HetNets Powered by Renewable Energy: a Cost Effective Paradigm for Sustainable Next Generation Cellular Networks

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Abstract

Renewable energy can become a key factor for sustainable next generation cellular networks. This work explores the possibility to feed base stations of a Heterogeneous Network with renewable energy sources, and analyzes implications of such choice with respect to a classical grid powered solution. Cost and CO_2 emission savings are evaluated for different scenarios, showing that properly powering Heterogeneous Network with renewable energy can be a sustainable and economically convenient solution for mobile operators.

Index Terms

HetNets, LTE, LTE-A, renewable energy, energy efficiency, sustainability, small cells, CAPEX, OPEX.

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I. INTRODUCTION

Can renewable energy play a role in reducing the deployment and running costs of the next generation cellular networks? Looking at how the current 3G networks are firmly attached to the electric grid, one would say no. But this could be different for next generation networks and in this paper we will investigate why.

It is widely recognized that the increasing popularity of cloud and Web 2.0 applications (e.g., Google, Facebook, Twitter, YouTube) together with the widespread use of new generation smartphones, netbooks, and tablets, will lead to a massive growth of data traffic from/to mobile users [1]. If the volume of traffic expected by 2015 [1] should be supported using current state-of-the-art network strategies, it would produce a relevant rise of both deployment and running costs, mainly driven by power consumption of network equipments, which, for handling a larger amount of traffic, will spend more energy than today. Moreover, the recent increasing trend of energy price will worsen the problem, thus pushing to the market only energy-efficient and sustainable solutions. Note that this cost increase should not be compensated by additional revenues, as subscription tariffs are expected to remain essentially flat.

At this moment, the leading approach towards next generation cellular systems envisions the adoption of Heterogeneous Network (HetNet) architectures [2]. According to this vision, several types of base stations (BSs) coexist within the cellular network, each one with different computational capability, power transmission, and coverage area.

HetNets seem an economically viable approach to meet capacity needs of new generation mobile services thanks to: the lower price of low-power BSs, the decrease of site acquisition/rental costs allowed by their small form factor, the simplified network planning, and the very limited maintenance costs.

In addition to such advantages, HetNets can benefit from the adoption of renewable energy sources (RES), which could fully sustain the needs of low-power base stations. This would also help contrasting the current 10% yearly increase of ICT contribution on the global carbon emissions, and therefore it would favour to meet the EU target of a 20% reduction in the carbon footprint by 2015 [3].

The use of RES to power cellular network has been first proposed in [4] back in the ~~year~~ 2001, where solar panels were proposed to feed a BS of a macro cell. Nevertheless, renewable sources are still to a large extent under exploited in present networks because they have not been economically viable so far. Let us consider a Photovoltaic (PV) plant as an example of renewable energy. Due to the high power consumption of a BS of a macro cell, very large solar panels and big size batteries are needed [4]. This is very expensive and causes an additional inflation in site acquisition/rental costs due to the additional room needed. Note that the size of solar panel and batteries can be reduced by resorting to multiple hybrid power sources (i.e., solar, wind, and diesel generators) installed into the same site [5]; however, this solution, while sometimes acceptable in scenarios like rural areas and developing countries [6] where the costs for connectivity to the electricity grid are prohibitive, is not in general effective in reducing the capital and operational costs of the site [2].

The advent of HetNets marks a turning point for the viability of the use of renewable energy in cellular systems. This because each low-power BS consumes alone very little power and, hence, it becomes relatively cheap to feed with renewable energy sources. Preliminary attempts in this direction are reported in [2]. Herein, we complement them by proposing a detailed cost-benefit analysis on the adoption of renewable energy in HetNets. Furthermore, we investigate the eco-sustainability of the HetNet paradigm, i.e., the ability of lowering CO_2 emissions by a clever usage of solar energy. In particular, after presenting in Sec. II a critical discussion on key features and novel approaches to HetNets powered by RES, we evaluate in Sec. III, cost benefits and CO_2 emission reduction deriving from the use of PV plants. We show that feeding low-power BSs with a PV plant represents, at this moment, a sustainable and convenient economical solution for a mobile operator.

