Abstract—The use of solar energy to power base stations of cellular networks is becoming increasingly interesting, in both areas where the power grid is not present or not reliable, and where the power grid is ubiquitous and reliable, but energy costs keep growing. In this paper, we investigate the dimensioning of the photovoltaic panel and energy storage of a hybrid base station powering system that can exploit both solar and grid energy. The objective of the dimensioning is the minimization of the total capital and operational expenditures over a period of 10 years, accounting for the evolution of technology and traffic load. Results show that in a south European city like Torino, a hybrid base station powering system allows significant cost and size reductions, with respect to the case of solar energy only (and of a diesel power generator), and roughly equals the cost of the grid-only case in 8–9 years. When the extra energy produced by the solar panel can be sold back to the grid, the hybrid systems allow significant savings with respect to the grid-only case. For the city of Aswan, with a production that is much higher than in Torino and more constant over the year, costs of pure solar and hybrid systems are significantly lower in absolute terms; hybrid systems result to be still advantageous with respect to pure solar systems.

I. INTRODUCTION

The use of renewable energy sources (sun, in particular, and wind, to a lesser extent) to power base stations (BSs) of cellular wireless access networks is becoming increasingly interesting for mobile network operators (MNOs), because of two main reasons. First, cellular services are now being provided in areas where the power grid is not present or not reliable; second, photovoltaic (PV) panels have been proved to be much more cost-effective than diesel generators (in some areas differences in cost are as high as an order of magnitude [1]). Orange, for example, has already deployed over 2,000 solar-powered BSs serving more than 3 million people in Africa, with a saving of 25 million liters of fuel and 67 million kg of CO₂ in 2011 [2]. These experiences, coupled with increasing energy costs, are making solar energy an interesting option also for countries where the access to the power grid is typically ubiquitous and reliable. For a recent survey of the use of renewable energy in cellular networks see [3], for recent related works see also [4], [5].

In a previous work [6], we discussed the dimensioning of the PV panel and the number of batteries to power one LTE macro BS which is disconnected from the grid (off-grid BS), proving that the BS can be powered by current technology PV panels with acceptable size, coupled with a reasonable number of batteries, and also showing that the resulting dimensioning strongly depends on the BS location, due to significant differences in solar radiation. We also observed that the resulting PV system dimensioning essentially depends on the solar radiation in the periods with lowest sunshine (worst-case dimensioning is necessary for off-grid operation). This is not critical for locations where the solar radiation exhibits small variations during a year, (the location we examined with these characteristics in [6] is Aswan in Egypt), but leads to significantly inefficient PV systems for locations with large seasonal variations of the daily solar radiation (we considered in [6] Torino and Palermo in Italy). This observation led to the question of how much can be gained in terms of overall cost of the BS powering system if some energy can be taken from the power grid, to cover periods with low PV generation due to low solar radiation, so as to allow the use of PV panels of smaller size and lower numbers of batteries. A recent work has proposed a hybrid diesel-solar energy system to power a BS [7], providing a proof of the feasibility of hybrid energy utilization.

In this paper, we approach the dimensioning of the powering system of a LTE macro BS which is equipped with a PV panel and a set of batteries, but is also connected to the power grid, to obtain energy in the periods in which the PV panel is not generating enough power, and batteries are depleted. The dimensioning is based on the minimization of the overall system cost over 10 years (the typical life span of a mobile network technology generation, as observed for GSM and UMTS), and includes the CAPEX (capital expenditures) due to the PV panel and the batteries (including the necessary battery replacements during the 10-year period), as well as the OPEX (operational expenditures) due to the power extracted from the power grid. In our computations, we consider the evolution of the traffic load and of the electricity price in the 10-year period, as well as the PV panel degradation and the improvement of battery technology.

The rest of this paper is organized as follows. Section II outlines the dimensioning methodology used in the paper. Section III provides details for the dimensioning methodology, in the case of a LTE macro BS with remote radio units. Sections IV and V present the application of the methodology to the locations of Torino and Aswan, respectively, and discuss numerical results. Section VI concludes the paper.
II. THE DIMENSIONING METHODOLOGY

Our procedure for the dimensioning of the powering system of a LTE macro BS which is equipped with a PV panel and a set of batteries proceeds along the following steps.

