Towards Zero Grid Electricity Networking: Powering BSs with Renewable Energy Sources

Marco Ajmone Marsan, Giuseppina Bucalo, Alfonso Di Caro, Michela Meo, Yi Zhang
Politecnico di Torino, Italy

***Abstract*—In this paper we study cellular access networks which solely rely on renewable energy. We consider a cellular network in which a mesh of base stations (BSs) that are powered with renewable sources, and interconnected with wireless backhaul links, cover the service area, and provide connection to few, typically remote, wired network accesses to the national and international backbone. In particular, we study how to dimension BS power generators and energy storage. We start by discussing the BS energy need, that depends on both the BS consumption model and the BS traffic profiles. Focusing then on some specific locations, we consider the use of photovoltaic (PV) panels, and dimension them based on the daily energy need of the BS and on typical radiative power of sun in the considered locations. Once the PV system has been dimensioned, we also evaluate the energy storage capacity that is needed to absorb energy production variability due to both daily and seasonal radiative power variations. Finally, we investigate the effectiveness of integrating the PV system with wind turbines, as well as the benefit induced on the system by base station sleep modes.**

I. Introduction

In 2012, the number of mobile phone subscriptions worldwide has reached 6 billion, and the number of base stations (BSs) has surpassed 4 million. If we consider that the world population is around 7 billion, and that in some countries the mobile phone penetration is well above 100% (in Italy it is close to 150%: many people have 2 or 3 phones and just a few have none), this means that a majority of adults worldwide today uses a mobile phone.

Experts predict that the next billion users of mobile communications will primarily come from emerging markets, and from rural areas, where the mobile phone is the main tool that allows people to be connected to the world [1]. As an indication of this trend, consider that the country with the highest percentage increment in the number of mobile phones in 2011 was Nigeria; this confirms the expectation that after a first wave of mobile telephony penetration in North America and Europe, and a second wave in Asia, the massive deployment of cellular systems is now moving to Africa.

This implies that the scientific and technical challenges in wireless cellular network design should become more and more tailored to the environments which are typical of developing countries and of rural areas. The main difference that exists in this case with respect to developed countries (e.g. Europe) is that the presence of a reliable and dependable power grid, which can be given for granted in most developed counties, and in significant areas of Asia (for example in large portions of China or India), is not a viable assumption in many developing countries and rural areas, specially within the African continent.

As a result, one of the main challenges in the deployment of wireless cellular networks in the countries with the higher potential increment of the number of customers in the coming years will lie in the possibility to provide power for BSs, and to do so reliably and at limited cost, in order to offer dependable services at prices compatible with the population income. Of course, providing power to recharge user terminals is also important, but this is less of a challenge, because of the limited amount of energy involved (simple solutions, such as dynamos, can be a very inexpensive option).

The traditional solution to power base stations in regions where the power grid is not available, or not dependable, relies on the use of diesel generators. However, diesel fuel is expensive (BSs consume an average of 1500 liters of fuel a month), and fuel transport can be extremely problematic in such areas, thus further increasing the cost (helicopters must be used for some remote sites!), not to mention the risk of fuel thefts.

Operators are actively seeking innovative solutions to this problem. Orange, for example, has already installed more than 2 thousand solar powered base stations in 18 countries in the Africa and Middle East region, serving over 3 million people in areas with bad quality electrical grid or no grid at all [2]. With respect to the use of diesel generators, this award-winning Orange project allowed saving 67 thousand tons of CO_2 in 2011. Forecasts predict that by 2014 the number of BSs powered by renewable energy will exceed two hundred thousand.

While this is the situation in developing countries, operators in developed countries are experiencing a reduction of their margins, which are not as good as they used to be, and are forecast to almost disappear in the near future. For this reason, operators are looking for possible approaches allowing them to reduce cost, and have identified energy as an interesting target for cost reduction.

In this paper we tackle problems which are at the root of carrier-grade networking approaches that solely rely on renewable energy. We call this field *Zero grid Energy Networking* (ZEN).

The ZEN concept is based on a mesh network of BSs that are powered solely with renewable sources, and interconnected with wireless backhaul links, so as to cover the service area, and provide connection to few, typically remote, wired network accesses to the national and international backbone.

The challenges inherent in the ZEN concept are many:

- How to dimension BSs, and their power generators and energy storage
- How to design a distributed mesh network of BSs that can provide the necessary bandwidth both in the access and in the backhaul components
- How to route data and schedule transmissions on such BS mesh networks
- How to design distributed, but coordinated BS sleep modes in periods of low traffic, in order to reduce energy consumption
- How to guarantee uninterrupted service, fault tolerance and survivability, so as to provide carrier-grade services to end users

In this paper, we look into the first problem, and investigate the requirements for power generation and energy storage in the case of LTE macro and micro BSs. In particular, we focus on the problem of dimensioning the renewable energy sources (RES) powering system for a typical LTE BS. The methodology we use is the following. We start by discussing the BS energy need, that depends on both the BS consumption model and the BS traffic profiles. Focusing then on some specific locations, we consider the use of photovoltaic (PV) panels, and dimension them based on the daily energy need of the BS and on typical radiative power of sun in the considered locations. Once the PV system has been dimensioned, we also evaluate the energy storage capacity that is needed to absorb energy production variaibility due to both daily and seasonal radiative power variations. Finally, we investigate the effectiveness of integrating the PV system with wind turbines.

II. BS Power Need

In this section, we compute the BS power need by combining BS consumption models with typical traffic profiles. In particular, we evaluate the daily BS power need that is then used as input to the RES system dimensioning problem that will be discussed in the following sections.

