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Minimum cost solar power systems for LTE macro base stations

Yi Zhang[a], Michela Meo[a,*], Raffaella Gerboni[b], Marco Ajmone Marsan[a,c]

[a] Department of Electronics and Telecommunications, Politecnico di Torino, Italy
[b] Department of Energy, Politecnico di Torino, Italy
[c] IMDEA Networks Institute, Leganes (Madrid), Spain

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ABSTRACT

This paper proposes an algorithm for the identification of the minimum cost solution over a 10 year time horizon to power an LTE (Long-Term Evolution) macro base station, using a photovoltaic solar panel, a set of batteries, and optionally also a secondary power source, which can be a connection to a (possibly unreliable) power grid, or a small Diesel generator. The optimization is formalised as an Mixed Integer Programming (MIP) problem, which, after linearization, can be solved with CPLEX. A heuristic algorithm is also proposed, with the objective of decreasing the computational complexity of the optimization. Numerical results show that a hybrid solar-grid (or solar-diesel) power system saves a significant fraction of the total cost, compared to a pure solar system, and to the traditional power-grid system, over the investigated 10-year period, in a south European city, like Torino in Italy, as well as in a location close to the tropic, like Aswan in Egypt. Our proposed heuristic algorithm can be used to obtain a solution within 10–20% of the optimum, at a computational speed 200 times faster than the MIP solution.

1. Introduction

Energy-efficient (or green) networking has been a hot research topic in the last decade. Several large international research projects have been launched in this field, like EARTH [1], TREND [2], and ECONET [3], funded by the European Commission under its 7th Framework Programme, and GreenTouch [4], the largest industry-driven initiative so far. In addition, many smaller initiatives, and curiosity-driven research, have contributed to the generation of a wide body of results in this area. Research has concerned all fields of networking, from access to core, from wired to wireless, but has surely focused mostly on cellular radio access networks, due to the increased relevance of wireless access, and to the recent introduction of the LTE technology, aiming at providing high bandwidth ubiquitous Internet access to an ever growing number of smart user terminals. Research has considered many different aspects, from more energy-efficient components and systems, to less energy-hungry application protocols, to greener network management procedures, and architectural variations [5–8].

However, in spite of all the attention given to energy consumption in networks, recent data indicate that the amount of energy used by networks keeps increasing. Probably, energy consumption goes up at a lower rate than it would have, without all the recent research in the field, but up it goes. The main reasons for this continuing growth in the case of cellular networks are (among others) that: i) the deployment of the new and more energy-parsimonious Base Station (BS) models is slower than expected, due to lagging operator investments because of the economic slowdown; ii) the new energy-aware network management procedures, mostly based on the switch-off of parts of the equipment in periods of low traffic, are not being adopted by operators, who fear that coverage holes may be generated, that QoS may be degraded, and that faults may occur at switch-on; and iii) more and more BSs are necessary to satisfy the exploding volume of traffic requests.

It thus becomes interesting to tackle the issue of energy consumption in communication networks from a different perspective, focusing on the *type* of energy which is consumed, since, if we can make networks green by consuming energy produced by renewable sources, the amount of consumed energy becomes less critical. Actually, the combination of renewable energy sources with energy-efficient equipment, protocols, and algorithms is extremely important, since only through an optimised system integration the use of renewable energy sources becomes viable.

In this paper we study the use of solar energy to power an energy-efficient LTE macro base station. By coupling a photovoltaic (PV) solar panel with batteries that can store the energy produced in high solar radiation periods, to be used during nights, as well as cloudy days, solar panels can power base stations at very limited cost, and thus provide an interesting option for both areas where

* Corresponding author.
E-mail addresses: name.lastname@polito.it (Y. Zhang), michela.meo@polito.it (M. Meo), name.lastname@polito.it (R. Gerboni).

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the power grid is not present or not reliable, and areas where the power grid is ubiquitous, but energy costs are high, and regulations may make it inconvenient to connect a BS to the power grid.

Today, especially in remote locations, a number of BSs already operate with no connection to the power grid. The most common solution to power off-grid base stations consists in installing a Diesel power generator, which requires large amounts of fuel, which is expensive in itself, but becomes extraordinarily costly when transport is problematic (helicopters are necessary when locations are really remote), and when fuel thefts occur.

In the recent literature, 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 [5]). Some Mobile Network Operators (MNOs), Orange for example, have already deployed over 2000 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 CO_2 in 2011 [9]. 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.

We investigate the cost of different solutions to power a LTE macro BS: i) the case of access to the power grid, ii) the case of a Diesel generator, and iii) the case of a PV panel with batteries. In addition, we also explore hybrid solutions, which consist in: iv) the use of a PV panel with batteries, coupled with a grid access, or a small Diesel generator.

In particular, in this paper, refining our previous works [10,11], we focus on the optimization of the total cost (including CapEx and OpEx) of the solar energy system that is installed to power a macro LTE base station. We consider a 10-year life span of the equipment, and over such period we account for expected changes in conditions, including the strong growth of the end user traffic demand, as well as the increase of the grid electricity price; in addition, we also consider the evolution of battery technology, and the reduction of the solar panel efficiency from year to year. Two are the reasons why we select a 10-year horizon. The first reason is that PV panels are designed to last at least 10 years. Therefore, during the 10-year horizon, there is no need to change PV panels, which would imply a complete replacement of the PV system. The second reason is that, up to now, new generations of mobile radio access technologies had an opportunity window of about 10 years before the deployment of a newer technology, as can be seen by looking at the cases of GSM and 3G. The currently deployed LTE BSs will probably be replaced by 5G technology in about the same time frame. Finally, predicting the energy consumption of 5G BSs beyond year 2025 is not within the scope of this paper.

We study the system through a Mixed Integer Programming (MIP) approach, aiming at cost minimization over the 10-year period, and we design a heuristic algorithm that allows computational complexity to be drastically reduced. Numerical results prove that minimum cost solar energy systems are a viable choice to power a LTE macro BS, and that hybrid energy systems (solar+grid or solar+diesel) can be the most effective choice.

This paper is organized as follows. Section 2 briefly overviews previous work in the field. Section 3 describes the architecture of our proposed hybrid BS power system. Section 4 formulates the problem of optimizing the total cost of the hybrid BS power system. Section 5 proposes a heuristic algorithm to solve the problem and reduce computation complexity. Section 6 shows simulation results, and Section 7 concludes the paper.

2. Related work

Research on the use of renewable energy sources (RES) to power BSs of radio access networks started only a few years ago. The authors of [12] provide quite a comprehensive survey of the state of the art in this field.

Several works focused on the allocation of resources in a portion of a network comprising a few BSs, some of which are powered by RES. For example, the authors of [13] propose optimal BS switch-on/off strategies to save energy within a radio access network, when some of the BSs are powered by RES. In [14], the authors propose an optimized method for RES utilization in a radio access network, based on a 2-BS model, considering hybrid powering systems comprising RES and access to the power grid. The same authors also investigate a green-energy-aware and latency-aware user association problem in [15]. However, these works do not consider in detail how energy is captured from RES, stored and consumed, and how RES can be combined with power grid use. Furthermore, these works do not account for the solar radiation variation during different portions of a day, and different season of a year, and thus with the corresponding variation in energy production.

If we look into the details of a hybrid energy system (RES and power grid), although several works were published in the area of energy engineering (e.g., [16,17]), only few papers appeared in the context of telecommunications with the aim to optimize the BS power system, including the variation of energy consumed for variable traffic load. A recent work proposes a hybrid diesel-solar energy system to power a BS [18], but does not try to optimize CapEx and OpEx. The authors of [19] propose the optimization of the cost of a PV-wind hybrid system to power a GSM/CDMA BS, accounting for wind and solar energy variations during the year, but do not consider the traffic variation during the day. In [20] the authors propose a service-adaptive method (i.e., the adaptation of capacity and coverage) for managing the PV and grid power resources to power a BS, and propose an implementation; however, they do not investigate the system CapEx and OpEx.