II. SYSTEM MODEL

We refer to the access part of 3GPP HetNet architecture [7] (see Fig. 1), i.e., a multi-tier and self-organized wireless access network composed of several types of BSs with different characteristics, all using the same access technology (i.e., Long Term Evolution (LTE) and/or LTE Advanced (LTE-A)) and sharing the same spectrum.

A. *Reference Scenario*

We adopt the following nomenclature:

- **Macro cells** cover a vast area and support a high number of users. Power consumption of a macro cell BS is on the order of few thousands of Watts. Their deployment is performed by the operator

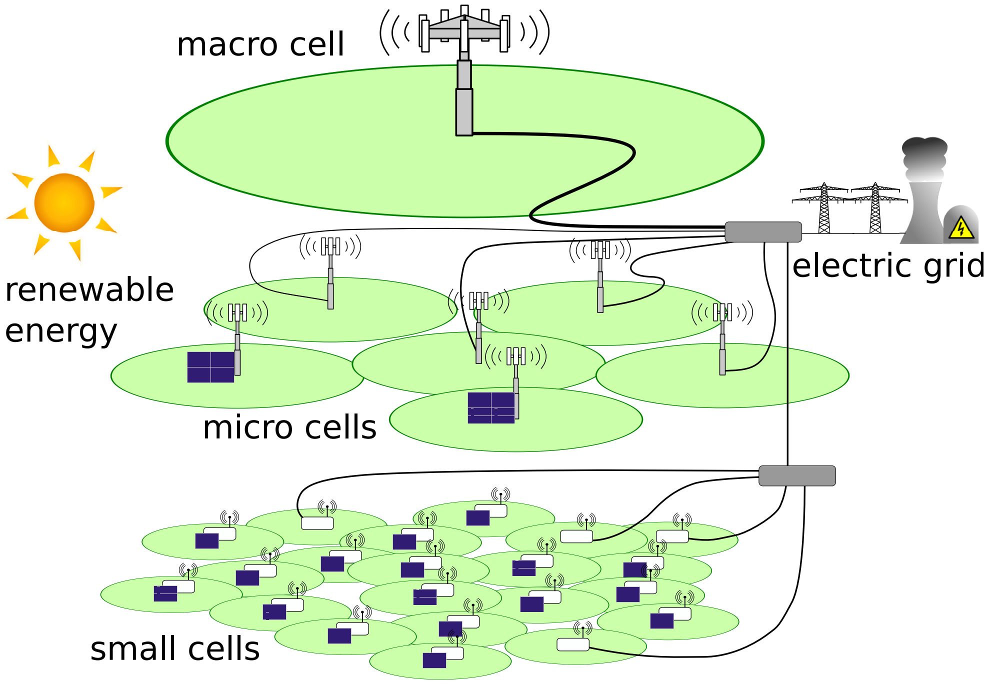

Fig. 1. Renewable HetNet architecture.

after a careful planning and site identification. Both Capital Expenditure (CAPEX) and Operative Expenditure (OPEX) are very high due to the price of the device, the site acquisition/rental costs, and the high energy consumption.

- **Micro cells** are characterized by a shorter range with respect to macro cells and, as in the previous case, they are installed directly by operators. The BS serving such type of cells, thanks to its smaller computational capabilities and power consumptions, offers lower CAPEX and OPEX with respect to the BS of a macro cell.
- **Small cells** require low-power, low range, and low energy consumption BSs. They are expected to provide improved coverage and capacity in indoor, metropolitan, and rural public spaces. Small cells can be deployed with a very loose planning (e.g., by an approximate site identification) or even with no planning at all. They can also be installed temporarily, for example, to cover a region with a high temporary demand of traffic in correspondence of special events (e.g., fairs, sports event).

B. Benefits of HetNet Powered by RES

All the BSs just discussed are originally intended to be connected to the electricity grid. Thus, the key characteristic of our proposal is the use of renewable energy to power (some of) them, as depicted in Fig. 1. Such an architecture would present the following benefits with respect to a fully grid-powered HetNet:

- cost savings in the long term, thanks to reduced OPEX;
- easier deployment, since a BS can be located even where it is difficult or impossible to get connectivity to the electricity grid and/or to install a wired backhaul to the core network;
- a reduction of carbon emissions, thanks to renewable energies.