In cellular wireless access networks, end users connect to BSs through a wireless channel and each BS, in turn, is connected to some other network element through either a wired or a wireless point-to-point link, which is part of the backhaul network. Several generations of cellular wireless access technologies exist, the most recent being LTE, which is also commonly called 4G. Using LTE, the downlink data transfer can reach data rates up to 100 Mbps, and adjacent cells can automatically configure in a sort of ”plug and play” fashion. LTE is an energy-efficient technology: assuming as a relevant power consumption metric for cellular wireless access networks the power necessary to serve each user [W/user], in [3] it is claimed that, in urban areas, with a typical user density of 300 users/km^2, LTE requires 18 W/user, to be compared against 27 W/user of WiMAX, and 68 W/user of HSPA. The power consumption of a cellular wireless access network is largely due to BSs, which can take up to 80% of the energy required to operate the network, including everything, from user terminals to core network elements [4].

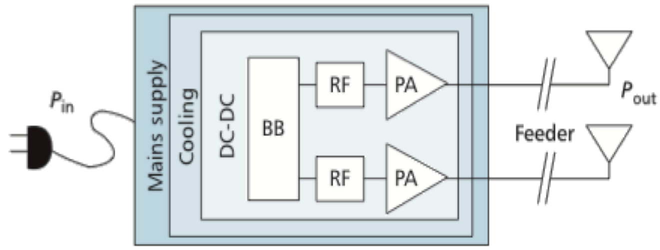

Fig. 1. Scheme of a BS.

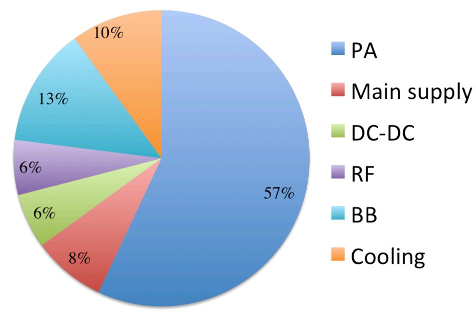

Fig. 2. Percentage power consumptions of various components of a BS.

In an urban area, an LTE macro BS can cover an area of about 0.22 km^2 with a range of about 500 m. In suburban/rural environments, the covered area can grow to 2.6 km^2 [4] with the same transmission power.

A BS (see Fig. 1) is comprised of a baseband unit (BB) and one or more transmitter/receiver (TRX), each one of which contains a radio frequency part (RF), a power amplifier (PA) and an antenna, connected through a feeder. In addition, a BS, which normally uses an input voltage of 48 V, also contains an AC-DC converter, a DC-DC converter, and a cooling system (sometimes just a fan).

In traditional deployments, BS equipment is located far from the antenna, so that long feeder cables are necessary, which induce high power losses. In the case of LTE BSs, quite often the RF and PA components can be located close to the antenna, so as to eliminate the feeder cable losses. This layout is called Remote Radio Unit (RRU) or Remote Radio Head. An additional advantage of the RRU layout is that in some cases cooling becomes unnecessary. In a LTE BS, the most power hungry element is the PA. LTE adopts an OFDM modulation scheme with high Peak to Average Power Ratio (PAPR) forcing the amplifier to operate in a linear region between 6 and 12 dB lower than the saturation point. This reduces the Adjacent Channel Interference (ACI), but increases the power consumption. The chart in Fig. 2 shows the percentage contribution to power consumption of the various components of an LTE macro BS.

The peak power consumption of a LTE macro BS is about 1350 W, in the case of 3 sectors, 2 antennas/PA per sector,

TABLE I
PARAMETERS OF THE CONSUMPTION MODEL FOR LTE BSs

Macro BS type	N_{TX}	P_{max} [W]	P_0[W]	Δ_p	P_{sleep} [W]
No RRU	6	20	130	4.7	75
With RRU	6	20	84	2.8	56

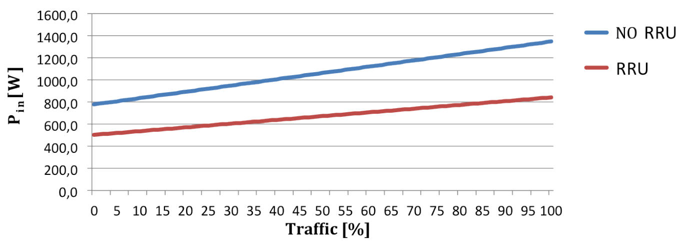

Fig. 3. Power consumption as a function of the load.

one carrier with 10 MHz bandwidth, and 2 x 2 MIMO. With a RRU configuration, the peak value decreases to about 800 W, thanks to a reduction of the energy consumed by the PA and by cooling. The actual instantaneous power consumption of a BS depends on the PA load, which in turn depends on the traffic carried by the BS. The relation between traffic load and power consumption can be expressed as in [4] by:

$$P_{in} = \begin{cases} N_{TX}\left(P_0 + \Delta_p P_{out}\right) & 0 < P_{out} < P_{max} \\ N_{TX} P_{sleep} & P_{out} = 0 \end{cases} \quad (1)$$

where N_{TX} is the number of antennas, P_{max} is the maximum power out of the PA at full load, P_0 is the power consumed when the RF output is null, Δ_p is the slope of the load-dependent consumption, and P_{sleep} is the power consumption when the BS is in sleep mode. Table I reports the parameter values for an LTE macro BS with and without RRU.

Fig. 3 shows curves of power consumption in W as a function of traffic, expressed as percentage of the peak.