The novelties of our work with respect to previous papers are: i) we focus on the global optimization of both CapEx and OpEx for a hybrid LTE BS power system (with PV and power grid); ii) we consider the variation of solar radiation in different times of the day, different seasons of the year, and different locations of the world; iii) we assume an evolutionary perspective for both the system efficiency and the BS traffic load, over the 10-year period; iv) we optimize the total cost over the 10-year time span before the introduction of a newer radio access network technology.

3. The BS power system

This section introduces the elements of the solar power system, as well as the overall BS power system architecture, and discusses the parameters that are used in our study.

3.1. Photovoltaic panels

Photovoltaic (PV) or solar panels are used to convert solar radiation into electricity. The PV panel instantaneous output power depends on the level of solar radiation, on the conversion efficiency, and on the power loss factor, that accounts for system losses during the power transformation. In this paper we assume a conversion efficiency equal to 16%, which is today common for standard PV panels.

The peak output power of a PV panel, usually measured in "kilowatt-peak" (kWp), is directly proportional to the panel size. A 1 kWp PV panel is defined as a PV module. The instantaneous output power of a 1 kWp PV module is directly related to the corresponding solar radiation, and can be expressed as $P = \frac{G}{1000} A\,\eta(G, T_m)$, 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 [10]. Therefore, the trend of the variation of the instantaneous power production of a PV panel is the same as the trend of the variation of the instant solar radiation (although the relation is non-linear). The amount of energy produced by a PV panel also depends on the location, which determines the amount of solar radiation, due to latitude, tilt, and weather conditions. The National Renewable Energy Laboratory of the United States has made available online a software named "PVWatts" [21], which allows the estimation of the different energy production patterns of PV panels located in different positions of the earth. We use the software "PVWatts" to obtain the amount of energy produced during a typical meteorologic year, and select two locations as examples: Torino in Italy and Aswan in Egypt. The climate and solar radiation patterns in these two cities are quite different. Torino has a typical cycle of four different seasons; in winter it is rainy and cold, while during the summer it is hot and sunny. Aswan locates near the Tropic of Cancer; it is usually hot and dry during the whole year, with limited seasonal variations. Our solar power system is tested in these two cities to analyse the most suitable conditions of the different power options.

3.2. Batteries

Batteries are used to store the energy which is not immediately used to run the BS, but becomes necessary at night or during the days when solar radiation is too low (i.e., rainy days or cloudy days, or days of short solar radiation in winter) to obtain enough electricity to power the BS. In our optimization of the BS power system, we simulate the battery charge and discharge to compute how many batteries are needed to avoid energy shortage at the BS. We consider a power loss factor equal to 85%, which means that 15% of the power is lost during the transition of charging/discharging batteries. Usually, the battery charge level (i.e., the percentage of energy inside the batteries with respect to the maximum) needs to stay above 30% to keep the batteries in a healthy condition for the lead-acid batteries we use in this paper.

We define a parameter named *PT*, as the *percentage of time* during the whole year when the batteries charge level is above 30%. For pure solar BS power systems, we need $PT = 100\%$. For hybrid solar-grid or solar-diesel systems, we can consider lower values of *PT*, since we assume that the BS can obtain energy from either the power grid or a small Diesel generator when the batteries are empty (i.e., their charge level reaches 0%). In this paper, we investigate three hybrid scenarios, with *PT* equal to 70%, 80%, and 90%.

An additional issue to be considered in the study of the BS power system over a 10-year period is the battery life. We assume that the system uses traditional lead-acid batteries, whose life is around 500 cycles [22]. This means that a battery must be replaced when the cumulative depth of discharge of the battery reaches 500 times its capacity. We account for the improvement of battery technology during the 10-year period. The lifetime of batteries improves when new batteries come to the market. According to [23], battery life is predicted to improve from 500 cycles at this moment to 3000 cycles in 2030.

3.3. The architecture of the BS power system

Fig. 1 shows the high-level architecture of the BS power system. A controller manages the energy flow from the three power sources (i.e., PV panel, batteries, and possibly grid/diesel as an additional power source) to the two power consumers (i.e., BS and batteries). The algorithm running on the controller dynamically switches the energy intake from the PV panel to the batteries to the additional power source, if present. Whenever the power generated by the PV panel is more than what needed to operate the BS, the extra power is sent to the battery. When the PV panel produces less power than needed by the BS, some energy is taken from batteries. If batteries are depleted, and the power generated by the PV panel is not sufficient to operate the BS, the additional power source is used, if present; otherwise, the BS must be switched off. In addition, if the BS power system is connected to the power grid, it may be possible to sell back the extra energy which is generated by the PV panel when the batteries are full (100% charge).

3.4. Power model of the LTE base station

The power consumption of the LTE macro BS can be approximated as a function of the output power of the power amplifier within the Radio Frequency (RF) module, [1]:

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

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, Δ_p is the slope of the emission-dependent consumption. The power out of the RF power amplifier is proportional to the traffic load of the BS.

To reduce the power consumption of LTE base stations, one effective technological choice consists in the adoption of Remote Radio Units (RRU), i.e., in the placement of radio units close to antennas, so as to reduce the power losses inherent in long antenna feed cables. In this paper, we use the power model of a LTE macro base station with RRU, as reference to conduct our study.

3.5. Traffic profile of the mobile users

A detailed daily profile of the traffic generated by mobile users is necessary to compute, together with the BS power model, the daily energy consumption of the BS. This quantity and the PV power generation during the day allow us to obtain the amount of energy which can be stored in the batteries, or needs to be drained from batteries (depending if the balance between the PV panel generation and the BS consumption is positive or negative). Fig. 2 shows the normalized traffic profile measured on a cell of an Italian mobile network operator, distinguishing between weekends and weekdays. The profile refers to a residential area, with peaks during the evening.

3.6. Evolution of the parameters over 10 years

In this paper, we focus on the computation of the cost of the BS power system, including CapEx and OpEx for a period of 10 years; during such a long time span, many of the key system parameters are bound to change, some by a significant amount. It is thus necessary to account for these variations in the cost computation, in order to achieve a careful assessment of the relative merits of the possible alternative solutions. The price of solar panels and batteries can be estimated from a recent report by NREL [24], concluding that the price of a lead-acid battery (12 V, 200 Ah) is approximately 150 €, and the price of 1 kWp PV panel is around 800 €. We collected data from reports and forecasts about the current levels and the predicted future evolution of PV and battery prices, traffic profiles, electricity prices, diesel fuel prices, battery technologies and PV panel efficiency, etc., in both Aswan and Torino. Table 1 shows the foreseen evolution of the BS power system parameters. We assume that the traffic load will follow a 50% CAGR from 2% in the first year to 76.8% in the 10th year [25]; the PV efficiency is known to degrade 1% each year [26]; the electricity and diesel prices are forecasted to increase 3% per year in Torino [27] and 20% per year in Aswan [28]. The gap between the actual and the predicted electricity and diesel prices between the two cities comes from the fact that Egypt has rich oil storage and