1) We identify the daily traffic profile for the BS, distinguishing weekdays and weekends, as well as residential and business areas. We then apply a scale factor to the traffic profiles, in order to account for the traffic growth, from today, with LTE at the beginning of its deployment as a new technology, to 10 years from now.

2) For each year of the considered 10-year period, by properly setting the traffic scaling factor, we use an energy consumption model to relate the BS power consumption to the carried traffic, and we compute the daily power consumption profile for the BS in the various cases (weekday/weekend, and residential/business). We then compute the power consumption profile over one week, and we extend it to the whole year.

3) For each year $y = 1, \ldots, 10$, we derive a possible dimensioning of PV size and batteries, proceeding as follows:

   a) We identify the daily profile of the solar radiation for the considered geographical location, for every day of the typical meteorological year. From this profile, we use standard coefficients to compute the energy generated by a PV panel of unit area; this computation also accounts for the progressive efficiency reduction of the PV panel with age.

   b) For increasing sizes of the PV panel, we compute the profile of the energy generated by the PV panel, and we subtract from it the daily profile of the energy consumed by the BS, computing the energy stored and drained into/from batteries, and also obtaining the minimum number of batteries necessary to keep the battery charge above 30% for a predefined percentage of time (PT) during the whole year.

4) For all the solutions identified above, in terms of the PV panel size and the corresponding minimum number of batteries, we compute the cumulative depth of discharge of batteries during one year, and from it we derive the battery duration.

5) For all generated solutions, we compute cost by adding the initial CAPEX for PV panel and batteries, the additional CAPEX for battery replacements, and the OPEX for the acquisition of power from the grid. We neglect other operational expenditures, which can be considered almost invariant with respect to the adopted solution.

6) We identify the solution which leads to the minimum cost over the considered 10-year period, accounting for the increase in traffic, the degradation of the PV system, and the increase in electricity cost. Year $y$ to which the solution corresponds, represents the reference year for dimensioning.

The rest of this paper provides more details for each step, as well as numerical results.

III. SYSTEM SETTING

In this section we provide details for the dimensioning procedure outlined before, considering a LTE macro BS with remote radio units (RRU).

The architecture of the BS powering system is depicted in Fig. 1. An energy management unit receives the power coming from the PV panel and the power grid, and can either inject power into the battery or drain power from it. The energy management unit uses the power of the PV panel, and if this is more than necessary to power the BS, it is also used to charge the battery. The battery power is drained when the PV panel production is not sufficient. The grid power is used only when the battery is depleted.

Fig. 2 shows the traffic profiles used in the dimensioning procedure. Traffic is measured at 30-minute intervals on cells of the network of an Italian mobile network operator, distinguishing weekdays and weekends, and residential (consumer) and business areas. Traffic profiles are normalized to peak traffic. To consider the increase of traffic in the 10-year span used for the optimization, we scale the traffic profile with a factor that accounts for the fraction of BS capacity that is used at peak traffic. We assume that, when the deployment of a new technology, such as LTE, starts, the peak traffic is very low, namely only 2% of the BS capacity. We then allow traffic to increase, scaling it up with a 50% Compound Average Growth Rate (CAGR) per year, as predicted in [8]. At the end of the 10-year period, the peak traffic reaches about 77% of the BS capacity, thus leaving some capacity margin. The second column of Table I reports the peak traffic load evolution over the 10 years.