The above advantages are expected not only to facilitate the upgrade to next generation networks by existing operators, but also to support new business models. In particular, we think that our architectural proposal would be significantly beneficial in the following use cases:

- *Network roll-out by low power operators*: a new trend in spectrum regulation for mobile broadband access consists of licensing spectrum to new operators subject to a low maximum power constraint. To be competitive with the services offered by traditional high-power operators, a cost-effective possibility is for the low power operator to roll out a dense network of small cells whose base stations are powered by renewable energy.
- *Capacity enhancements for traditional operators*: adding low-power nodes fed by renewable energy sources to an existing radio access network, a mobile operator would be able to easily and quickly achieve an improvement in network capacity at a competitive cost.
- *Cable-less coverage extension*: BSs supplied by renewable energy and connected to the core via a wireless backhaul are entirely cable-less. Hence, they furnish a cost-effective solution to quickly provide or extend the coverage in rural areas as well as in developing countries, thus, it would help in reducing the digital divide.

C. Open Issues and Novel Approaches

The introduction of RES, however, poses relevant technical challenges to be considered in addition to the well known issues related with HetNet (e.g., interference management, radio resource allocation and admission control, mobility management, mobile backhauling) that are already being investigated. In particular, the main problem introduced by RES is the unpredictable and changing time varying amount of energy they can harvest. For example, the power harvested by a wind turbine provides intermittent power, unreliable and difficult to predict; also, solar panels can gather energy only during the day and the harvested quantity is affected by variable phenomena such as clouds, rain, season changes, latitude. Then, the focus of network management is not on the minimization of the energy consumption, as normally done in green networking so far, but on the *energy sustainability* (concept introduced first in [8]), i.e., on the definition of procedures, protocols, and algorithms aiming at sustaining traffic demands and meeting the quality of service requirements of mobile users by using only the amount of harvested energy. Therefore, the system should be able to dynamically reconfigure itself to respond to energy source dynamics. In this respect, self-organization capabilities of HetNets are expected to facilitate the design of network management strategies. Though solving the open issues of HetNet powered by RES is out of the scope of this paper, we list a set of possible approaches that can be helpful for future research in this field:

- **Radio Resource Management (RRM)** techniques shall balance the load between macro, micro, and small cells and enable energy-aware data schedulers, so that the harvested energy can sustain traffic demands minimizing the probability of outage due to a BS running out of energy.
- **Admission control** algorithms shall assure high radio resource utilization while preventing heavy traffic overloads, when they could decrease the total network lifetime.
- **Mobility management** strategies shall provide seamless communications by properly executing handover in case of a BS is going down due to the depletion of its energy.
- **Interference management** among all these types of cells is expected to be handled by smart distributed algorithms, taking into account the dynamics of the energy sources too.

III. SYSTEM ANALYSIS

This section describes the advantages in terms of costs and CO_2 emissions of distinct HetNet topologies that a mobile operator can have from the adoption of BSs fed by PV plants.

A. Costs due to energy consumption of a grid powered LTE base station

Energy needs of an LTE BS can be evaluated by superposing the consumptions of its main components, such as the antenna interface, the power amplifier, the radio frequency transceiver, the baseband interface, and the power supply unit. Without loss of generality, our studies encompass two extreme traffic conditions: the "idle" case, where the BS is on, but there is no traffic; the "full load" case, where the BS transmits at its maximum power because the cell is highly loaded. Results obtained in this way will be useful to characterize the range of possible behaviors that a HetNets can span.

In fact, while the "full load" condition captures BS needs at the maximum level of traffic, the "idle" case, yields a lower bound on the energy consumptions, land occupation for the PV unit, and battery size. The analysis of this case can be done as a first step by an operator in order to check whether the minimum requirements are satisfied in the intended location for the future BS. If this is not the case, then a location change might be needed or else, a connection to the grid is possible.