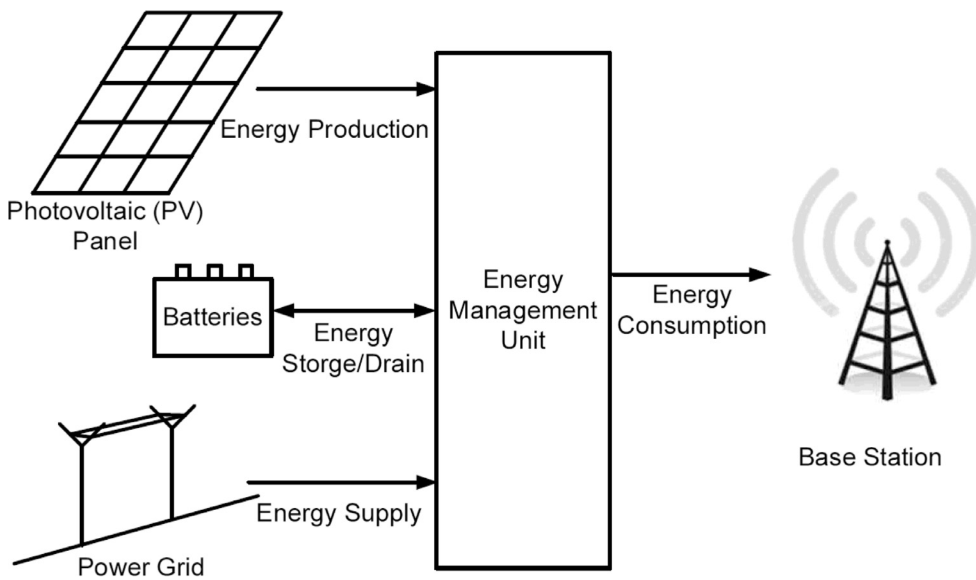

Fig. 1. Architecture of the BS power system.

Table 1
Prediction of the values of the parameters of the BS power system in the 10-year period.

Year	Peak traffic load	PV efficiency reduction	Electricity price [€ /kWh]		Diesel price [€ /liter]	
			Torino	Aswan	Torino	Aswan
1	0.020	1	0.217	0.070	1.600	0.490
2	0.030	0.99	0.223	0.084	1.648	0.588
3	0.045	0.98	0.230	0.098	1.696	0.686
4	0.067	0.97	0.236	0.112	1.744	0.784
5	0.101	0.96	0.243	0.126	1.792	0.882
6	0.151	0.95	0.249	0.140	1.840	0.980
7	0.227	0.94	0.256	0.154	1.888	1.078
8	0.341	0.93	0.262	0.168	1.936	1.176
9	0.512	0.92	0.269	0.182	1.984	1.274
10	0.768	0.91	0.275	0.196	2.032	1.372

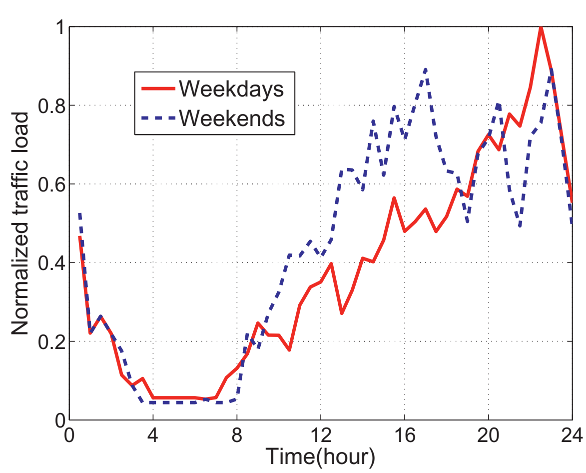

Fig. 2. Traffic profiles measured on an operational cellular network.

exploitation, while Italy imports from other countries most of its oil and electricity. However, because of the economic globalization, the gap is forecasted to become smaller and smaller in the next years, therefore the prices in Aswan follow a higher increase rate.

4. Mathematical formulation

4.1. Optimization of the yearly cost

For starters, we formulate the cost minimization problem over one year (the system parameters are kept constant in this interval), and then we extend our optimization to the 10-year period, accounting for the evolution of the system parameters.

The time granularity is defined by the parameter Δ, which is used to calculate energy production and consumption. Since the traffic and the energy production profiles that we use contain data for every half hour, the finest time granularity that we can use is Δ =30 min. With this choice, the number of intervals in one year, that is denoted by T, becomes $T = 17,520$. If we reduce the time granularity to Δ =120 min, we get $T = 4380$. For each interval Δ we define appropriate variables in the mathematical formulation.

The following is the definition of the problem.

Parameters:

- S_i: Energy production of 1 kWp solar panel in the ith interval, $i \in [1, T]$; S_i is measured in Wh.
- E_i: Energy consumed by the BS in the ith interval, $i \in [1, T]$; E_i is measured in Wh.
- B: Capacity of energy storage for one battery; B is measured in Wh.
- C_{PV}: Cost of 1 kWp PV solar panel; C_{PV} is measured in Euro/kWp.
- C_{batt}: Cost of one battery; C_{batt} is measured in Euros.

- C_{grid}: Cost of 1 Wh of electricity obtained from the power grid. Alternatively, we can use C_{diesel}: Cost of 1 Wh of electricity obtained from a Diesel generator. C_{grid} and C_{diesel} are measured in Euro/Wh.

Variables:

- x_i: Charge of batteries normalized to the capacity B, $x_i \in [0, 1]$, $i \in [1, T]$.
- y_i: Variable used to define the battery charge and possible energy deficit after the generation and consumption in time slot i, $i \in [1, T]$. y_i is measured in Wh.
- n: Number of batteries, $n > 0$.
- p: Size of the solar panel; p is measured in kWp.
- a_i: Variable that indicates if the battery charge is above 0.3; needed to define the constraint on PT for hybrid systems.
- b_i: Amount of energy taken from the grid or the Diesel generator in the ith interval, $i \in [1, T]$; b_i is measured in Wh.

Objective function:

$$minimize: \tag{2}$$

$$C_{total} = C_{PV} \times p + C_{batt} \times n + C_{grid/diesel} \times \sum_{i=1}^{T} b_i \tag{3}$$

Constraints:

$$y_i = \min\{B \times n \times x_{i-1} + p \times S_i - E_i, B \times n\} \tag{4}$$

$$B \times n \times x_i = \max\{y_i, 0\} \tag{5}$$

$$b_i = \max\{-y_i, 0\} \tag{6}$$

$$x_1 = 1 \tag{7}$$

$$0 \le x_i \le 1,\ i \in [2, T] \tag{8}$$

$$a_i = \begin{cases} 0 & \text{if } x_i < 0.3 \\ 1 & \text{if } x_i \ge 0.3 \end{cases} \tag{9}$$

$$\sum_{i=1}^{T} a_i/T \ge PT \tag{10}$$

Constraint (4) imposes that each battery cannot be charged above its capacity B; (5), instead, defines the actual battery charge. In the case of a pure solar BS power system (i.e., no connection to the grid, and no Diesel generator), $PT = 100\%$, and constraint (10) imposes that all variables a_i are equal to 0, i.e., $x_i \ge 0.3$. This means also that y_i is never below 0, and b_i is always 0. Indeed, in the pure PV case, no energy is bought from the grid or supplied by the diesel generator; the battery charge is never below 30%. Instead, in the case of a hybrid BS power system, some variables a_i can go to 0, meaning battery charge below 30%, and in some cases the variables y_i become negative, meaning that the batteries are depleted ($x_i = 0$) and some energy corresponding to b_i is purchased from the grid.

4.2. Analysis of computational complexity and linearisation

The complexity of solving this MIP problem is very high, because of the large number of variables and constraints, especially when a fine granularity (small values of Δ) is chosen.