In order to account for the variability of the BS power consumption with traffic, we need to consider realistic traffic profiles. To this end we use results of measurements in an operational network, separately considering a business area and a mainly residential or consumer area, during either weekdays or weekend. The traffic profiles are shown in Fig. 4. The traffic, that is normalized to the peak value, is measured on a cell in a business area or in a residential area of a network in operation; the solid markers identify the profile of a week-day, empty markers refer to a week-end day. Traffic values are obtained by averaging the measurements (at 15 minute intervals) collected during a week, and are then normalized to the peak value in the cell.

In both business and residential areas, the peak traffic is reached during week days, but at different times: at 11.30 in business areas and around 23 in residential areas. As expected, during weekends, traffic is very low in business areas, always less than 20% of peak traffic. During weekdays, traffic is high from 10 to 19, always within 60% of the peak. On the contrary,

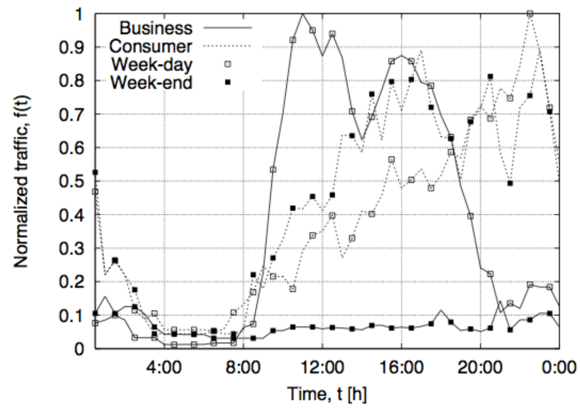

Fig. 4. Daily traffic profiles for a cell in a business area and a cell in a consumer area, week-day and week-end profiles measured in a network in operation.

TABLE II
DAILY CONSUMPTION [KWH]

	No RRU		With RRU	
	Week-day	Week-end	Week-day	Week-end
Business	23.9	19.5	15.2	12.5
Consumer	23.8	24.7	15.2	15.7

for consumer areas, traffic profiles in weekend and weekdays are similar, with an increase from 8 until 23. From traffic profiles, we can compute the BS power consumption profiles, assuming that the peak traffic leads to the maximum power consumption of the BS (this is a conservative assumption, since each BS is typically overprovisioned).

The total daily energy consumption in kWh for each case is reported in Table II.

III. RENEWABLE ENERGY SOURCES

We consider in this study the renewable energy sources which seem most adequate to power BSs: sun and wind. Photovoltaic (PV) modules can be used to convert solar radiation into electricity. The output power of a PV module is directly proportional to the solar radiation, and can be expressed as:

$$P = \frac{G}{1000} A\eta(G, T_m) \quad [kW] \quad (2)$$

where A is the module area in m^2, G is the solar radiation in W/m^2 and $\eta(G, T_m)$ is the module efficiency, which depends on radiation and temperature. A set of modules forms a PV panel. A set of panels forms a PV system, which is characterized by a *peak power* expressed in peak kW (denoted by kWp). To compute the number of modules required to generate a given peak power P_p, the following expression is used:

$$N = \lceil \frac{P_p}{P_{nom}} \rceil \quad (3)$$

where P_{nom} is the nominal power of the PV module. Some of the best PV modules on the market have P_{nom} equal to 333 W. Each module has an area of 1,63 m^2, meaning that 1 kWp is obtained with a panel of about 5 m^2.

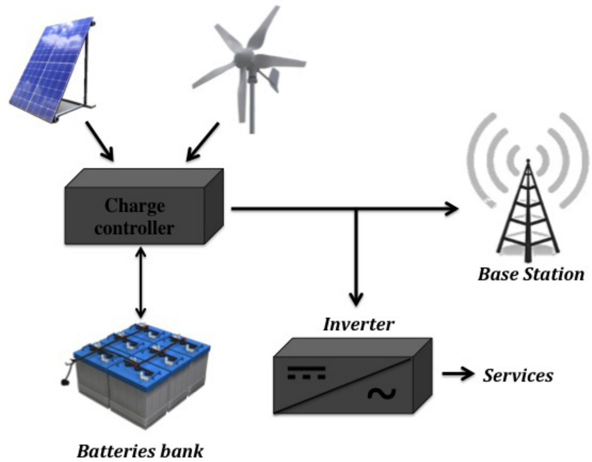

Fig. 5. Scheme of a BS powered with renewable energy sources.

Electricity can be generated from wind by using turbines, which convert the kinetic energy of the air flow into electricity. For a flow of air with density ρ in kg/m^3 and speed v in m/s, the generated power in Watt is:

$$P = \frac{\rho}{2} C_p \mu A v^3 \quad [W] \tag{4}$$

where C_p is the Betz limit, i.e., the max coefficient for an ideal turbine, equal to 0.6, and μ is the efficiency, A is the area swept by the rotor in m^2.

IV. Powering a BS with Renewable Energy

Fig. 5 shows the scheme of a BS powered by renewable sources (sun and/or wind). The generated power feeds a charge regulator, which provides power to the BS, and directs any excess power to an energy storage system. The inverter generates the AC power which will be again converted to DC inside the BS. Note that some energy could be saved by omitting the inverter, but this is normally not the case in real systems, since AC may be useful for several service functions. The energy stored in the battery is used whenever the power generated by the renewable sources is not sufficient to operate the BS.