At the same time, macro, micro, and small cells will be embraced in our analysis to emphasize the major role that the topology plays when renewable energy sources are exploited.

Tab. I reports both energy demands of different types of BSs [9] and their yearly OPEX due to the power consumption, evaluated by considering the average price of the electricity for Italian industries, i.e., 0.1463 €/kWh (see the Europe's Energy Portal, available at http://www.energy.eu). We remark that these expenses are completely avoided if the network is powered by a RES.

B. Costs due to PV installation

Since a PV plant is able to produce energy only during daylight periods, we need to jointly adopt it with a storage equipment to guarantee a complete isolation from the network. In this way, excess energy, generated during daylight periods, can be accumulated using the storage and, then, used during the night.

The procedure for sizing the plant for each considered BS is described in what follows.

1) The rated power of the PV plant, representing the maximum amount of power that a solar plant can generate, depends on the power needs, P, of the BS, the number of hours in a year, h_{year} (supposing that the BS is always active), and the number of hours of insolation in a year, h_{ins}:

$$PV_{RatedPower} = \frac{P \cdot h_{year}}{h_{ins}} \tag{1}$$

The PV plant has a land occupation equal to

$$PV_{landOccupation} = \frac{PV_{RatedPower}}{\eta \cdot I_{ST}}, \tag{2}$$

where η and I_{ST} are the average system efficiency (for a polycrystalline-silicon module, it is equal to 14%) and the standard solar radiation (equal to 1000 W/m^2), respectively (values are taken from TrinaSolar TSM-PC05 data-sheets).

2) Considering the average insolation period of the region where the BS is deployed, it is possible to estimate the amount of energy generated by the PV plant at each hour of the day (i.e., the production profile). Then, we can evaluate: the excess energy generation during the daylight time, $e_{daylight}$, when the solar panel production is higher than the load; the energy deficit during the night, e_{night}; and the amount of energy that can be accumulated by the PV plant after a whole day, e_{day}.

3) For the BS of a macro cell, the nominal power of the storage device is computed by considering two extreme sky conditions: 7 contiguous days of clear sky (for defining the maximum storable energy during the summer) and 7 contiguous days of heavily cloudy sky (for estimating the battery

discharge rates during winter). After 7 days of clear sky, supposing to have a completely empty storage at the beginning of this period, the peak amount of energy to be stored is equal to: $e_{week\_clear\_sky} = 6 \cdot e_{day} + e_{daylight}$. During the winter, in the worst case, solar panels do not generate any amount of energy during 7 contiguous days. With this assumption, the storage system should provide a total energy equal to $e_{week\_winter} = P \cdot 24h \cdot 7$. Now, considering a Lithium-Ion battery with an efficiency equal to 90% and a full discharge time equal to 4 hours [10], the nominal power ~~rating~~ should be equal to $e_{week\_clear\_sky}/4/0.9$ and $e_{week\_winter}/4/0.9$ for both of considered conditions. To conclude, the battery size is obtained by averaging the two aforementioned quantities, thus obtaining $0.5 \cdot e_{week\_clear\_sky}/4/0.9 + 0.5 \cdot e_{week\_winter}/4/0.9$.

4) Differently from the macro cell, which should be always operative for offering the base connectivity to users, a full availability of both micro and small cells could be not a mandatory goal. Hence, the rating of the storage system could be consequently reduced to $(3 \cdot e_{day} + e_{daylight})/4/0.9$, which grants for a 0.82% reduction of the yearly availability of the BS for each week of cloudy sky. In fact, in 7 consecutive days without solar light, this sizing of the storage is able to feed the base station for 4 days (this value is obtained by dividing accumulated energy into storage system, $3 \cdot e_{day} + e_{daylight}$, by the amount of energy consumed by a BS in a day), thus leaving the site unavailable for the remaining 3 days (i.e., the 0.82% of the year).
5) The CAPEX related to the entire PV system can be evaluated by considering that the cost of a Lithium-Ion battery and a PV plant is equal to 3500 €/kW [10].