The formulation above contains two kinds of non-linearities. One stems from the min and max functions that appear in the equations. For instance, constraint (4) includes a min function that defines a limit for the battery charge. CPLEX can deal with this kind of nonlinearities, as long as the solution set is convex. The other non-linearity derives from the product of two variables. In our case, the term $n \times x_i$ in constraint (4) is the product of two of the problem variables. CPLEX cannot handle this kind of non-linear constraints. It is thus necessary to introduce a linearization, or to use a fixed point approach. We decided to use the latter option, fixing the value of n and solving the MIP problem for the chosen value, and then changing the value of n and again solving the MIP problem. We let the value of n vary in the range [0, 50], and we select the value of n that provides the best result (i.e., the lowest total cost) as the final optimal solution.

For a PC with Intel i5 dual-core CPU and 4 GB of main memory, the process of finding the solution in the case Δ =30 min takes 2–3 h. In the case Δ =120 min, the computation time reduces to around 10–15 min. Obviously, this implies some sacrifice in the accuracy of the final results. To investigate the sensitivity of the optimization solution to the chosen time granularity, in Table 2 we show an example of the results obtained with the two values of time granularity in the case of Torino, under full traffic load, and pure solar system. The results show that the sacrifice in accuracy is only around 1%, which seems acceptable. Other cases, with different choices of the load, presented similar accuracy. In the next sections, we will report the results of CPLEX for a time granularity equal to $\Delta = 120$ min.

4.3. Dimensioning over a 10-year period

In the previous section, we have discussed the minimization problem over a one-year period. When looking at the 10-year period, the system parameters must be modified year by year, according to the evolution of the parameters that was described in Section 3 and reported in Table 1. To optimally dimension the system for a 10-year period of operation, we proceed as follows. We repeat the system dimensioning process up to 10 times, using the parameters referring to each year, from the 10-th, down to the 1-st. Once the dimensioning is obtained for a set of parameters' values corresponding to a given year, the system evolution is simulated for the 10-year period. During this simulation, it may happen that the dimensioning obtained for a given year is not sufficient for another year (for example, because of the violation of the constraint on PT). This typically happens when the parameters refer to one of the first years of the 10-year period, where traffic is low and the PV panel is at the peak of its efficiency, so that the system dimensioning is not sufficient for a later year with higher traffic and lower PV panel efficiency. This is why we start with year 10, and we go down until we find a year for which the dimensioning is insufficient. When this happens, the dimensioning for such year (say year k), as well as for all other previous years (all years $i \le k$) can be considered inapplicable. During this simulation, the possible cost of battery replacements, due to batteries reaching the maximum number of charge and discharge cycles, is also taken into account. Finally, the best dimensioning is decided as the applicable one with the minimum total cost, taking into account initial investment, battery replacements, and energy purchase (if any).

For the case of Torino, whose detailed results will be discussed in Section 6, we found that the system dimensioning is possible only when the one-year optimization is performed using the parameters of the 9th or 10th year. In order to better explain why, consider an example. Assume that the system dimension is optimized using the parameters for the first year. When a 10-year long period is simulated, as time goes by, the PV panel efficiency degrades and the traffic load increases to such an extent that the requested constraint on PT cannot be met in the years following the first. For this reason, more conservative assumptions on the parameters (such as values corresponding to the 9th or 10th year) are needed to guarantee that the constraint on PT is met for the whole period. When considering the total cost, the dimensioning for the

Table 2
Impact of time granularity Δ, case of Torino.

Time granularity Δ[*hour*]	PV size [kWp]	No. batt.	PV+batt. cost [k€]	Total cost [k€]	Gap [%]
0.5	4.5	15	5.807	8.115	1.34%
2	4.8	14	5.853	8.007	0

9th year results more convenient than the dimensioning based on 10th year parameters. The best dimensioning is thus the one obtained by running the one-year optimization with the parameters of the 9th year.

In the case of Aswan, the second location we consider in this paper, the optimization with the parameters of the 10th year is the only one that guarantees that the constraint on *PT* is met for the whole 10 year period.

5. A heuristic algorithm

Although the reduction of the time granularity in the MIP makes the computation time for one instance of the one year optimization as low as about a quarter of an hour, the total computation time necessary to obtain solutions using CPLEX remains very long. Indeed, each problem instance has to be solved 50 times for each of the admissible values of the number of batteries, due to the non-linear constraints resulting from the products of two variables, as we mentioned in the previous section. Therefore, the total computation time to obtain the global optimum is of the order of several hours. While this can be acceptable for the final tuning of the selected option, it is clearly too long for the what-if analysis that is necessary to explore possible variable settings in terms of RAN technology, network deployment, BS layout (e.g., small cells), resource allocation algorithms (e.g., sleep modes), service offering, etc. With the objective of a consistent reduction of the computation time, we propose a heuristic algorithm for the approximate solution of the optimization problem.

5.1. Pseudocode

The pseudo code of the heuristic algorithm is reported in Algorithm 1.

The heuristic can handle both the pure solar and the hybrid solar-grid (or solar-diesel) BS power systems. The algorithm includes 3 layers of nested loops. The most external loop spans the size of the PV panel, starting from 0 up to the maximum considered PV panel size in kWp. The most internal loop spans the considered number of time slots in the year. The third loop spans the number of batteries, starting from 0 up to the maximum considered number. During the loop execution, if the battery charge does not meet the *PT* constraint, the program jumps out of the most inner loop and one more battery is considered. The middle and most external loops stop when the minimum number of batteries is found. Thus, for the different admissible values of PV size, the minimum required number of batteries is calculated. Finally, the best PV panel size is selected, according to the lowest value of total cost.

5.2. Computational complexity

The proposed heuristic has much lower complexity as compared with the MIP solution through CPLEX. In the worst case, the heuristic algorithm examines each value of the 3 loop layers, so that the total number of examined cases is equal to the product of three integer values: the maximum *PV* panel size in kWp multiplied by the maximum number of batteries, and by the number of time intervals in a year. In practice, this amounts, in the worst case and for the finer considered time granularity, to $20 \times 50 \times 17,520$, which is about 17 million. The search for the global optimum with this heuristic approach requires about 1 minute.

Table 3
Dimension of PV panel and batteries from 1st year to 10th year, case of Torino with $PT = 100\%$ and $PT = 90\%$, one-year optimization done with CPLEX for parameters of the 9th year.

Year	$PT = 100\%$		$PT = 90\%$	
	PV size [kWp]	No. batt.	PV size. [kWp]	No. batt.
1	12.8	36	7.6	10
2	12.8	36	7.6	10
3	12.8	38	7.6	11
4	12.8	41	7.6	12
5	12.8	41	7.6	12
6	12.8	42	7.6	12
7	12.8	43	7.6	12
8	12.8	44	7.6	12
9	12.8	45	7.6	13
10	12.8	47	7.6	15

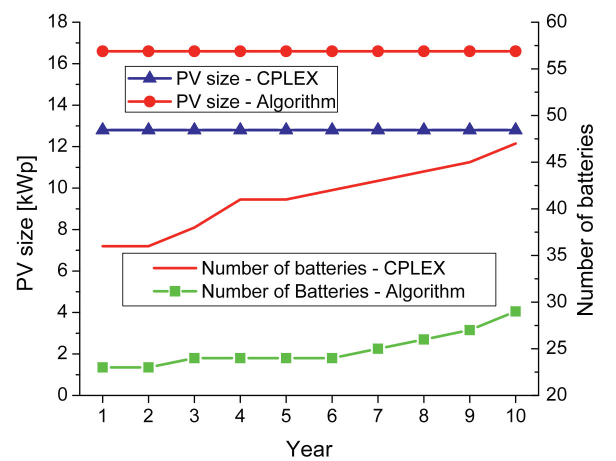

Fig. 3. Comparison of PV size and number of batteries between the solution obtained with CPLEX and the heuristic algorithm; *PT* =100%, case of Torino.

