispersion throughout the year. An example calculation of such PV-wind turbine 1 kWp+1 kWp system located in Poland is presented in Fig. 6. In this case, a much more evenly distributed energy production can be achieved which leads to lower oversizing in the off-grid installation.

4. Evaluation of energy consumption for different cellular levels and applications

The ecological footprint of cellular networks can be reduced mainly by two ways: adopting RES or redesigning some subsystems to improve its energy efficiency. When the network is in operational state, the cost of adopting such measures could be prohibitive, as it includes acquiring, substituting, and installing new equipment. This is the reason why many operators preferred to modify their operating protocols to save energy, as this has less cost although the performance of the network could be affected [2]. Among the various options for reducing energy consumptions, it is possible to identify five categories [2]:

1) improving energy efficiency of hardware components. The energy savings could be really important, but the cost of implementation is also very high, which limits its applicability on deployed and operating cellular networks;
2) turning off components selectively. This proposal is commonly adopted as BS sleeping modes: the BS is switched off (or switched to a low-power mode) during off-peak periods. The impact of this technique in the energy consumption is interesting and the implementtation costs are low. However, the network parameters, mainly the QoS, suffer due to its use, as capacity decreases even if other countermeasures are implemented [38, 39];

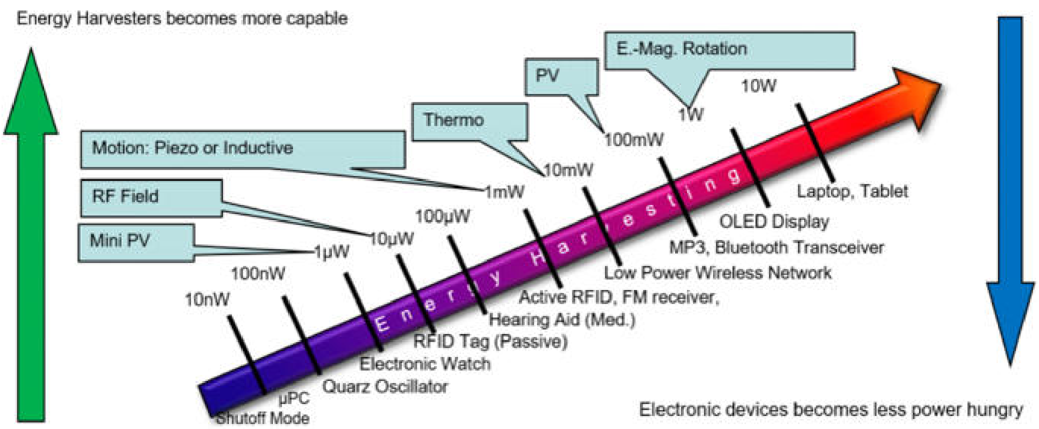

Fig. 5. General estimation of electric energy harvesting methods potential in various branches of electronics [33].

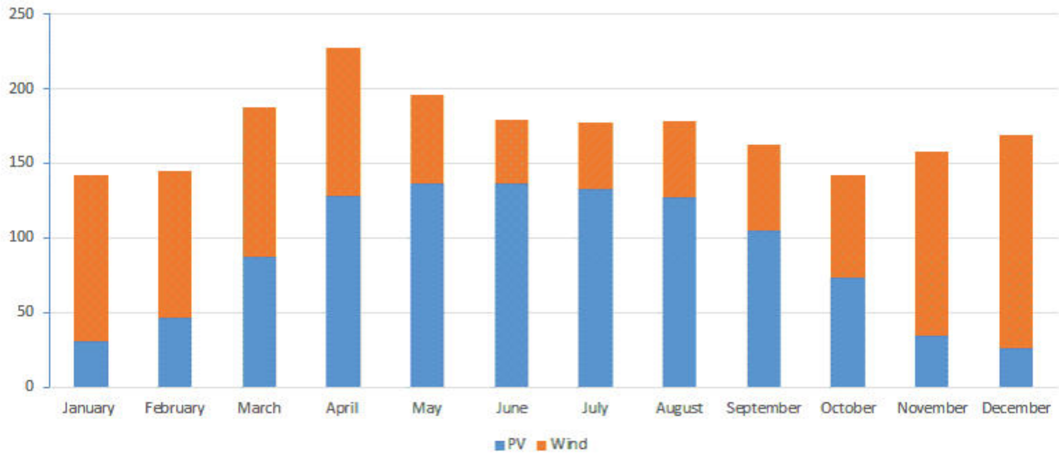

Fig. 6. Yearly energy production from mixed PV – wind generator systems of maximum power (1 kWp +1 kWp).

