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Procedia Computer Science 109C (2017) 825–832

Procedia Computer Science

www.elsevier.com/locate/procedia

The 7th International Conference on Sustainable Energy Information Technology (SEIT 2017)

Technical Economic Analysis of Photovoltaic Systems in Heterogeneous Mobile Networks

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Abstract

Mobile telecommunications operators are having to deal with an unprecedented increase in energy consumption due to the installation of heterogeneous mobile networks (HetNets), which are based on the deployment of macrocells and simultaneous use of large numbers of small cells. Although it has an efficient energy strategy, HetNets leads to a considerable increase in the consumption of energy, owing to its densification, because the importance of Backhaul is often overlooked. The use of renewable sources of energy is suggested as a means of overcoming this problem, since it entails diversifying the energy matrix and reducing the volume of CO_2 emissions in the environment, as well as being economically viable. Thus, the aim of this study is to make a techno-economic assessment of the acquisition and installation of photovoltaic systems within HetNets, while taking account of the combined energy consumption of radio networks, fronthaul and backhaul. On the basis of the results, there was clear evidence of its financial viability with regard to the adoption of the photovoltaic framework, as well as the environmental sustainability ensured by a considerable reduction in CO_2 emissions.

Keywords: Heterogeneous Mobile Networks, Grid-connected Photovoltaic System, CAPEX, Renewable Energy

1. Introduction

Currently, the ICT represents 0.5% of global energy consumption[1,2]. Moreover, it is expected that this rate will increase as the result of the growing densification of heterogeneous mobile networks (HetNets). This context has caused a good deal of concern to the mobile network operators who foresee that improving energy efficiency not only requires environmental responsibility but will also involve financial factors since a significant proportion of the operating expenses can be attributed to the cost of electric power.

Several alternative means of overcoming this problem have been explored in the literature, such as a reduction of energy consumption in the front/backhaul links, the shutdown of redundant Base Stations (BSs) in periods of

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10.1016/j.procs.2017.05.346

low traffic, the allocation of resources for the optimization of energy efficiency and the design of architectures for HetNets[3,4,5,6,7,8]. However, none of these alternatives focuses on the explicit reduction of CO_2 emissions by using renewable and clean sources.

Owing to constant concerns over the environment, a promising alternative has been to diversify the energy matrix by incorporating renewable types of energy sources, in particular photovoltaic systems. This is because it is economically viable to make substantial reductions in CO_2 emissions and depending on a number of variable factors, it is able to meet the energy needs of a particular geographical region and be adapted to different meteorological conditions[9,10,11].

Some countries like Germany, a world leader in terms of photovoltaic capacity, have invested heavily in sources of renewable energy as an alternative supply of energy. About 32% of this country's energy is renewable and largely consists of photovoltaic systems even though its sunniest region has a rate of solar irradiance that is 40% below the least sunny region in Brazil[12].

A number of different research studies have investigated the question of energy efficiency within HetNets but despite this, as far as we are aware, none of them has analyzed the viability of investing in the photovoltaic equipment needed to generate energy for the mobile networks infrastructure and its transport layer. To this end, this work presents analytical models that cover the technical-economic planning, acquisition and implantation of photovoltaic systems in HetNets. Moreover, it is analyzed the feasibility of establishing renewable energy sources (photovoltaic systems within HetNets) as alternative infrastructure for huge mobile network systems.

The rest of this work is structured as follows. In Section 2, we discuss the questions of HetNets, photovoltaic energy systems and Capital Expenditure (CAPEX). The design of photovoltaic systems is investigated in Section 3, and the results are analyzed in Section 4. Finally, Section 5 summarizes the conclusions.

2. Heterogeneous mobile networks, the Photovoltaic system and CAPEX

2.1. Heterogeneous mobile network design

This work makes use of the heterogeneous mobile network designs set out by Fiorani et al.[5], in which the authors examine several of the deployment alternatives for the radio sector and transport layer of the network, to estimate the costs incurred by the installation of photovoltaic systems in the scenario of heterogeneous mobile networks. In this work, two types of base stations (BS) are used : macro and small cells, where indoor users can be served by both macro and small internal BSs, whereas outdoor users are only served by macro BSs.

In this scenario, there are two strategies for the installation of small cells. The first is based on the concept of indoor Distributed Radio Architecture (DRA), which is a form of installation executed by network operators employing engineering techniques. The second uses Femto cells, that are characterized by the disordered use of small BS's, which are generally installed at random by the end-users of the heterogeneous mobile networks.