5.3. Gap between CPLEX and algorithm

We now assess the accuracy of the heuristic algorithm by comparing the results with those we obtain through the MIP formulation.

Table 3 shows the evolution of the system size over the 10-year period for the case of Torino and $PT = 100\%$ or $PT = 90\%$; the results are obtained using CPLEX to solve the MIP formulation. The one-year optimization is performed, as previously explained, using the 9th year parameters. The panel size is constant over the 10-year period because panels are not changed, once they are installed. The number of batteries, instead, increases year by year to sustain the increased need for energy due to growing load. In the case of $PT = 100\%$, the system needs larger panel size and more batteries, due to the tighter constraint.

To show the difference between the solution obtained through the MIP formulation and the heuristic approach, Fig. 3 reports the chosen PV size and number of batteries in the 10-year period, for $PT =$ 100%. The results for CPLEX have smaller size of PV panel

Algorithm 1 Pseudocode of the heuristic algorithm: Find the combination of PV size and number of batteries that minimizes the total cost of the BS power system.

```
%%%%% Start initialization
PT = 70% or 80% or 90% or 100%;
length = 17520;
Battery_capacity = 2.4(kWh);
Max_PV = 20(kWp);
Max_battery = 50;
Array Unit_production[length] are pre-calculated;
Array Consumption[length] are pre-calculated;
Sum_PT[p] = 0;
Grid_energy = 0;
%%%%% End initialization
%%%%% Main loop: Try different values of PV size, for each PV
size find minimum no. of batteries
for p = 0; p < Max_PV * 10; p++ do
  PV_size[p] = p * 0.1;
  Number_of_batteries[p] = 1;
  while Number_of_batteries[p] < Max_battery do
    Battery_status[p][0] = Number_of_batteries[p] *
    Battery_capacity;
    for i = 0; i < length; i++ do
      if Battery_status[p][i]/Battery_status[p][0] < 0.3 then
        PT_flag[p][i] = 1;
      else
        PT_flag[p][i] = 0;
      end if
      Sum_PT[p] = sum_PT[p] + PT_flag[p][i];
      if Sum_PT >= (1 − PT) * length then
        Flag_feasible = 0;
      else
        Battery_status[p][i+1]=MIN{(Battery_status[p][i]+
        PV_size[p] * Unit_production[i]−Consumption[i]),
        Battery_status[p][0]};
        Flag_feasible = 1;
      end if
      if Battery_status[p][i] < 0 then
        Grid_energy[p] = Grid_energy[p] − Battery_status[p][i];
      end if
    end for
    if Flag_feasible == 0 then
      Number_of_batteries[p] = Number_of_batteries[p] + 1;
    else
      Break;
    end if
  end while
  cost[p] = Cost_PV * PV_size[p] + Cost_battery *
  Number_of_batteries[p] + Cost_grid_energy * Grid_energy[p];
end for
%%%%% End main loop
%%%%% Among the found solutions look for the minimum cost
one
for m = 0; m < Max_PV * 10; m++ do
  Find the smallest cost[m];
end for
return cost[m], Grid_energy[m], PV_size[m] and Number_of_
batteries[m];
```

(y-axis on the left), but larger number of batteries (y-axis on the right). Similar results for the case of PT =90% are shown in Fig. 4. Although the dimension for PT =90% is much smaller than the dimension for PT =100%, the comparison of CPLEX and algorithm is the same: CPLEX results require smaller PV size but larger number of batteries.

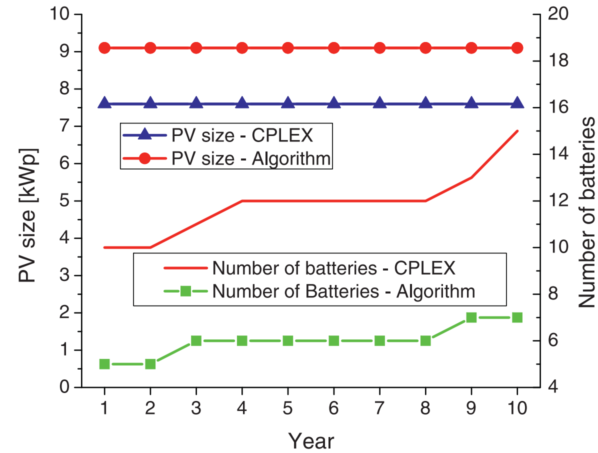

Fig. 4. Comparison of PV size and number of batteries between the solution obtained with CPLEX and the heuristic algorithm; PT =90%, case of Torino.

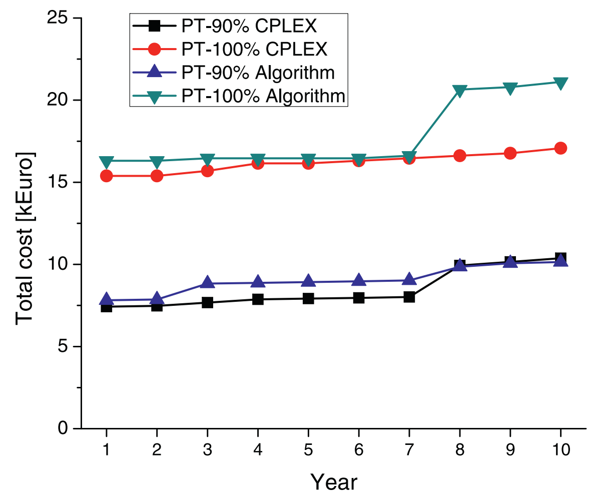

Fig. 5. Comparison between CPLEX and the heuristic algorithm in the case of Torino with no energy sell-back.

We now consider the difference between the solutions in terms of the total cost of the system. The total cost is computed as the sum of the initial investment, including the cost of the PV panel and batteries, and the additional cost that occurs during the 10-year period to increase the number of batteries, if needed, and to replace the batteries once they are exhausted. In order to compute when the batteries are exhausted, the battery charge status is simulated over the whole period. A detailed discussion of this will be provided in Section 6. Moreover, when PT < 100%, some cost due to energy purchase from the power grid is also taken into account.

Fig. 5 shows the comparison between the total cost for the solutions obtained with CPLEX and the heuristic algorithm. The gap for PT = 90% is within 10%, while the gap for PT = 100% is within about 20%. Larger gaps appear from the moment in which the batteries are being replaced, e.g., from the 8th year for PT = 100%, and the 3rd year for PT = 90%. For the solution obtained from the heuristics, the number of battery replacements is higher than for the CPLEX solution. This is because the heuristics returns a larger PV panel size and lower number of batteries, which means more battery cycles and more frequent battery replacements. Note that sometimes the results of the heuristics are more convenient than those of CPLEX. This is due to two reasons: 1) the CPLEX results are calculated by relaxed granularity, i.e. 2 h, which reduces the accuracy of the optimum solution; 2) the optimization is only done for one year and not over the whole 10-year period, because, as al-

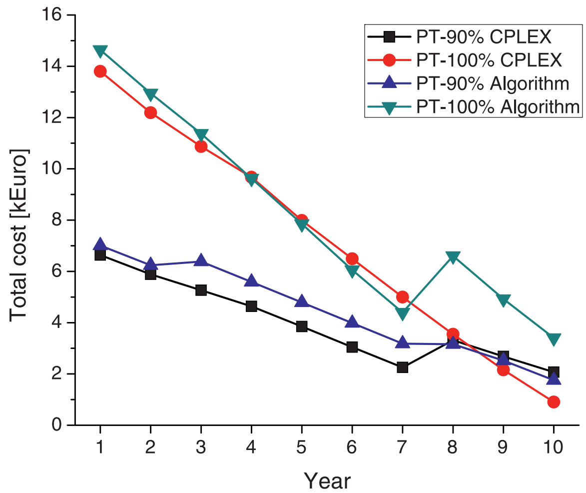

Fig. 6. Comparison between CPLEX and the heuristic algorithm in the case of Torino with energy sell-back.