The relation between the power consumption of a LTE macro BS and its traffic load $\rho$ can be expressed as:

$$P(\rho) = N_{TX} (P_0 + \Delta_p P_{max}) \quad 0 \leq \rho \leq 1,$$

where $N_{TX}$ is the number of antennas, $P_{max}$ is the maximum power out of the RF power amplifier, $P_0$ is the power consumed when the RF output is null, $\Delta_p$ is the slope of the emission-dependent consumption [9]. In our numerical analysis, we assume typical values for a LTE macro BS with RRU: $N_{TX} = 6$, $P_{max} = 20$ W, $P_0 = 84$ W, $\Delta_p = 2.8$. Using this expression, for each measured traffic value and
traffic scaling factor, we obtain the BS power consumption of a given case (residential or business), and we derive the daily power consumption profile (power vs time) for the BS in weekdays and weekends. From the daily profiles, the power consumption profile over one week is derived, and is then extended to one whole year, assuming all weeks to be equal in terms of traffic (this is a conservative assumption, since we neglect the effect of holidays).

The solar radiation and power generation profiles are obtained from PVWatts [10], which is a well-known tool for the computation of the power generated by a PV panel with predefined peak power (kWp) in the typical meteorological year. The PV panel peak power is directly proportional to its size; standard PV technologies require about 5 m² for 1 kWp. We assume that the degradation of the efficiency of the solar panel is 1% per year, as shown in the third column of Table I [11].

<table>
<thead>
<tr>
<th>Year</th>
<th>Peak traffic load</th>
<th>PV efficiency</th>
<th>Electricity price [€/kWh]</th>
<th>Diesel price [€/liter]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aswan</td>
<td>Aswan</td>
</tr>
<tr>
<td>1</td>
<td>0.020</td>
<td>1</td>
<td>0.217</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>0.030</td>
<td>0.99</td>
<td>0.223</td>
<td>0.084</td>
</tr>
<tr>
<td>3</td>
<td>0.045</td>
<td>0.98</td>
<td>0.23</td>
<td>0.098</td>
</tr>
<tr>
<td>4</td>
<td>0.067</td>
<td>0.97</td>
<td>0.236</td>
<td>0.112</td>
</tr>
<tr>
<td>5</td>
<td>0.101</td>
<td>0.96</td>
<td>0.243</td>
<td>0.126</td>
</tr>
<tr>
<td>6</td>
<td>0.151</td>
<td>0.95</td>
<td>0.249</td>
<td>0.14</td>
</tr>
<tr>
<td>7</td>
<td>0.227</td>
<td>0.94</td>
<td>0.256</td>
<td>0.154</td>
</tr>
<tr>
<td>8</td>
<td>0.341</td>
<td>0.93</td>
<td>0.262</td>
<td>0.168</td>
</tr>
<tr>
<td>9</td>
<td>0.512</td>
<td>0.92</td>
<td>0.269</td>
<td>0.182</td>
</tr>
<tr>
<td>10</td>
<td>0.768</td>
<td>0.91</td>
<td>0.275</td>
<td>0.196</td>
</tr>
</tbody>
</table>

### IV. CASE STUDY: TORINO

In this section we apply the dimensioning procedure described above to the case of the city of Torino, in Northern Italy. In the considered scenario, the 9-th year turns out to be the reference year for dimensioning. The results shown below refer to this case.

### A. Number of Batteries and Battery Replacement

As explained in step 3 of the procedure, we consider progressively increasing panel sizes and derive the PV panel power generation profile from which we compute the energy stored and drained into/from batteries. We then derive the minimum number of batteries necessary to keep the battery charge above a predefined level (set to 30%) for a percentage of time \((PT)\) during one year.

The charge status of the batteries with \(PT = 100\%\) and \(PT = 70\%\) can be simulated as shown in Fig. 3 and Fig. 4, respectively. The green portions of the graph correspond to the actual charge status of the batteries. Instead, the red zone over 100% represents the energy loss (or the energy that could be sold back to the power grid, if possible) due to power generation when battery charge is 100%. The red zone below zero in Fig. 4 represents the energy which is necessary to operate the BS when the battery is depleted, and which must be taken from the power grid. In the case of \(PT = 100\%\), to guarantee continuous operation of the BS even in winter when production is low, the size of the PV panel and the number of batteries are significantly larger than in the case of \(PT = 70\%\); the battery status is almost always above 90% in spring, summer and autumn, meaning that the overprovisioning of the solar system in these periods is significant. On the contrary, in the case with \(PT = 70\%\), the battery charge and discharge is distributed more evenly during the whole year, and some energy is drained from the power grid in winter.