Following the described procedure, we evaluated PV and storage ratings and its costs for all the types of LTE base stations in both "idle" and "full load" scenarios. In our study, we assumed that the BS is always active ($h_{year} = 8760$) and that the solar panel is oriented in a Mediterranean country, where $h_{ins} = 1400$. We computed the production profile taking into account the average insolation data for Southern Italy, estimated during the month of July 2011 (see http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php). Results are summarized in Tab. I.

C. Analysis of CO_2 emissions

According to latest estimations provided by the International Energy Agency and taking Italy as a reference, about 386 g of CO_2 are produced for each kWh of the electricity coming from the grid. To evaluate the real CO_2 savings, we subtract the amount of carbon emissions generated during the realization of PV system that, if distributed during the entire life of the plant, could be considered equal to 20 g/kWh [11]. Starting from these assumptions, we computed the amount of CO_2 saved in a year for each kind of BS (see Tab. I). As a summary, for every deployed low power BS powered by RES, the operator can save a yearly amount of CO_2 emissions varying from 42 to 364 kg, depending on the type of BS.

D. *Cost analysis*

From results in Tab. I, it is straightforward to note that photovoltaic energy sources are not well suited for powering the BS of a macro cell, because it would require a very huge storage and a very high PV land occupation, with a consequent increase of PV/Storage plant and site rental costs. On the opposite, for other types of BS, the following analysis will show that with a reasonable low investment for the installation, the use of RES can be economically convenient for an operator.

At the time of writing, some 3G low-power and small range devices on the market are advertised with a Mean Time To Failure of 100000 hours (≈ 11.4 years) [12]. Hence, based on the considerations of the previous sub-sections, we analyze herein the economical convenience that a mobile operator could achieve after 10 years.

We compare two possible scenarios:

- grid-powered, that is, all nodes are attached to the grid;
- partial-grid-powered, that is, only BSs of micro and small cells are fed by a PV plant.

The costs for connecting a BS to electricity grid, as well as the number of micro and small cells within the coverage area of interest, can greatly vary according to environmental settings and network requirements, thus making harder to predict economical advantages. For these reasons, we evaluated the cost savings due to the introduction of PV-enabled BSs by varying the CAPEX of the grid connection (we assumed that such costs are very similar for all type of nodes) and the number of micro and small cells.

In Fig. 2, cost savings, C, achieved by an operator using an RES by varying costs of grid connection is reported. Values on y-axis are obtained by the following formula: $C = C_{grid} + C_{energy} - C_{PV}$, being C_{PV} the cost of installation of the PV/storage system and C_{grid} and C_{energy} the CAPEX due to the connection to the grid and the OPEXs due to the energy consumed during 10 years, respectively. All common costs (i.e., initial investments of each BS, OPEX related to the energy consumed by the macro cell, site rental/acquisition and maintenance costs, etc.) have not been considered since they are the same either using renewable energy or the grid.

When a HetNet made by one macro cell and several small cells is considered, cost savings can be achieved for extremely low grid connection expenses.

TABLE I

Power needs, OPEX due to energy consumption, PV and storage ratings, PV installation costs, and CO_2 savings for LTE base stations.

Results	**Traffic conditions**	**LTE base stations**		
		BS of a macro cell	BS of a micro cell	BS of a small cell
Power needs, as in [9]	idle [W]	735	110	13.5
	full load [W]	1350	144.6	14.7
Yearly OPEX due to energy consumption. Computed by considering average price of electricity for Italian industries: 0.1463 €/kWh	idle [€]	941.97	140.97	17.3
	full load [€]	1730.14	185.32	18.84
PV power ratings: maximum power generated by solar panel in a year, obtained with Eq. 1	idle [kW]	4.6	0.7	0.08
	full load [kW]	8.45	0.9	0.09
PV land occupation: obtained with Eq. 2	idle [m^2]	32.86	4.91	0.6
	full load [m^2]	61.43	6.46	0.65
$e_{daylight}$: excess energy generation during daylight time obtained considering solar panel oriented in a Mediterranean country and average insolation data for Southern Italy in July 2011 (worst case analysis)	idle [kW]	24.5	3.7	0.5
	full load [kW]	45.5	4.9	0.40
e_{night}: energy deficit during night	idle [kW]	8.7	1.3	0.16
	full load [kW]	15.98	1.71	0.17
e_{day}: amount of energy that can be accumulated by the PV plant after a whole day, obtained as the difference between $e_{daylight}$ and e_{night}	idle [kW]	15.82	2.38	0.3
	full load [kW]	29.5	3.22	0.32
Storage ratings: size of the storage device computed following the procedure described in Sec. III-B	idle [kW]	33.7	3	0.37
	full load [kW]	62.4	4.06	0.4
CAPEX for the PV/storage plant. Computed by considering the cost of a Lithium-Ion battery and a PV plant equal to 3500 €/kW [10]	idle [k€]	134.05	12.92	1.6
	full load [k€]	248	17.36	1.7
CO_2 **emissions**: amount of carbon emissions saved during a year thanks to the adoption of PV systems	idle [kg/year]	2357	353	42
	full load [kg/year]	4328	364	47