3) optimizing energy efficiency of the radio transmission process. It consists of improving the management of time, frequency, and space domains. As sleep modes, they do not need hardware modifications, as they are implemented at configuration (software) level. The problem is, again, the inevitable trade-offs between energy saving and network performance: deployment efficiency—energy efficiency, spectrum efficiency—energy efficiency, bandwidth—power and delay—power [40, 41];
4) planning and deploying heterogeneous cells. Smaller cells provide service to smaller areas, with less energy consumption as propagation distances are reduced and then, the required transmitted power is much lower. The problem is an increase in interference probability and, when the proposal is going to extremes and too many small cells are created, the sum of consumptions of all these small cells could overpass the macro-cell equivalent;
5) adopting renewable energy resources. The costs of adopting a new energy grid are large, and the benefits when applied to existing networks are not high. Remote regions, or developing, as well as undeveloped countries, should have the opportunity to use such options as wind, solar, or hydro power in new cellular network deployments, since these off-grid BSs were the only possible solution in many cases, although they were traditionally powered by fuel generators. The effect of using such solutions in operating networks is less, as the cost of installation could be balanced by the energy savings. Of course, the environmental effect should be added to the economic effect.

The current situation provides an opportunity to greenish networks based on RES, as new communication networks are under deployment or will be built in coming years. Among different elements that make up the cellular network, BSs are the main target to be supplied by renewable energies. This is a consequence of the analysis of the distribution of power consumption per component: BS at least 60% (and up to 80%), switching subsystem less than 20%, core transmission less than 15%, and data centre around 5% [42]. As the number of BS increases with the denser designs of 5G networks, the total energy consumed by the network will grow (in fact, data from operators confirm that fact).

There are specific characteristics of the cellular networks that limit, so far, the effectiveness of energy consumption reduction, starting with their design objectives: their goal is to provide the best service to clients, not to save energy. Besides, they are traditionally designed to successfully deal with peak situations and manage unexpected events, which leads to over-sizing the installed infrastructures. Redundancy and extra-capacity concepts have positive consequences, as the QoS is always fine, but negative because of the facilities infra-utilization. All these are an opportunity for green energy and new supply networks [2].

Analysing data from Tables 1 and 2, relating to power consumption, respectively for operator A and operator B in Spain, a simulation showing the requirements for BS to be supplied by PV systems was prepared. The simulations were conducted using Photovoltaic Geographical Information System (PVGIS), which is an online tool supported by the European Commission. It provides information about solar radiation and PV system performance for any location in Europe and Africa, as well as a large part of Asia and America. PVGIS is a free and open access online software allowing, among other things, calculations of the electricity generation potential for different PV technologies and configurations. PVGIS uses high-quality high-spatial and temporal resolution data of solar radiation obtained from satellite images.

Figures 7 and 8 present the data calculated for each operator separately, including various types of BS and their topology. The graphs show information on the values of PV power and area of PV modules, needed to cover the specific demand. Free-standing, crystalline silicon solar panels with the efficiency of 20% and optimized slope and azimuth in Madrid, Spain as a geographic central point, were used as boundary conditions in the performed simulations for the Spanish case. Additionally, the same data were compared, theoretically assuming that the PV installation is in the central Poland (i.e., the city of Lodz, near Warsaw). The results show that in order to cover the same annual energy demand, the installation in Poland would have to be 53% larger compared to that in Spain, where large surfaces covered with solar panels would also be required, depending on the type of BS.

Computations performed for the levels of the multilayer network closest to the user (i.e., WSN and WiFi nodes), based on the data from Table 3, clearly demonstrated that