A. BS powered with PV panels

For a detailed estimation of the energy production of a PV system, we have used the data of the PVWatts simulator [15], which was developed in the context of a project of the National Renewable Energy Laboratory (NREL) of Golden, Colorado. The inputs to be given to PVWatts are:

- Geographic position
- Peak power in kW
- DC-AC loss factor (including all losses in the conversion chain)
- Panel tilt and azimut

The simulator outputs the hourly power generation, exploiting the internally stored historical data about solar radiation in the Typical Meteorological Year (TMY) for the chosen location. In our study we considered 3 locations: Torino and Palermo in Italy, and Aswan in Egypt, so as to investigate the viability of the approach in both southern Europe and North Africa, and in locations with quite different solar radiation. While the average daily solar radiation in Torino, on a plane with optimal inclination, is 4 kWh/m^2, in Aswan it reaches 6.8 kWh/m^2, and in Palermo 5.09 kWh/m^2.

TABLE III
Loss factors

Actual peak wrt nominal	0.950
Inverter	0.920
Mismatch among modules	0.980
Diodes and connections	0.995
DC cables	0.980
AC cables	0.990
Dirt	0.950
Availability	0.980

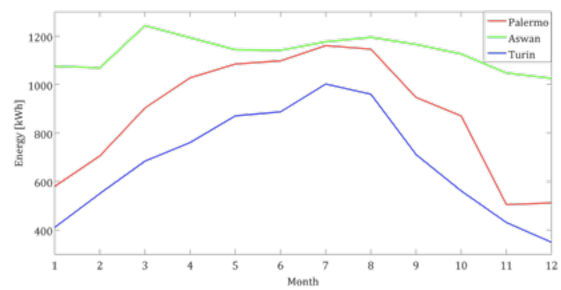

Fig. 6. Monthly energy production of a 8 kW peak power PV plant in the three considered locations.

The DC-AC loss factor is the product of many individual loss factors, that include losses due to the presence of the inverter, diodes, connectors and cables, losses due to dirt and periodical maintenence events. We use typical values for each of this factor and achieve an overall loss factor equal to 0.77. The detailed list of value of the parameters used for deriving the results is reported in Table III. For simplicity, we neglect the impact of shadowing due to buildings, assuming the PV panels are carefully positioned, and of aging, which can induce losses equal to 1% per year.

Fig. 6 shows the average monthly energy production in kWh for the three locations, as predicted by PVWatts in the case of a system with 8 kW peak power. It can be noted that the PV system in Aswan has a much more constant energy production with respect to both Palermo and Torino; overall, the Aswan system generates 66% more energy with respect to the one in Torino.

A first estimation of the PV system size that can be used to power a BS in the different cases under consideration is made by looking at the month with the minimum energy production (December for Torino and Aswan, and November for Palermo). For such months, the energy production of an average day is computed; the result is shown in Fig. 7, versus the time of the day. Obviously, production is zero at night, and

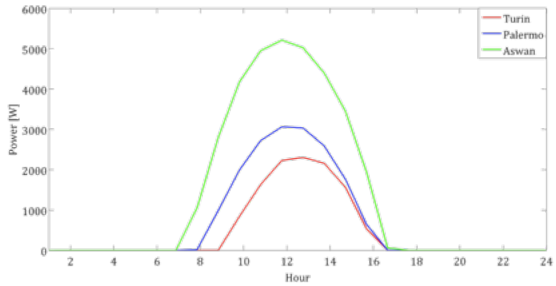

Fig. 7. Energy production of a 8 kW peak power PV plant in the three considered locations for the typical day of the month with minimum radiation.

TABLE IV
STARTING VALUES FOR PV SYSTEM DIMENSIONS IN KWP

	No RRU	RRU
Torino	18	12
Palermo	12	8
Aswan	8	6

peaks around noon, when the solar radiation is maximum.

The value of the nominal peak power for the PV system that can provide the energy necessary to power the BS on average, is computed in the case of the weekend residential traffic profile, which is the one which requires the highest amount of energy (the difference with respect to other traffic profiles is minor). Both configurations with and without RRU are considered. The choice of the nominal peak power value is made so that the energy produced during an average day of the worst month is sufficient to power the BS. Results are reported in Table IV. To power a BS with no RRU in Torino a PV system with 18 kWp is needed; this means a surface of 90 square meters! In the most favorable case (Aswan with RRU) these values reduce to 8 kWp, i.e., 40 square meters.

Unfortunately, these sizes, which are already quite problematic, do not account for the need for some excess energy production, necessary to compensate for fluctuations in energy production in different days, by generating energy to be stored in batteries to cope with periods of reduced or no production, and do not consider the losses which are introduced by the presence of energy storage units. These values however produce starting points for the dimensioning of systems which include energy storage, as discussed next.

B. Batteries

Batteries are needed to store energy so as to power the BS when the production from the PV panels is low or null. We consider simple 12 V lead-acid batteries with capacity 200 Ah, which are often used in conjunction with PV panels. The choice of the number of batteries required for a smooth operation of the BS is quite delicate and it must account for a number of aspects: i) the characteristics of the periods of high energy production and periods of low or no production; ii) the limits on the Depth of Discharge (DoD) of batteries, i.e., the minimum charge level required not to damage the batteries;

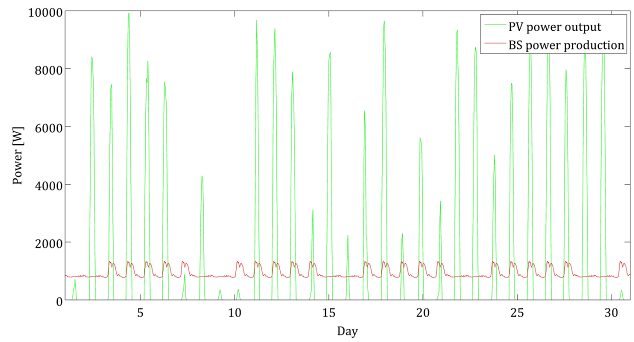

Fig. 8. Production and consumption for the month of December in Torino; 20kWp system.

iii) the number of discharge cycles (one discharge is counted when the battery charge becomes lower than the allowed DoD) before the battery replacement; iv) the battery efficiency η_b, which reflects the fact that not all energy input in the battery can be extracted; normally the value of η_b is around 85%.