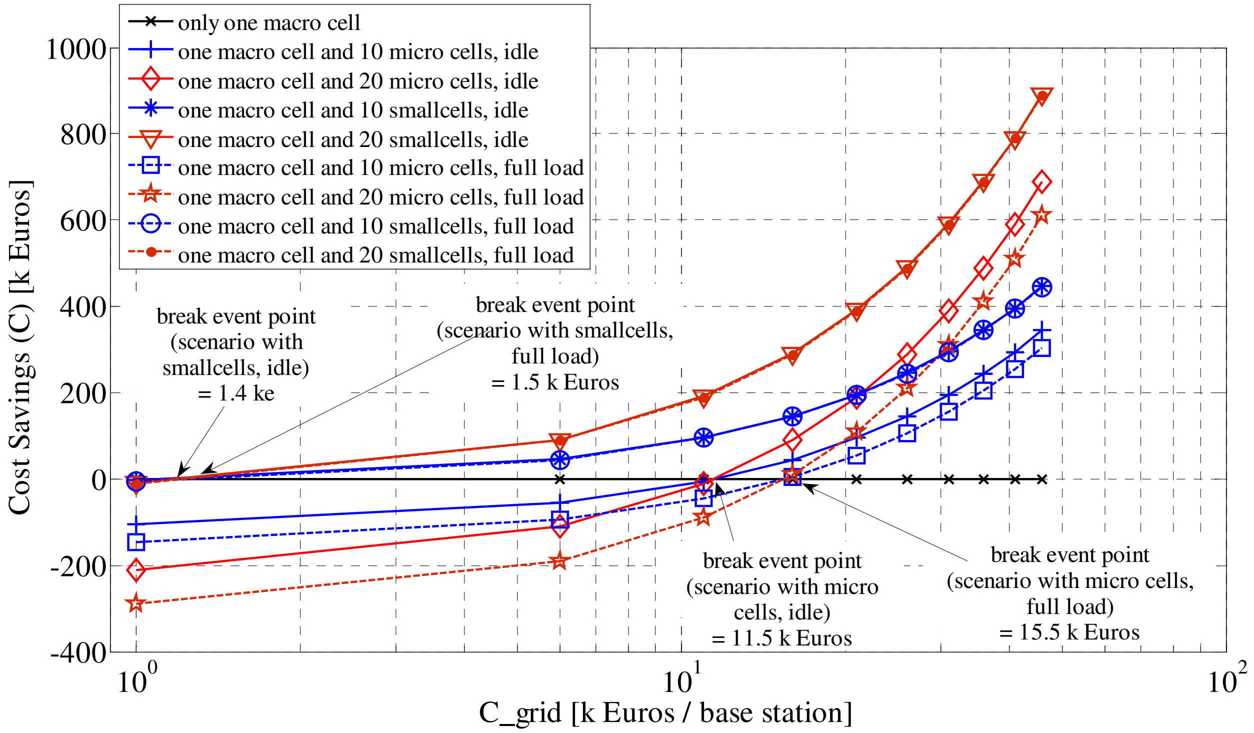

Fig. 2. Cost-savings achieved by mobile operators after 10 years in a scenario with one macro cell and several small cells (or micro cells).