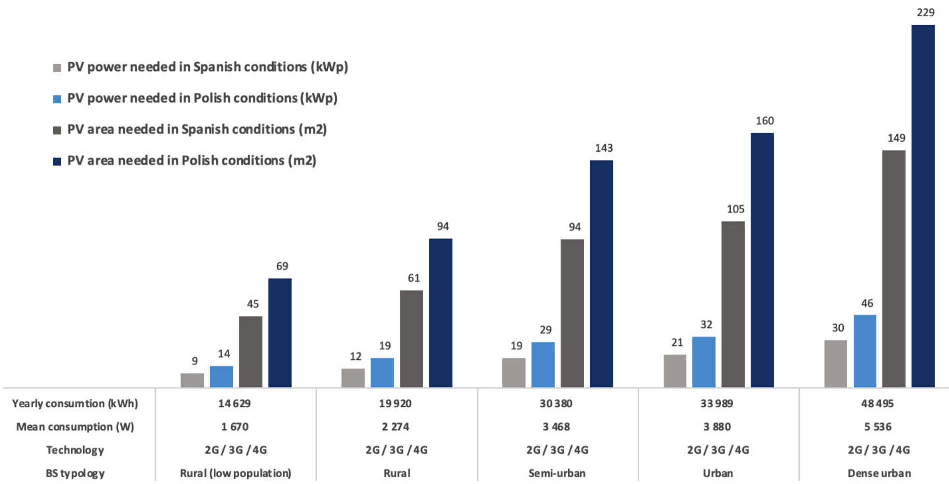

Fig. 7. PV power and area needed for operator A consumption data, in Spain and Poland conditions.

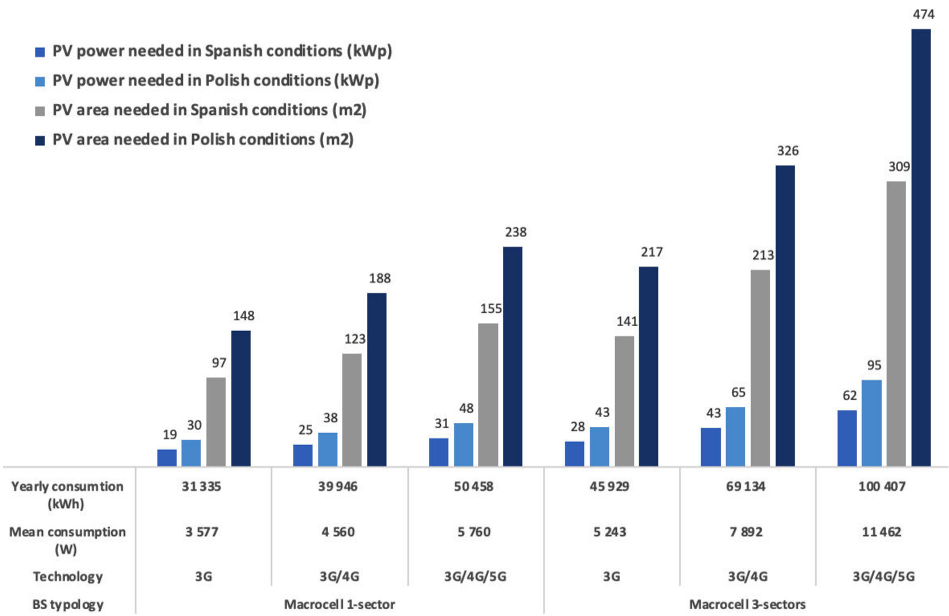

Fig. 8. PV power and area needed for operator B consumption data, in Spain and Poland conditions.

it would be easily possible to support them with renewable energy. This is caused by the fact that the power demands in these cases are of the very small values, for example 0.0000261 Wp of PV, which represents the area of 0.00000013 m^2. As the values are so minor, the authors decided not to present full sets of calculations: nodes of this kind could be supplied by PV installations, and in fact there are such solutions on the market.

These results may be further improved when PV generators will be combined with small wind turbines in off-grid systems, however, in this case a specific analysis of the local conditions is necessary and thus it is difficult to estimate overall performance.

5. Discussion

In Mediterranean-area countries (based on the Spain example), the PV power supply for rural areas is quite viable, demanding 40–60 m^2 of modern module area. This is a typical value of private micro installation, eminently easy to arrange in low-populated locations. It is particularly interesting due to the need of communication grid development and supply difficulties in these regions. In urban BS, with strong supply requirements, the viability decreases as the necessary surface increases.

Moreover, for the off-grid applications, locations with lower annual insolation variability, such as Spain (Fig. 4), are great for reducing the necessary battery capacity. In places with more unstable insolation times, an efficient battery system should be carefully designed, which would represent a supplementary installation cost as could be the case of Poland. Additionally, in these places the energy safety issues, and communication stability are real problems which may be successfully addressed by independent or semi-independent energy production systems. For these regions, the combination with the small wind generator systems is highly recommended due to the perfect compensation of annual PV generation variety.