Fig. 5 shows the minimum number of batteries needed to run the system during the 10-year period, for different values of \(PT\), assuming that the PV panel size does not change during the whole time span (the PV panel is however dimensioned according to the requirements of the 9th year, as resulting by our methodology), and computing the necessary number of batteries year by year (note that this implies that the number of batteries changes over the 10-year period, installing additional batteries when necessary, while the PV panel remains the same). As \(PT\) increases, the constraint on the battery charge becomes tighter and, hence, the number of requested batteries increases; in addition, as years go by, the reduction of the PV panel efficiency combined with the traffic increase make the requested number of batteries increase as well. However, since the 9-th year is considered as a reference for dimensioning, the system results slightly overdimensioned in the first 8 years, and this prevents the number of batteries from growing very significantly.

The simulation of batteries status, like in Fig. 4, allows the computation of the total battery discharge over one year, as the sum of all battery discharges. This value, combined with the maximum number of discharge cycles allowed for batteries before replacement, gives the time between battery replacements. The lifetime of the commonly used lead-acid batteries today is about 500 battery cycles, which means 500 total battery discharges, or smaller discharges that sum up to the same amount [12]. We compute the battery replacement by introducing the battery lifetime computation, in an evolution-
Fig. 3. Example of battery status for a system with kWp=16.6, 27 batteries, \( PT = 100\% \) (i.e., without grid power), during the 9-th year under the residential traffic profile, in Torino.

Fig. 4. Example of battery status for a system with kWp=4.3, 5 batteries, \( PT = 70\% \), during the 9-th year under the residential traffic profile, in Torino.

In [13] it is shown that the lifetime of the lead-acid batteries in 2030 will be around 3000 battery cycles, much better than today, at roughly the same price as today. Thus, we assume a linear growth of the number of battery cycles from 500 to 3000 cycles in the time span from today to 2030 and, whenever we replace batteries during the 10-year period, we use the newest model of batteries, using the projection above as a reference for the number of cycles per battery lifetime.

### B. Minimum Cost Systems

The cost of the BS powering system is computed by putting together CAPEX and OPEX. The price of solar panels and batteries can be estimated from a recent report by NREL [14], concluding that the price of a lead-acid battery (12 V, 200 Ah) is approximately 200 USD and the price of 1 kWp PV panel is around 1,000 USD (equivalent to 155 \( \text{€} \) and 770 \( \text{€} \), respectively). As regards power drawn from the grid, we use the (admittedly high) electricity price for Italy of around 0.217 \( \text{€} \)/kWh, and apply a price increase of 3\% per year in the 10-year period [15], as shown in the 4th column of Table I.

From simulation, we found that the system dimensioning leading to the minimum cost, summing CAPEX and OPEX, uses year 9 as reference. The results of the dimensioning, deriving from 9-th year parameters, for the case of \( PT \) equal to 70\%, 80\%, 90\%, and 100\% (this last case implies an off-grid BS) are reported in Table II. The cases for \( PT \) equal to 70\% and 80\% show a significant saving of PV panel dimension compared to the off-grid case (4.3 kWp vs. 16.6 kWp, corresponding to 21 m\(^2\) vs. 83 m\(^2\)), as well as an important cost reduction. The last column of Table II shows the revenue assuming that the excess energy (i.e., the red zone above 100\% in Fig. 4) can be sold back to the power grid. This revenue is computed by assuming the selling price to be equal to half the buying price, i.e., 0.12 \( \text{€} \) in the first year, and 0.1488 \( \text{€} \) in the 9-th year, with the same yearly increase as the electricity price (3\% per year).