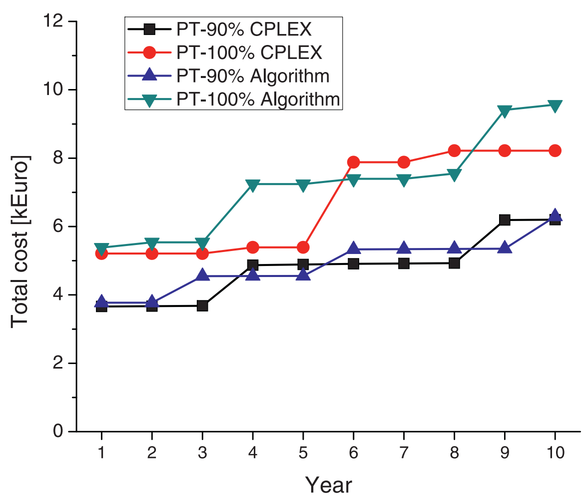

Fig. 7. Comparison between CPLEX and the heuristic algorithm in the case of Aswan, no energy sell-back.

ready discussed, the parameter evolution and battery replacements make the formulation non-linear and infeasible. Hence, the CPLEX results are not always the true optimum over the whole 10-year period.

Fig. 6 shows the comparison between the results of CPLEX and the results of heuristics, with energy sell-back ($PT = 100\%$ and 90%). This means that when energy is produced that cannot be stored because the battery is fully charged, the energy can be sold back to the power grid. We assume that the selling price is half the cost at which energy is purchased from the power grid. The figure shows that the gaps between CPLEX and heuristics are similar to those of the case without energy sell-back, shown in Fig. 5.

Similar to what we do with Torino, we compare the results of CPLEX and the heuristic algorithm for the case of Aswan; results are reported in Fig. 7, assuming that energy cannot be sold-back. The largest gap, in this case, is around 30%, but the differences at the end of the 10-year period are within 15%. The results for the case with energy sell-back are very similar and omitted here for the sake of brevity.

The results show that while the solutions obtained with the two approaches are similar, there is a systematic difference with the heuristic solutions selecting larger PV panel size and smaller number of batteries. However, when the total cost is considered,

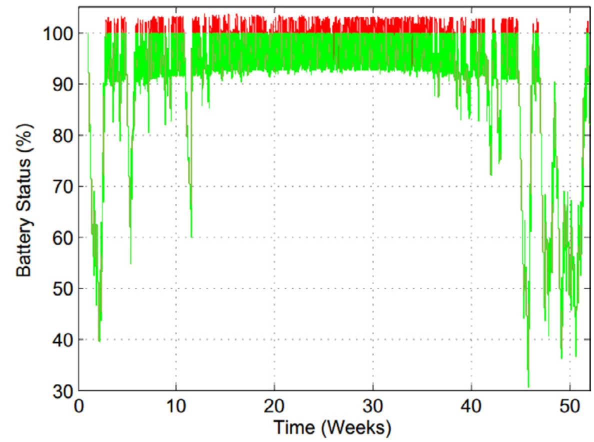

Fig. 8. Example of battery status for a system with kWp=16.6, 27 batteries, $PT = 100\%$ (i.e., without grid power), during the 9th year under the residential traffic profile, in Torino.

the differences between the solutions become rather small. We can conclude that the heuristic approach leads, in shorter time, to solutions whose cost is comparable with the solutions obtained with CPLEX. Hence, in the following, we will use the heuristic approach.

6. Comparing powering systems

In this section, we compare the effectiveness of the different considered powering systems for both Torino and Aswan. As we mentioned in previous sections, the two considered cities have quite different solar radiation patterns that lead to quite different results. Given the good accuracy provided by the heuristic algorithm and its lower computational complexity, in what follows we derive all results using the heuristic algorithm.

6.1. The case of Torino

6.1.1. System dimensioning

We start by considering the case of Torino for different values of PT, focusing on the one year optimization, that, for Torino, is performed using the system parameters of the 9th year. Table 4 reports the PV panel size, the initial number of batteries, the initial cost, the cost due to the amount of energy bought from the power grid (when $PT < 100\%$) and the reward due to sold-back energy. The results show that the hybrid solar-grid energy system ($PT < 100\%$) saves a lot in terms of cost and PV panel dimension with respect to the pure PV case ($PT = 100\%$); savings are from 50% to 70%. If 1 kWp PV panel roughly corresponds to 5 m^2 [21], the size of the PV panel of the hybrid system with $PT = 70\%$ is around 20 m^2, which is much more feasible for installation than the size of the PV panel for the pure solar energy system that is about 80 m^2.

For the same case, Fig. 8 shows the simulation of the battery charge status for the pure solar system ($PT = 100\%$). The red part of the curve refers to the amount of energy that cannot be stored inside the batteries. This part of energy is sold back to the power grid, if this is possible, and it is wasted otherwise.

The green part in Fig. 8 represents the battery charge status. The battery status is kept above 30%, which is a threshold that provides a safety margin in the design. The figure also clearly shows that the energy production bottleneck is in winter (at the beginning and the end of the year) where the discharge of the battery is much deeper. Therefore, to satisfy the requirement during the winter season, more batteries and larger PV panels have to be installed, and this leads to a larger energy wastage during summer. By integrating the percentage of battery charging and discharging,

Table 4
Size and cost of the powering system for the 9-th year dimensioning case, in Torino.

PT	PV size [kWp]	No. batt.	PV+batt. cost [k€]	Grid cost [k€ /y]	Pay back [k€ /y]
70%	4.3	5	4.07	0.16	0.240
80%	4.3	7	4.38	0.12	0.229
90%	9.1	7	8.07	0.05	0.850
100%	16.6	27	16.92	0	1.832

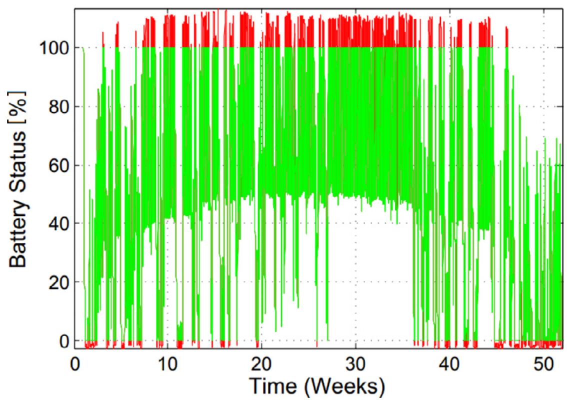

Fig. 9. Example of battery status for a system with kWp=4.3, 5 batteries, *PT* =70%, during the 9th year under the residential traffic profile, in Torino.