As the forthcoming energy challenge, a constant increase of the energy production and distribution costs, especially taking into account environmental expenses of the combustion methods and growing importance of the energy safety issues can be certainly distinguished. Thus, the renewable-based generation, namely PVs, is extremely attractive given the constant technology advancement and increasing production volume, which has recently led to a 50% price reduction every decade. Besides, the ongoing research and development will probably lead in the coming years to a reduction of the required surface occupied by solar panels for generating a given amount of electric power. This will open the door to extend the current conclusions on the applicability of this technology in the cellular network deployment.

Regarding the small-scale communication networks, for the comprehensive analysis of the practical PV implementation in the IoT network, cooperation with the local power supply grid in various configurations (energy back-up systems, main supply, temporarily used source, etc.) must be determined for each case.

6. Conclusions

This paper presents an attempt to consider the approach to using renewable energy sources for electrical energy supply in multilevel cellular communications networks for Spain, as an example with real data, and Poland as a comparison. These countries were selected as two extreme regions of EU with varied communication grid demands. The authors selected PVs as the most promising and stable green power supply, as well as easy to maintain equipment and more constant depending on the specific geographical area. Investigation on the current power demand and energy needs at BSs in Spain was the starting point for supporting computer simulations which formed the basis for a quantitative analysis conducted for the purpose of this work.

It is clearly visible that that the generation progress of cellular communication networks is a real challenge from the energy supply point of view. Nevertheless, the performed simulations indicated the real possibility of PV-based renewable energy sources power generation even for the 5G infrastructure.

Given the different levels in the cellular network ecosystem, the closest to the user, such as those provided by Wi-Fi or WSN nodes, appear to be easily supplied by PV cells. The same occurs when rural BS is considered in the countries with high and stable solar irradiation, such as Mediterranean countries. In areas where insulation times are more unstable, a battery system should be needed. When moving to semi-urban, urban, or dense urban configurations, the energy consumption in these BS will hinder the use of off-grid PV applications, even these renewable energy sources could reduce the consumption of traditional carbon energy.

Current development of PV cells and modules keeps open the question regarding the possibility of creating a full-green cellular network for future mobile generations. It seems that it could be a chance for some 5G deployments, mainly at those levels closer to the users or in rural BS. Given the evolution of the technology, the proposal will surely be implementable for 6G or any other beyond-5G systems.

Authors' statement

Research concept and design, I.C. and M.S.; collection and/or assembly of data, K.Z. and I.C.; data analysis and interpretation, K.Z. and M.S.; writing the article, I.C., K.Z. and M.S.; critical revision of the article, M.S.; final approval of article, K.Z. and I.C.

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References

[1] Europe's moment: Repair and Prepare for the Next Generation. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. *European Commission*. (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0456&from=en

[2] Wu, J., Zhang, Y., Zukerman, M. & Yung, E.K.-N. Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey. *IEEE Commun. Surv. Tutor.* **17**, 803–825 (2015). https://doi.org/10.1109/COMST.2015.2403395

[3] Fehske, A., Fettweis, G., Malmodin, J. & Biczók, G. The global footprint of mobile communications: the ecological and economic perspective. *IEEE Commun. Mag.* **49**, 55–62 (2011). https://doi.org/10.1109/MCOM.2011.5978416

[4] Wu, J., Wong, E. W. M., Chan, Y.-C. & Zukerman, M. Power consumption and GoS tradeoff in cellular mobile networks with base station sleeping and related performance studies. *IEEE Trans. Green Commun. Netw.* **4**, 1024–1036 (2020). https://doi.org/10.1109/TGCN.2020.3000277

[5] Osseiran, A. *et al*. Scenarios for 5G mobile and wireless communications: The vision of the METIS project. *IEEE Commun. Mag.* **52**, 26–35 (2014). https://doi.org/10.1109/MCOM.2014.6815890

[6] Wang, W., Li, X., Liu, D., Cai, Z. & Gong, C. Multilevel power modeling of base station and its ICs. *China Commun.* **12**, 22–33 (2015). https://doi.org/10.1109/CC.2015.7112041

[7] Chang, K.-C., Chu, K.-C., Wang, H.-C., Lin, Y.-C. & Pan, J.-S. Energy saving technology of 5G base station based on internet of things collaborative control. *IEEE Access* **8**, 32935–32946 (2020). https://doi.org/10.1109/ACCESS.2020.2973648