Fig. 6 shows the total cost, obtained by adding CAPEX and OPEX year by year, versus time, when no energy sell-back is possible, for different values of \( PT \). As a reference for the off-grid case, we also consider the case of power production through a diesel generator. We assume a cost of 5,000 USD for a 20 kW generator, which produces 15 kW operating at 3/4 load, and burning approximately 5 liters of fuel per hour [16]. Therefore, the produced 15 kWh cost about 8 euro (according to the current Italian price of diesel fuel). We...
increase this cost of a factor 1.5 to account for the inefficiency in the power generation, due to daily variability in the power absorbed by the BS. Finally, we assume that the price of diesel fuel grows at the same rate as the price of electricity (3%), as shown in the 5th column of Table I. These assumptions for the diesel generator apply to a geographical location with reliable infrastructure, as the one considered here. In areas with limited infrastructure, the cost of the whole supply chain can become up to one order of magnitude larger.

Observing the results in Fig. 6, we see that in the case with $PT = 100\%$, batteries need to be replaced only once, at the 8-th year; instead, for all other cases, batteries are replaced twice, as can be seen from the small steps in cost. In addition, batteries are added along the time axis, when necessary. The pink line refers to the case of a BS powered from the grid only (i.e., with no PV panel and no battery). The results show that the hybrid cases, in which some energy can be bought from the grid, achieve significant reductions of the total cost with respect to the fully renewable (off-grid) solution. The total cost after 10 years for the cases of $PT = 70\%$ and $PT = 80\%$ is about 75\% lower than the pure solar system. These solutions are also cheaper than the grid-only case, starting from the 8-th year on. The cost of using a diesel generator is much higher than those of hybrid and pure grid solutions, and becomes quickly much higher than the pure solar solution.

We now consider the case in which the extra energy produced by the PV panel, that cannot be stored in already fully charged batteries, can be sold back to the power grid. Fig. 7 shows the cumulative total cost, which is initially equal to the CAPEX, and then decreases with time when there is a positive balance between the revenues obtained by selling the extra energy, and the cost of buying energy to power the BS when the batteries are depleted. In the cases with $PT = 70\%$ and $80\%$ (which are the most effective when energy cannot be sold back, as in Fig. 6), the curves are almost flat, meaning that OPEX and energy sell-back roughly balance.

When the system is dimensioned for $PT = 100\%$, instead, the size of the PV panel must be quite large, in order to guarantee that even in periods with low production, such as winter, the produced energy is enough to power the BS; this implies a large extra production of renewable energy in other periods, which translates into significant revenues, so that the corresponding cost curve in the figure is steeply decreasing. However, this case normally corresponds to an off-grid operation, so that the BS cannot inject the extra energy production into the power grid, and cannot obtain the revenues associated with the extra energy sell-back, unless some specific power distribution system is envisioned. For this reason, in the case of $PT = 100\%$ we report in Fig. 7 both curves with and without the extra energy sell-back, the latter being more realistic.

In all the considered cases, except the one with $PT = 100\%$ and no energy sell-back, the systems with renewable energy start being convenient with respect to the grid-only case, 5 or 6 years after installation.

In the off-grid case, the pure solar solution is more expensive than a diesel generator only in the first years, when CAPEX dominate, but quickly becomes much less expensive, and at the end of the 10-year period the cost of the pure solar solution is about two thirds of the cost with a diesel generator.

Similar results were derived for other cases, such as for the business traffic profile, but are not shown for the sake of conciseness. We also studied the case of other locations, e.g., the city of Aswan in Egypt, where the variation of solar radiation over a year is much less than in the case of Torino considered so far. The results for Aswan are discussed in the next section.
TABLE III
SIZE AND COST OF THE POWERING SYSTEM FOR THE 10-TH YEAR DIMENSIONING CASE, IN ASWAN