To dimension the number of batteries needed by the BS powering system, we simulated one whole year of operation using the data of the Typical Meteorological Year (TMY). We chose the number of batteries so as to guarantee that during the year the battery charge level never goes below 30%, which means DoD equal to 70%, considering, hour by hour, the energy generated by the PV system and the energy consumed by the BS.

Fig. 8 reports the results of the simulations for the Torino site, and only for the month of December (which is the most critical one, corresponding to the lowest energy production). The energy production curve is reported in green for a PV system with 20 kWp; the energy consumption is the red curve in the case of a BS in a business area. Note the variable height of the daily peaks of energy production: some days have minimal energy production.

The yearly behaviors of the charge level of batteries for a BS in a residential area for Torino and Aswan are reported in Figs. 9 and 10. We show the residential area case, which is more critical, since the traffic load is similar for weekdays and weekends; the business area case instead can take advantage of the fact that during weekends traffic is very low, and so is energy consumption, thus batteries can be more easily recharged. The red portions of the curves correspond to energy generated by the PV system which is lost, because the battery is already fully charged. The green portions of the curves show the charge level, when lower than 100%. As can be seen, the battery charge level never drops below 30%, as desired (note that total battery discharge is still possible, due to meteorological deviations from the TMY). This is achieved for a minimum amount of energy storage, which corresponds to the battery dimensioning for the BS.

The results of the simulations led us to the dimensioning of the peak power of the PV system, and of the number of batteries. Results are reported in Table V.

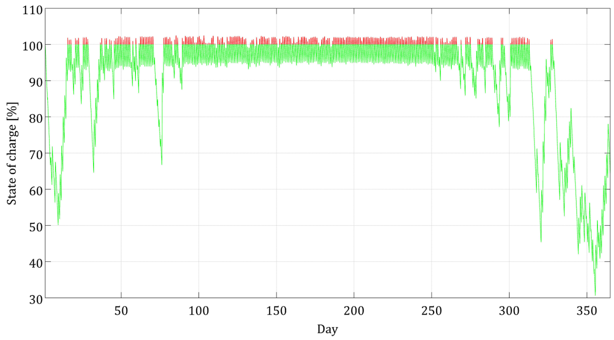

Fig. 9. Simulation of batteries charge levels, for the case of a residential area in Torino.

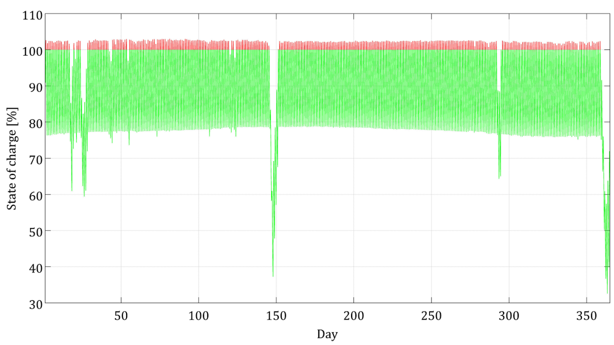

Fig. 10. Simulation of batteries charge levels, for the case of a residential area in Aswan.

The conclusions that can be drawn from the results heavily depend on the BS location and type. In the case of a BS with RRU located in Aswan, a 6x5 m PV system is necessary, with 16 batteries. This seems not very convenient, but doable. On the contrary, a BS with no RRU located in Torino requires a 10x10 m PV system, with 75 batteries, which seems unrealistic. Considering that the primary aim of our investigation is in developing African countries and rural areas, we could consider the result acceptable. Nevertheless, in order to explore better opportunities, in the next section we investigate the benefits of mixing sun and wind as renewable energy sources.

C. *BS powered with PV panels and wind turbines*

Wind has the characteristic of being much more variable than sunlight, but this variability brings with itself the advantage of not being constrained to daytime periods, and to specific seasons. As such, wind turbines can provide a very effective complement to PV panels to power BSs, especially

TABLE V
WHOLE PV SYSTEM DIMENSIONING

Location	No RRU			With RRU		
	Size [kWp]	No. batt.	Panel area [m^2]	Size [kWp]	No. batt.	Panel area [m^2]
Torino	20	75	97.8	14	45	68.5
Palermo	16	50	78.2	10	32	48.9
Aswan	8	30	39.1	6	16	29.3

TABLE VI
AVERAGE YEARLY AND DAILY PRODUCTION OF WIND TURBINE SYSTEMS

	Torino		Palermo		Aswan	
	3.2 m 2 kW	4.5 m 3 kW	3.2 m 2 kW	4.5 m 3 kW	3.2 m 2 kW	4.5 m 3 kW
Yearly [kWh]	648	710	1542	1682	3995	4371
Daily [kWh]	1.8	1.9	4.2	4.6	10.9	12

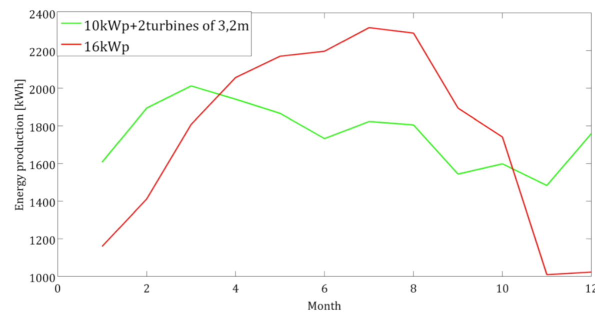

Fig. 11. Production of a purely PV system and an hybrid PV/wind system in Palermo.

during nights, and months of low solar radiation. Since precise data about the daily wind force in given locations are not available, we account for the average annual wind speed in the three locations we consider in this paper: Torino 3 m/s, Palermo 5.5 m/s, and Aswan 4 m/s, and derive the yearly energy production for turbines with diameter 3.2 m and 4.5 m. The results are in Table VI.