[8] Connolly, D., Lund, H. & Mathiesen, B. V. Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renew. Sustain. Energy* Rev. **60**, 1634–1653 (2016). https://doi.org/10.1016/j.rser.2016.02.025

[9] Koval, V., Sribna, Y., Kaczmarzewski, S., Shapovalova, A. & Stupnytskyi, V. Regulatory policy of renewable energy sources in the European national economies. *Energy Policy J.* **24**, 61–78 (2021). https://doi.org/10.33223/epj/141990

[10] de Llano-Paz, F., Calvo-Silvosa, A., Iglesias Antelo, S. & Soares, I. The European low-carbon mix for 2030: The role of renewable energy sources in an environmentally and socially efficient approach. *Renew. Sustain. Energy Rev.* **48**, 49–61 (2015). https://doi.org/10.1016/j.rser.2015.03.032

[11] Kelm, P., Mieński, R. & Wasiak, I. Energy management in a prosumer installation using hybrid systems combining EV and stationary storages and renewable power sources. *Appl. Sci.* **11**, 5003 (2021). https://doi.org/10.3390/app11115003

[12] Energy Transition Outlook – A global and regional forecast of the energy transition to 2050. *DNV* https://www.dnv.com/Videos/energy-transition-outlook-a-global-and-regional-forecast-to-2050-208611#

[13] Wang, W., Liu, D., Zhang, Y. & Gong, C. Energy estimation and optimization platform for 4G and the future base station system early-stage design. *China Commun.* **14**, 47–64 (2017). https://doi.org/10.1109/CC.2017.7927576

[14] Shanmugavalli, R. & Subashini, P. Energy consumption analysis in WSN based on node placement strategies. *Int. J. Eng. Technol.* **7**, 531–535 (2018). https://doi.org/10.14419/.v7i3.12.16173

[15] IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems – Local and Metropolitan Networks – Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz Band – Corrigendum 1. in *IEEE Std 802.11b-1999/Cor 1-2001* 1–24 (2001). https://doi.org/10.1109/IEEESTD.2001.93363

[16] IEEE Standard for Information technology – Local and Metropolitan Area Networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput. in *IEEE Std 802.11n-2009 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, and IEEE Std 802.11w-2009* 1–565 (2009). https://doi.org/10.1109/IEEESTD.2009.5307322

[17] Guegan, L. & Orgerie, A.-C. Estimating the End-To-End Energy Consumption of Low-Bandwidth Iot Applications for Wifi Devices. in *IEEE International Conference on Cloud Computing Technology and Science (CloudCom)* 287–204 (2019). https://doi.org/10.1109/CloudCom.2019.00049

[18] Electricity usage of a Wi-Fi Router. *EnergyUseCalculator.com* https://energyusecalculator.com/electricity_wifirouter.htm

[19] Goss, S. The German energy market review. *Energy Brainpool GmbH & Co. KG.* (July 2020). https://blog.energybrainpool.com/en/the-german-energy-market-review-july-2020/

[20] Demand for electricity in Spain falls by 3.9% in September 2019. *RED Electrica de Espana* https://www.ree.es/en/press-office/news/press-releases/2019/10/demand-electricity-spain-falls-3-9-september

[21] Monthly Energy Review. *U.S. Energy Information Administration (EIA)* (2021). https://www.eia.gov/totalenergy/data/monthly/archive/00352105.pdf

[22] Liying, L. & Jiuping, X. Multi-objective generation scheduling towards grid-connected hydro–solar–wind power system based the coordination of economy, management, society, environment: A case study from China. *Int. J. Electr. Power Energy Syst.* **142**, 108210 (2022). https://doi.org/10.1016/j.ijepes.2022.108210

[23] Yi L. *et al*. Increases in China's wind energy production from the recovery of wind speed since 2012. *Environ. Res. Lett.* **17**, 114035 (2022). https://doi.org/10.1088/1748-9326/ac9cf4

[24] Elbahnasy, I. & Ellerman, K. An Approach for Cost And Configuration Optimization of Horizontal Axis Wind Turbine (HAWT). in *International Conference on Renewable Energies and Power Quality (ICREPQ'14)* 779–784 (2014). https://www.icrepq.com/icrepq'14/486.14-Elbanasy.pdf

[25] Gomaa, M. R., Rezk, H., Mustafa, R. J. & Al-Dhaifallah, M. Evaluating the environmental impacts and energy performance of a wind farm system utilizing the life-cycle assessment method: A practical case study. *Energies* **12**, 3263 (2019). https://doi.org/10.3390/en12173263