<table>
<thead>
<tr>
<th>$PT$</th>
<th>PV size [kWp]</th>
<th>No. batt.</th>
<th>PV+batt. cost [k€]</th>
<th>Grid cost [k€/y]</th>
<th>Pay back [k€/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>3.3</td>
<td>5</td>
<td>3.69</td>
<td>0.019</td>
<td>0.017</td>
</tr>
<tr>
<td>80%</td>
<td>3.9</td>
<td>5</td>
<td>3.76</td>
<td>0.014</td>
<td>0.024</td>
</tr>
<tr>
<td>90%</td>
<td>3.9</td>
<td>6</td>
<td>3.92</td>
<td>0.012</td>
<td>0.024</td>
</tr>
<tr>
<td>100%</td>
<td>5</td>
<td>15</td>
<td>6.15</td>
<td>0</td>
<td>0.109</td>
</tr>
</tbody>
</table>

V. CASE STUDY: ASWAN

In this section, we use most of the input parameters for the case of Torino (i.e., the evolution of the residential traffic profile, the PV panel efficiency, the cost of PV panel and batteries in the next 10 years) also for another location: the city of Aswan, in Egypt. However, we adapt the prices of electricity and diesel to the local values in order to calculate CAPEX and OPEX. This is necessary because, due to the much higher amount of local oil and electricity production, the prices of electricity and diesel in Aswan are much lower than in Torino at present [17], as shown in Table. I. However, we assume that prices exhibit a higher increase rate (20% instead of 3% per year) because of globalization [18].

We adopt the same optimization and simulation methodology used to study the case of Torino also to obtain results for Aswan. In this case we find that the 10-th year must be used as reference for PV dimensioning. Table III shows the dimensioning results for Aswan. We immediately see that the PV panel size and the number of batteries required in Aswan are both much smaller than for Torino. This is because the solar radiation in Aswan is higher and more constant over the whole year. Therefore, the same unit of PV panel in Aswan produces much more energy than in Torino. To visualize the difference in more detail, Fig. 8 and Fig. 9 show the battery status during the 10-th year for the case of $PT=100\%$ and $PT=70\%$ in Aswan, respectively. Comparing these results to the case of Torino shown in Fig. 3 and Fig. 4, we observe deeper battery charges and discharges, but also a relatively more stable depth of discharge in the case of Aswan. In addition, due to the high variations in solar radiation between summer and winter in Torino, the PV system is usually over-dimensioned in summer, which leads to large amounts of excess energy generation during summer. This excess energy is either wasted, if no energy sell-back is possible, or sold back to the grid. In Aswan, solar radiation is much more constant over the year, so that the dimensioning of the PV system better matches the BS power consumption during the whole year.

Similar to the case of Torino, we simulate the expected CAPEX and OPEX for the case of Aswan in a period of 10 years, and we obtain the total cost shown in Fig. 10 (without energy sell-back) and Fig. 11 (with energy sell-back). In both figures, the cost for the cases of $PT=70\%, 80\%, 90\%$ is almost the same, but significantly lower than for the case of $PT=100\%$. Therefore, the proposed hybrid energy system allows large cost savings compared to the pure solar system also in Aswan. However, in this case, because of the much lower prices of electricity and diesel, the hybrid energy system has roughly the same cost level as the diesel generator, and has higher cost than the pure power grid system over the 10 year period. In addition, in the case of Aswan, the cost difference between the two cases with and without energy sell-back are small, as we can see by comparing Fig. 10 (without energy sell-back) and Fig. 11 (with energy sell-back). This result is due to the fact that the PV system can be dimensioned very efficiently, thanks to the constant solar radiation of Aswan, so that the amount of excess produced energy is rather small.

It should be noted, however, that in our cost computations we do not account for OPEX in addition to battery replacement, so that for example we neglect the cost related to diesel fuel transport. While this can be reasonable in and around Torino, or in the city of Aswan, fuel transport can become a
uses both renewable energy and the power grid, can reduce the total cost, especially in locations with seasonal variations of the produced energy; cost reduction can be as high as 75% with respect to a pure solar system in a location like Torino, case in which the hybrid system roughly balances the cost of the grid-only case in 10 years. Hybrid systems lead to cost reduction of up to 50% also in locations, like Aswan, in which the energy production is quite constant over the year. Whenever extra energy can be sold back to the grid, the system becomes further cost-effective. The solar solutions are often less expensive than the use of a diesel generator.

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