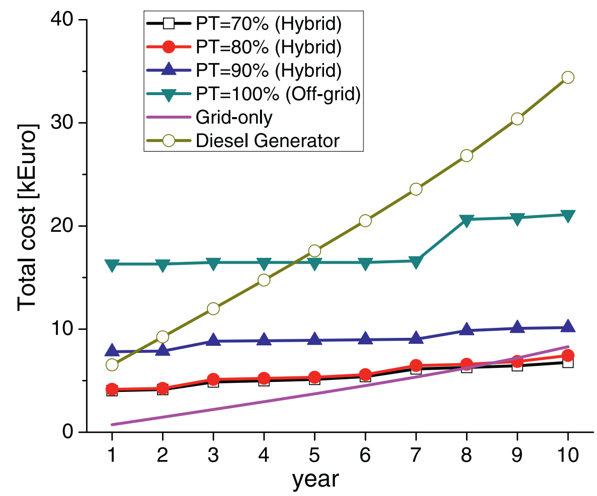

Fig. 10. Total cost for some values of *PT*, no energy sell-back, in Torino.

we compute how many battery cycles are consumed during the year. Then, the time when the battery is exhausted can be computed.

Fig. 9 shows the battery status of the hybrid solar-grid energy system (the case *PT* =70% is shown as an example). Similar to Fig. 8, the red part on the top stands for the wasted (or, if possible, sold back) energy and the green part represents the battery status. For *PT* =70% the percentage of time in which the battery status is above 30% is 70% of the entire year. The red part at the bottom stands for the amount of energy that is taken from the power grid. We assume that the BS uses energy from the power grid only when the battery is empty. The battery discharge in this figure is more balanced during the whole year with respect to Fig. 8. The discharging of the battery is much deeper, leading to a shorter life time of the battery. However, the savings of the dimensioning of the system is large due to smaller CapEx (smaller PV panel size and fewer batteries) and the larger number of battery replacements does not impair the advantage of the hybrid system. We will discuss the cost on 10 year periods in the next section.

6.1.2. Capex and opex in a 10 year period

Now we focus on the system cost during the whole 10 year period. Fig. 10 reports the case in which energy sell-back is not possible, i.e., the energy that is produced, but cannot be stored in the battery or consumed, is wasted. The figure shows the comparison between the cases of pure solar, hybrid solar-grid, grid only and diesel generator. The break-even point between the hybrid systems with *PT* = 80% and 90% and the grid only case is around the 8th year, meaning that taking all costs into account (CapEx and OpEx) the hybrid system starts being cheaper than the grid-only powering from the 8th year. As previously observed, hybrid systems cost much less than the pure solar system, with savings from 50% to 70%. The case with diesel generator is the most expensive one, even more expensive than the pure solar system from the 5th year. These results demonstrate that the proposed hybrid systems not only have the advantage of renewable energy which is clean and sustainable, but are also cost effective with respect to the traditional power grid.

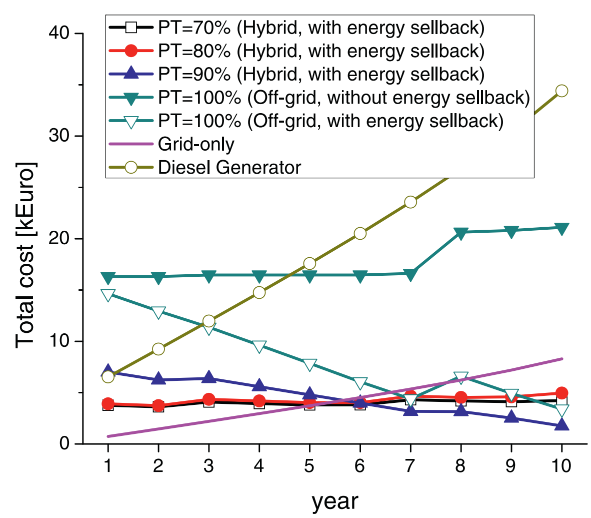

Fig. 11. Total cost for some values of *PT*, with extra-energy sell-back, in Torino.

Fig. 11 shows the results for the case with energy sell-back. In these cases, hybrid systems reduce cost from the 6th year with respect to the power grid. The pure solar system, being dimensioned with larger panels, results more convenient than the hybrid systems. However, the pure solar systems are usually deployed in rural areas where there is no access to the power grid, so that extra-energy cannot be sold back. Therefore, for comparison purposes, we also show the pure solar energy system without energy sell-back. The hybrid system with sell-back saves about 70% to 80% of the cost by the 10th year compared to the pure solar system without sell-back.

Table 5
Size and cost of the powering system for the 10th year dimensioning case, in Aswan.

PT	PV size [kWp]	No. batt.	PV+batt. cost [k€]	Grid cost [k€ /y]	Pay back [k€ /y]
70%	3.8	5	3.69	0.019	0.017
80%	3.9	5	3.76	0.014	0.024
90%	3.9	6	3.92	0.012	0.024
100%	5	15	6.15	0	0.109

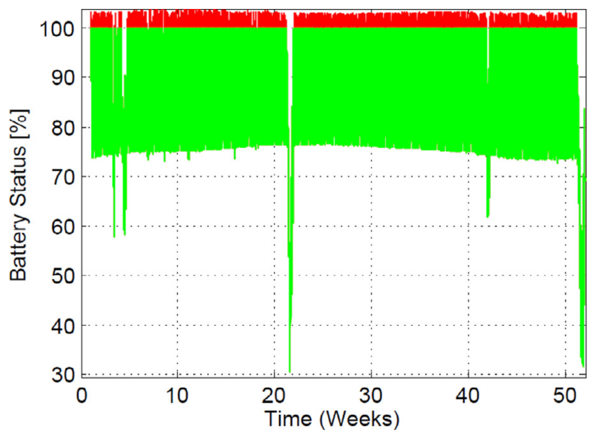

Fig. 12. Battery status, *PT* =100%, in Aswan.

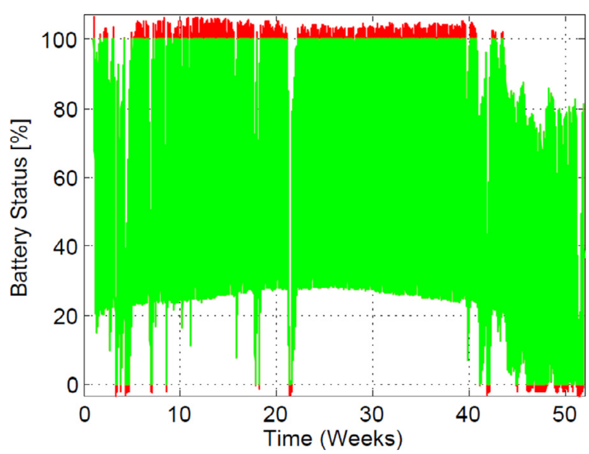

Fig. 13. Battery status, *PT* =70%, in Aswan.

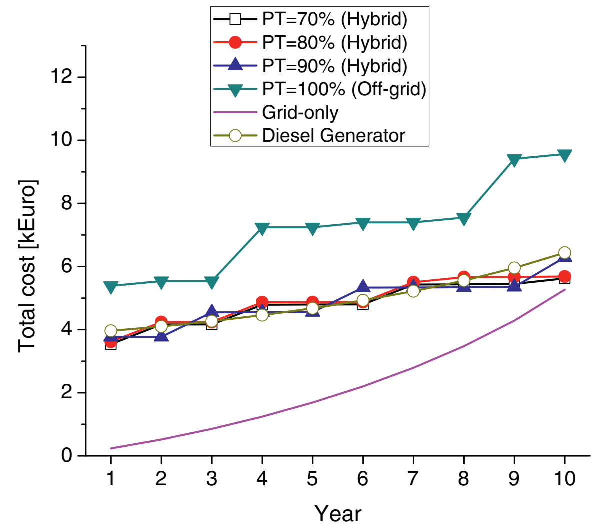

Fig. 14. Total cost for different values of *PT* in Aswan, no energy sell-back.