On the other hand, in a HetNet composed by one macro and several micro cells, the adoption of photovoltaic energy is convenient only if the CAPEX for the connection to the grid is larger than 11.5 k€ and 15.5 k€ in scenarios with “idle” and “full load” conditions, respectively (see break-even points in Fig. 2).

In general, we can observe that the economical gain for mobile operators increases with the number of micro and small cells and the CAPEX of grid connection.

We remark that the presented cost savings analysis is valid independently on the way each BS is connected to the core network. In the case the backhaul is deployed through a wired link, its CAPEX and OPEX are the same for both grid-powered and partial-grid-powered scenarios. Hence, they do not have any impact on the results showed in Fig. 2. If the BS is connected to the core network through a wireless link, economical benefits achievable by mobile operators could be even higher with respect to those discussed in this section due to the absence of the cabling.

Another way to notice the convenience of RES adoption is depicted in Fig. 3, which reports the extra amortization period for PV/storage system installation in scenarios with 20 micro cells or small cells,

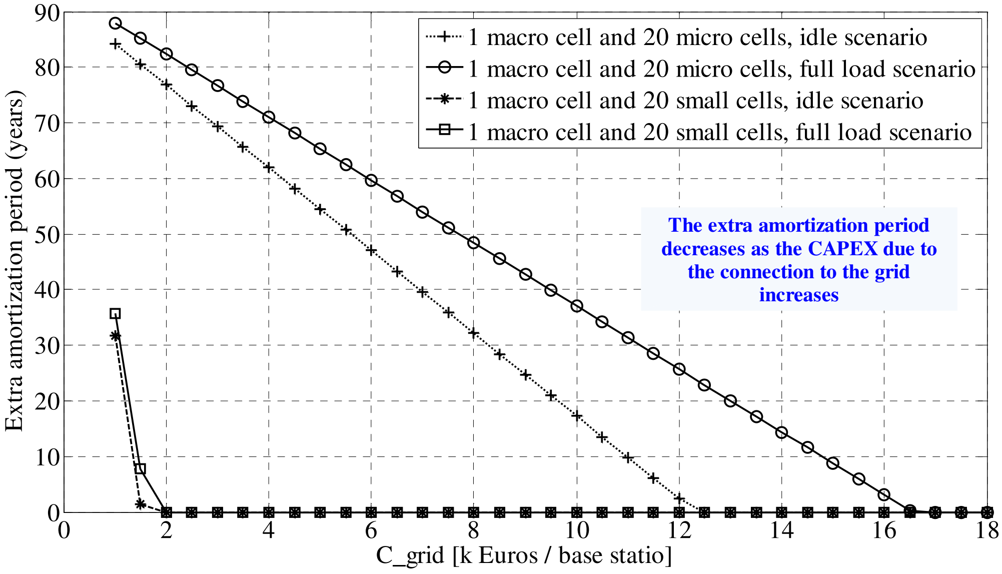

Fig. 3. Extra amortization period due to the cost of the installation of the PV-storage system in scenarios with one macrocell and several smallcells (or microcells).

defined as $max\,[0, (C_{PV} - C_{grid})/C_{energy}]$: the extra initial cost of the PV plant is amortized after very few years and with very low CAPEX due to connection to the grid, when small cells are deployed.

We can thus conclude that the deployment of partial-grid-powered HetNets represents, at this moment, an economically convenient and sustainable solution for mobile operators. Note that such an architecture could become even more attractive in the future by optimizing the activity of micro/small cells based on the traffic load they have to serve and on the status of energy available at the storage equipments.

IV. CONCLUSIONS

In this paper, the viability of photovoltaic energy sources in HetNets has been investigated for several topologies and traffic profiles, based on real product and insulation data. Reported results clearly demonstrate that renewable energy can be an economically viable solution for mobile operators, if used for feeding low-power BSs, and that the overall economical gain they can bring increases with the number of low-power BSs. Furthermore, thanks to a significant reduction of CO_2 emissions, HetNets powered by photovoltaic energy can really become a sustainable paradigm for next generation cellular systems.

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