The values for Torino indicate a very small energy production, which seems not worth the increased complexity of a hybrid wind/solar system. The same conclusion applies also for Aswan; here the average amount of energy generated per day is more than double in absolute terms with respect to Torino, but if we consider that the energy generated by the PV system in the worst month, December, is over three times higher in Aswan, also in this case the contribution of wind turbines seems not worth the extra complexity. The case of Palermo is different: the 10 kWp PV system for the case with RRU produces about 13,200 kWh per year, an amount which can be obtained also using a hybrid system comprising a PV system with 4kWp and two wind turbines with 3.2 m diameter. Looking in more detail at wind speed in Palermo, we observe a monthly average speed around 4.5 m/s in summer and between 6.0 and 6.4 in winter months. The fact that wind is stronger in months of lower solar radiation suggests that the two energy sources can complement each other very well in this case. This is confirmed by Fig. 11 that compares the energy production of the 16 kWp PV system with the one of a hybrid system comprising a 10 kWp PV system and two wind turbines with 3.2 m diameter. The production curve of the hybrid system is flatter; this is a very good result, since it implies that the energy needs of the BS are satisfied all year, with limited excess generation, contrary to the case of a pure PV system, which is correctly dimensioned for the winter months, but results largely overdimensioned in summer.

TABLE VII
DIMENSIONING OF AN HYBRID SYSTEM IN PALERMO

	Business profile		Consumer profile	
	No RRU	With RRU	No RRU	With RRU
PV [kWp]	10	4	10	5
Turbine diameter [m]	2	2	2	2
No. batteries	21	20	36	20

The resulting dimensioning for a hybrid system in Palermo is presented in Table VII, for both cases of RRU and no RRU, and both business and residential traffic profile.

V. IMPACT OF BS SLEEP MODES

Sleep modes are today considered one of the most promising approaches to reduce the power consumption of cellular networks [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. Indeed, while all the BSs of a cellular network are normally necessary to provide the desired QoS to end users during periods of high traffic, in periods of low traffic only a fraction of the BSs is sufficient to provide the same services, and some BSs can enter low-power sleep modes. This means that a significant portion of the hardware of the BSs that can enter sleep mode are switched off, starting from the most power hungry elements, like the power amplifier. Of course, sleep modes require a careful network design in order to guarantee that by putting some BSs to sleep no coverage hole is generated. In this section we provide a very preliminary assessment of the impact of sleep modes on the dimensioning of renewable power sources for BSs, by assuming that a fixed fraction of the BSs can be put to sleep in periods of low traffic without generating coverage holes and still guaranteeing quality of service.

Sleep modes can be of different sorts, depending on the portions of the BS equipment that is switched off. In the case of partial switch-off, the BS can be switched on rapidly, in the order of fractions of seconds, but the power consumption remains non-negligible, around 30% of the power consumption at full load. In the case of total switch-off, the power consumption goes down to almost zero, but the switch-on time is of the order of minutes. The power consumed by a BS in the case of partial switch-off in our study is assumed to be 450 W in the case with no RRU, and 336 W with RRU.

In this very preliminary evaluation we assume that half the BSs in a given area can enter sleep mode when the traffic is below 50% of peak [10]. We assume that all BSs have the same traffic profile, which is a reasonable assumption in an area with uniform utilization (all business or all residential traffic) and we use the traffic profiles of Fig. 4. We use the identifier BS0 for the BSs that go to sleep, and BS1 for those that remain active.

Fig. 12 shows the energy consumption profiles for both types of BS in the case of the business traffic profile and no RRU. In particular, in the top plot, the green curve shows the weekday traffic profile and the red line indicates the threshold below which BSs of the type BS0 go to sleep and BSs BS1 absorb the traffic. The middle and bottom plots in the same figure, show the power consumption profiles of BS0 and BS1, respectively, in the case of partial switch-off. Note that in the periods of sleep the power consumed by BS0 is constant at 450 W. Observe also the (small) power consumption increase of BS1 around the switch-on and switch-off times of BS0.

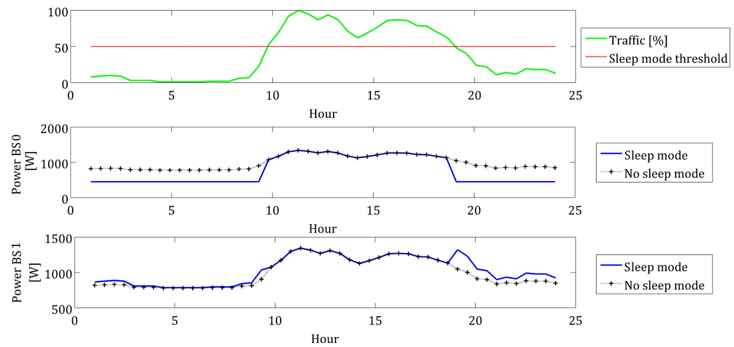

Fig. 12. Energy consumption profiles with sleep modes, case of business profile and no RRU. Profile with load threshold (top), profile for the BSs that enter sleep mode (middle), profile for the BSs that are always active (bottom).