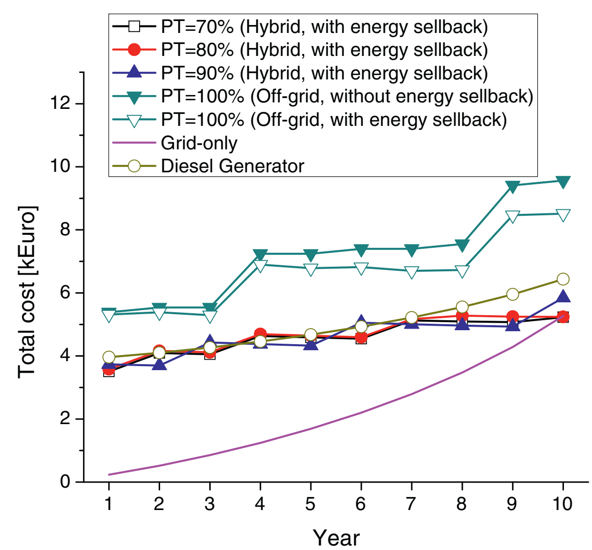

Fig. 15. Total cost for different values of *PT* in Aswan, with extre energy sell-back.

6.2. Aswan results

6.2.1. System dimensioning

As previously mentioned, in the case of Aswan, the 10-year dimensioning leads to choose the parameters' setting corresponding to the 10th year (it was the 9th year in the case of Torino). Indeed, only the conservative case of the 10th year parameters leads to a system that can guarantee the constraint on *PT* for the whole period. Table 5 shows the results of the optimization on year 10. Observe that the system, in terms of PV panel size and number of batteries, is much smaller than for the case of Torino. This is due to both the facts that in Aswan the solar radiation is higher and the seasonal variations are smaller than in Torino. Moreover, also the gap between hybrid systems and the pure solar system is much smaller than the case of Torino.

Fig. 12 shows the battery status of the pure solar system (*PT* =100%), while Fig. 13 shows the battery status of the hybrid system (*PT* =70%). Comparing these two figures with Figs. 8 and 9, observe that the battery has deeper charging and discharging in the Aswan case than in the Torino case. In Aswan, the solar radiation is almost constant during the whole year; hence, there is no bottleneck effect in winter. The least energy production time in Aswan is in May and December, when rain is more frequent than in other months. Deeper battery charging and discharging leads to more battery cycles.

6.2.2. CapEx and OpEx in a 10 year period

Fig. 14 shows the comparison of different powering systems (for the cases of pure solar, hybrid solar-grid, grid only and diesel generator) in Aswan, without energy sell-back, while Fig. 15 shows the results with energy sell-back. By comparing the two figures, observe that the amount of energy that is sold-back is so small that the two figures are almost the same. This is due to the dimensioning of the PV system that well fits the energy need of the BS.

From the two figures, we also see that the hybrid system saves with respect to the pure solar system, as in the case of Torino, and it is almost equivalent in cost to the diesel generator (consider however that we only account for the cost of fuel, which in Egypt is very low, excluding transport, etc). The cost for the hybrid systems is instead higher (about 10% higher at the end of the 10-year period) than for the connection to the power grid; this is because in Egypt the price of grid power is quite low. Again, consider that we do not include the cost of connecting the BS to the power grid, which can be marginal within the city of Aswan, but very high in the surrounding rural areas.

The increase of cost for the power grid with time in Aswan is faster than in Torino (see Figs. 10 and11), because the price increase rate (20% per year) is much higher than the one in Torino (3% per year).

7. Conclusion

In this paper we studied powering systems for LTE macro BSs that make use of solar energy, either relying on renewable energy only, or using a mix of renewable energy and traditional supply. We formulated the problem of the optimal choice of the PV panel size and number of batteries with a Mixed Integer Programming problem of cost minimization. We also proposed a heuristic algorithm which is much more computationally efficient than the MIP problem solution, while being reasonably accurate.

To discuss the effectiveness of the investigated BS powering systems, we considered two locations, Torino and Aswan, with quite different solar energy generation patterns. The results show that hybrid systems are much more effective than pure solar energy system. In addition, in the case of Torino, hybrid systems also reduce cost with respect to the traditional power-grid system and to a diesel generator. In Aswan, hybrid systems are economically equivalent to diesel generators, and somewhat more expensive than an existing connection to the power grid, because the electricity and diesel prices are both very low in Aswan.

Our study shows that powering BSs with renewable energy sources is today not only possible at reasonable costs, but also in many cases less expensive with respect to more traditional power supply approaches. The forecast technology advances in both solar cells and batteries will make the solar solution even more attractive in the years to come.

Acknowledgment

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Yi Zhang received his B.E. and Ph.D. degree both from Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2007 and 2012, respectively. He was a visiting Ph.D. student at University of California, Davis, U.S.A. from September 2008 to August 2010. He was a postdoctoral researcher at Politecnico di Torino, Italy from November 2012 to May 2015. From June 2015 he has been a postdoctoral researcher at Trinity College Dublin, Ireland. His research interest includes energy-efficient wireless networks and optical networks. He has co-authored over 5 IEEE and Elsevier journal papers. He has served as a Technical Program Committee member for over 10 IEEE and ACM conferences.

Michela Meo received the Laurea degree in Electronic Engineering in 1993, and the Ph.D. degree in Electronic and Telecommunications Engineering in 1997, both from the Politecnico di Torino, Italy. Since November 2006, she is associate professor at the Politecnico di Torino. She co-authored about 200 papers and edited a book with Wiley and six special issues of international journals, including ACM Monet, Performance Evaluation, and Computer Networks. She chairs the Steering Committee of IEEE OnlineGreenComm and the International Advisory Council of ITC. She was program co-chair of several conferences among which ACM MSWiM, IEEE Online GreenComm, IEEE ISCC, IEEE Infocom Miniconference, ITC. Her research interests include the field of performance evaluation and modeling, green networking and traffic classification and characterization.

Raffaella Gerboni received the MSc in Energy Nuclear Engineering in 2000 and a PhD in Energy Engineering in 2006 both from the Politecnico di Torino. She received a five year contract as a Researcher at the Energy Department of Politecnico where she has been also a Post Doc Fellow Researcher for more than five years. She has authored a book chapter with Woodhead–Elsevier and co-authored a book chapter with Springer. She is member of the Editorial Board of the International Journal of Contemporary Energy and serves as a reviewer for 3 Elsevier Journals. Her expertise is focused on energy systems analysis and on clean and efficient energy technologies. She has been responsible for MSc and Specializing Master Courses.

Marco Ajmone Marsan holds a double appointment as Full Professor at the Department of Electronics and Telecommunications of the Politecnico di Torino (Italy), and Research Professor at IMDEA Networks Institute (Spain). He earned his graduate degree in Electrical Engineering from the Politecnico di Torino in 1974 and completed his M.Sc. in Electrical Engineering at the University of California at Los Angeles (USA) in 1978. In 2002, he was awarded a “Honoris Causa” Ph.D. in Telecommunication Networks from the Budapest University of Technology and Economics. From 2003 to 2009 he was Director of the IEIIT–CNR (Institute for Electronics, Information and Telecommunication Engineering of the National Research Council of Italy). From 2005 to 2009 he was Vice-Rector for Research, Innovation and Technology Transfer at Politecnico di Torino. Marco Ajmone Marsan is involved in several national and international scientific groups: He was Chair of the Italian Group of Telecommunication Professors (GTTI); the Italian Delegate in the ICT Committee and in the ERC Committee of the EC’s 7th Framework Programme. He is a Fellow of the IEEE and he is listed by Thomson-ISI amongst the highly-cited researchers in Computer Science. He has been principle investigator for a large number of research contracts with industries, and coordinator of several national and international research projects.