[26] Khan, S. & Haque, I. Enhanced Audio-Visual Warnings for Reducing Bird Fatalities at Wind Turbines. in 3rd *International Conference on Green Energy and Technology (ICGET*) 1–6 (2015). https://doi.org/10.1109/ICGET.2015.7315115

[27] Wójcik, G. P. The Polish Invention – Vertical Wind Power Stations – Renewable Energy Sources' Future. in 3rd *International Symposium on Energy Challenges and Mechanics* (2015). https://www.nscj.co.uk/ecm3/sessions/181_GrazynaWojcik.pdf

[28] Muhammad, A., Aamer, S. & Nafez Mumatz Quadri, M. An overview of aerodynamic performance analysis of vertical axis wind turbines. *Energy Environ.* **8**, (2022). https://doi.org/10.1177/0958305X221121281

[29] O'Shaughnessy, E. Trends in the market structure of US residential solar PV installation 2000 to 2016: An evolving industry. *Prog. Photovolt.* **26**, 901–910 (2018). https://doi.org/10.1002/pip.3030

[30] 6th International Technology Roadmap for Photovoltaics (ITRPV) Report. *Solar Choice* (2015). https://www.solarchoice.net.au/blog/news/2015-international-technology-roadmap-for-photovoltaics-released-040515/

[31] Weiss, K. A., Klimm, E. & Kaaya, I. Accelerated aging tests vs field performance of PV modules. *Prog. Energy* **4**, 042009 (2022). https://doi.org/10.1088/2516-1083/ac890a

[32] Green, M. *et al*. Solar cell efficiency tables (Version 60). *Prog. Photovolt.* **30**, 687–701 (2022). https://doi.org/10.1002/pip.3595

[33] Hayes, M. Synergies between Energy Harvesting and Power Eelectronics. *IEEE PELYS Young Profesionalist Webinar*. (2016). https://resourcecenter.ieee-pels.org/education/webinars/PELSWEB010202016.html

[34] Ighodalo Okhueleigbe, E. & Godswill, O. Mini-hydro turbine: solution to power challenges in an emerging society with abundance of water. *Am. J. Eng. Technol. Manage.* **2**, 7–12 (2017). https://doi.org/10.11648/j.ajetm.20170202.11

[35] Rudzka, R. *Renewable energy generator with water generating system.* (Lodz University of Technology, 2021).

[36] Woźny, J., Gozdur, R., Guzowski, B. & Bernacki, Ł. Micromagnetic simulation of thermal generation of spin waves using MuMax3. *Acta Phys. Pol.* **137**, 737–740 (2020). https://doi.org/10.12693/APhysPolA.137.737

[37] Adetunla, A., Rominiyi, O., Adaramola, B. & Adeoye, A. Development of a wind turbine for a hybrid solar-wind power system. *Heliyon* **8**, e11458 (2022). https://doi.org/10.1016/j.heliyon.2022.e11458

[38] Marsan, M. A., Chiaraviglio, L., Ciullo, D. & Meo, M. On the effectiveness of single and multiple base station sleep modes in cellular networks. *Comput. Netw.* **57**, 3276–3290 (2013). https://doi.org/10.1016/j.comnet.2013.07.016

[39] Soh, Y. S., Quek, T., Kountouris, M. & Shin, H. Energy efficient heterogeneous cellular networks. *IEEE J. Sel. Areas Commun.* **31**, 840–850 (2013). https://doi.org/10.1109/JSAC.2013.130503

[40] Chen, Y., Zhang, S., Xu, S. & Li, G. Y. Fundamental trade-offs on green wireless networks. *IEEE Commun. Mag*. **49**, 30–37 (2011). https://doi.org/10.1109/MCOM.2011.5783982

[41] He, G., Zhang, S., Chen, Y. & Xu, S. Fundamental Tradeoffs And Evaluation Methodology for Future Green Wireless Networks. in 1st *IEEE International Conference on Communications in China Workshops (ICCC)* 74–78 (2012).
https://doi.org/10.1109/ICCCW.2012.6316478

[42] Han, C. *et al.* Green radio: radio techniques to enable energy-efficient wireless networks. *IEEE Commun. Mag.* **49**, 46–54 (2011). https://doi.org/10.1109/MCOM.2011.5783984