TABLE VIII
IMPACT OF BS SLEEP MODES

			Partial sleep		Deep sleep	
		BS1 [kWh]	BS0 [kWh]	Save [%]	BS0 [kWh]	Save [%]
Business	No RRU	24. 7	18.5	10.5	12.2	29.3
	With RRU	15. 7	12.4	8.2	7.7	30.0
Consumer	No RRU	25.7	17.1	8.2	10.3	47.7
	With RRU	16.6	11.6	7.6	6.5	32.9

The daily energy consumption for both types of BS and for the two types of traffic profiles are summarized in Table VIII, in the case of partial sleep and deep sleep. The daily energy consumption reductions are of the order of 10% for the case of partial sleep and they grow to 30-45% when deep sleep modes are used.

By repeating the PV system dimensioning, as in the previous sections, for the case in which half the BSs can go to sleep mode when the traffic is below 50% of peak, we obtain the results of Table IX, that refers to the consumer traffic profile and the case of no RRU, that are the most consuming cases considered so far. With a partial BS switch-off, peak powers of the powering system decrease by 2 to 4 kWp, corresponding to a reduction in the area of the PV panels of 10 to 20 m^2. Instead, with a total switch-off, peak powers decrease by 4 to 8 kWp, corresponding to a reduction of area of the PV panels of 20 to 40 m^2. The number of batteries reduces also significantly, becoming almost half in some cases. Of course, this reduction only applies to half the BS, those that are put to sleep.

For the case of Palermo, we also report in Table X the result of the dimensioning of a hybrid system in the case of BSs which allow sleep mode.

We see that by adding 1 or 2 wind turbines, and by using sleep modes, and RRU, the size of the PV systems becomes manageable (2-6 kWp, i.e., 10-30 m^2, and 13-14 batteries) for

TABLE IX
PV SYSTEM DIMENSIONING: NO RRU, CONSUMER PROFILE

	No sleep		Partial sleep		Deep sleep	
	kWp	No. batt.	kWp	No. batt.	kWp	No. batt.
Torino	20	75	18	61	12	42
Palermo	16	50	12	40	8	28
Aswan	8	30	6	23	4	19

TABLE X
HYBRID SYSTEM DIMENSIONING: CONSUMER PROFILE IN PALERMO, 2 KWP TURBINES WITH 3.2 DIAMETER

	No RRU			With RRU		
	No. turb.	PV kWp	No. batt.	No. turb.	PV kWp	No. batt.
Partial sleep	1	6	22	1	6	14
Deep sleep	2	8	22	1	2	13

those BSs which implement sleep mode.

VI. THE CASE OF MICRO BS

In this section we briefly look into the case of LTE micro BSs, and the possibility of powering them with PV panels. The parameters of a typical LTE micro BS that allow the computation of the BS power consumption from (1) are reported in Table XI. The energy consumption versus traffic function for a LTE micro BS has a linear behavior, depicted in Fig. 13.

Considering the usual traffic profiles of Fig. 4, we compute the daily energy consumption for a LTE micro BS, in the cases of no sleep, partial sleep, and deep sleep. As before, we assume that sleep modes are activated for half the BSs, when their traffic becomes less that 50 % of the peak value. Results are reported in Table XII. It can be immediately observed that the daily energy consumption of micro BSs is much lower than for macro BSs. As with macro BSs, the deep sleep mode allows saving significantly more energy with respect to the partial sleep mode.

Repeating now for micro BSs the same procedure reported in previous sections for the case of macro BSs, we can first dimension the size of the PV panel so that the daily generated energy equals the daily consumed energy. Starting from this value, we can refine the dimensioning of the PV panel, including batteries, with their constraints and losses. The final result of the dimensioning of the PV panel and the number of batteries necessary to power a LTE micro BS under the consumer traffic profile, in the three considered locations, are reported in Table XIII. We see that the case of micro BSs is much more manageable that the case of macro BSs. Indeed, in the case of Aswan the required PV size is between 15 and 20 m^2, and the number of batteries is between 6 and 8. Even the most critical case, Torino, only requires PV sizes between 30 and 40 m^2, and 20-24 batteries.

TABLE XI
PARAMETERS OF THE CONSUMPTION MODEL FOR LTE MICRO BSS

N_{TX}	P_{max} [W]	P_0 [W]	Δ_p	P_{sleep} [W]
2	6.3	56	2.6	39

TABLE XII
IMPACT OF SLEEP MODES FOR MICRO BS

		Partial sleep		Deep sleep	
	BS1 [kWh]	BS0 [kWh]	Save [%]	BS0 [kWh]	Save [%]
Business	3.80	2.48	13.7	1.93	21.3
Consumer	3.98	2.21	14.9	1.63	23.0

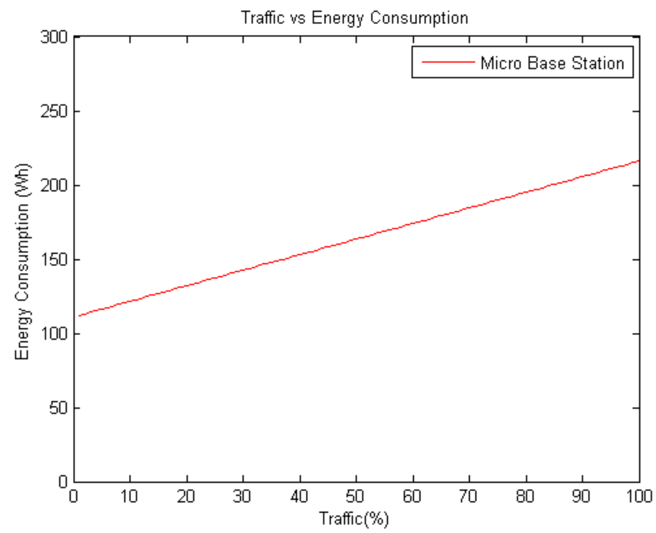

Fig. 13. Energy consumption of a micro LTE BS as a function of traffic load.

TABLE XIII
PV SYSTEM DIMENSIONING FOR MICRO BS: CONSUMER PROFILE

	No sleep		Partial sleep		Deep sleep	
	kWp	No. batt.	kWp	No. batt.	kWp	No. batt.
Torino	8	24	7	23	6	20
Palermo	6	14	5	15	5	11
Aswan	4	6	3	8	3	6

VII. DISCUSSION ABOUT CAPEX AND OPEX

In this section, we compare the Capital Expenditure (CapEx) and Operational Expenditure (OpEx) of the BSs powered by: a) solar panels; b) diesel generators; and c) power-grid, from which we assess the potential advantages of renewable energy utilization in terms of cost. We compute the CapEx and OpEx over a 20 years period, because typically the lifetime of solar panels is 20 years [16]; similarly, the BSs are usually substituted by the next-generation telecommunication technologies every 20 years. The lifetime of the battery model we are using (lead-acid, 12 V, 200 Ah) is 500-800 battery cycles [17]; thus, for our computation, we use the most pessimistic assumption of 500 battery cycles. From the number of battery cycles needed per year by the PV system, we derive the number of times that the batteries should be renewed in a 20 years period. Table XIV reports the size of the PV system in kWp and the number of batteries needed in 20 years for micro base stations in Torino and Aswan. The number of battery cycles in Aswan

TABLE XIV
SIZE OF PV PANELS, NO. OF BATTERY CYCLES PER YEAR, AND NO. OF BATTERIES USED IN 20 YEARS. CASE OF A MICRO BS UNDER CONSUMER TRAFFIC PROFILE.

		No sleep	Partial sleep	Deep sleep
Torino	PV(kWp)	8	7	6
	No. batt. cycles per year	68	59	67
	No. batt. needed for 20 years	48	46	40
Aswan	PV(kWp)	4	3	3
	No. batt. cycles per year	128	130	89
	No. batt. needed for 20 years	30	27	22

TABLE XV
COMPARISON OF CAPEX, OPEX AND THE TOTAL COST FOR THREE CASES. CASE OF TORINO, MICRO BS WITHOUT SLEEP MODE, CONSUMER TRAFFIC PROFILE.

	CapEx (euro)	OpEx (euro)	Total (euro)
PV system	17600	negligible	around 18000
Diesel generator	1000	214000	215000
Power Grids	0	17520	17520

is larger than in Torino because charging and discharging is more frequent and deep in Aswan (as previously shown in Figs. 9 and 10).

From the results in Table XIV, we compute the CapEx for the whole PV system, including the cost of PV panels and batteries. The price of the PV panel is about 1,000 euro per kWp, and the price of the lead-acid batteries is about 200 euro [18]. The maintenance cost of the PV Panel is \$6/kWp - \$27/kWp, which is less than 1%-5% of the overall cost, so that the OpEx of the PV system can be considered negligible [19]. For the BS without PV system we consider the CapEx to be the cost of the diesel generators needed for powering the BS. We consider a 2 kW diesel generator, which is enough for powering micro BSs. The price of fuel is about 1.5 euro per liter, the price of the diesel generator (CapEx) and the cost of the diesel consumption for 20 years (OpEx) are listed in Table XV [20], together with the CapEx and OpEx of the case of renewable energy sources case. The table reports also the case in which the power grid is used. The price of commercial electricity is about 0.2 euro per kWh in Italy. Note that, in the comparison, we do not include the cost of the BS itself because it has the same price for all three cases.

From Table XV we observe that the PV system is not only energy-efficient, but also cost-efficient. It costs about the same as traditional power grids, and it costs much less than a diesel generator. In rural areas or in developing countries, in which power grids are not always available or reliable, the use of renewable energy utilization is the most energy-and-cost-efficient way for powering BSs.

VIII. CONCLUSIONS

In the new context of sustainable networking, we have investigated in this paper the possibility to power cellular access network BSs relying on renewable energy sources only, i.e., with no energy acquired from the power-grid. In particular, we have considered LTE macro and micro BSs carrying realistic traffic profiles that were collected from cells in business and consumer areas of a network in operation. Based on the typical energy need of the BSs, the photovoltaic powering system was dimensioned for three locations with different typical solar radiation values.

The dimensioning shows that the size of the photovoltaic panels is quite large, between 70 and 100 square meters in the considered Italian locations. These values suggest that individually powering zero-grid BSs is not always feasible. In the cases of windy areas, the additional support of wind turbines can reduce the size of the panels of about 30-50%; more sophisticated radio technologies can also improve the situation. Finally, the use of sleep modes that reduce the consumption of a fraction of BSs when the traffic is low, leads to a further reduction of the system size.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 257740 (Network of Excellence TREND) and the Italian Ministry of University and Research under the project EFFICIENT.

The authors are thankful to Raffaella Gerboni of the Department of Energy of Politecnico di Torino, for providing material and documents, and for fundamental suggestions and fruitful discussions.

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