Architectures based on DRA, can be distinguished both with regard to their framework and the technologies applied in the network transport layer. In the Macro+DRA-CF (DRA Curb Fronthaul Architecture), as shown in Fig. 1 (a), the Remote Radio Units (RRU) were installed in street booths that were able to communicate with more than one building. The RRUs are interconnected with a microdatacenter (Hotel DU) located in the central office, by means of fiber optics using the protocols of the radio-over-fiber (RoF) system. However, in the Macro+DRA-BF (DRA Building Fronthaul Architecture), as shown in Fig. 1 (b), the RRUs are hosted inside each building, and each RRU is directly linked to an Optical Network Unit (ONU). The ONUs interconnect the buildings to a central office through a Dense Wavelength Division Multiplexer (DWDM) – a Passive Optical Network (PON) infrastructure – and to the Optical Line Terminal (OLT), which in turn is connected to the DU Hotel.

In a similar way to the DRA-based projects, Fiorani et al.[5] includes the use of two projects based on femto cells, one based on mature technologies, which employ Very-high speed Digital Subscriber Line (VDSL), Digital Subscriber Line Access Multiplexer (DSLAM) and Carrier Ethernet Switch transmission protocols, referenced as Macro+Femto-CB (Femto-Based Curb Backhaul), as shown in Fig. 1 (c). The other project is based on Next-Generation Passive Optical Network 2 (NG-PON2) technologies, consisting of ONUs and OLTs, referenced as Macro+Femto-BB (Femto-Based Building Backhaul), as shown in Fig. 1 (d).

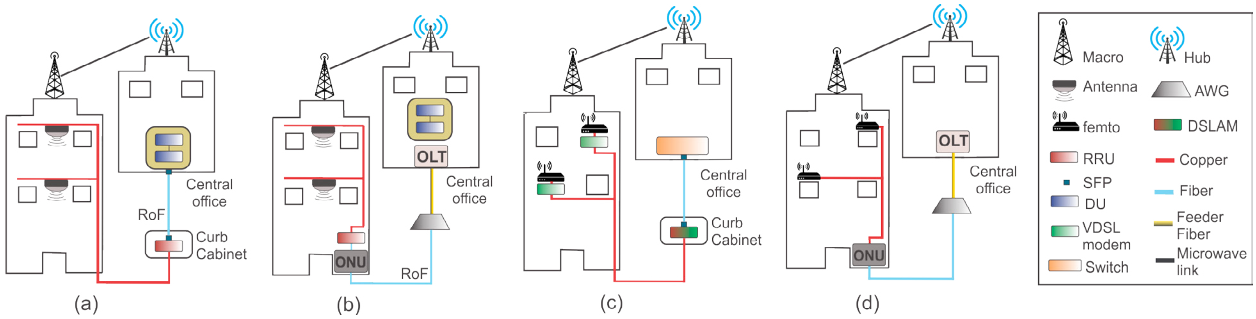


Fig. 1. (a) DRA curb fronthaul architecture. (b) DRA building fronthaul architecture. (c) Femto-Based curb backhaul. (d) Femto-Based building backhaul.

2.2. Characterization of the Photovoltaic energy system

The energy of the sun can be used directly in the form of light and heat, and is converted into electric power by photovoltaic cells, the performance of which can be affected by a wide range of factors, especially the intensity of the solar irradiance on the Earth (kWh/m^2/day), which can vary according to the region and season of the year.

Photovoltaic systems can be classified into two main categories, namely: off-grid and grid-connected [13]. The choice of either of these alternatives depends on factors such as the application, availability and particular constraints of each project, as well as cost benefits. Off-grid systems are characterized by not being connected to the power grid, and are in general used in remote areas, whereas grid-connected systems do not store energy. Instead, the energy can be partially stored in the utility network, where it acts as a supplementary source.

Hence, the basic structure of a photovoltaic system comprises a (i) photovoltaic module, (ii) an inverter and, (iii) the bidirectional electrical power meter. The photovoltaic module is the basic unit of the power generation subsystem, and is formed of a set of interconnected solar cells with the aim of generating enough voltage and current. The inverter acts by turning the direct voltage and current received from the photovoltaic module into an alternating current. The bidirectional meter records the energy received from the utility and the energy coming from the photovoltaic system that is added to the grid, which will add credit compensation for electric power in the case of grid-connected model. [10,11,14,15].

2.3. Capital Expenditure of the Photovoltaic energy system

Considering the design of the photovoltaic system it is important to analyze its technical and economic viability. This involves estimating the costs related to capital expenditure, which include hardware acquisition and installation costs. In photovoltaics, the CAPEX can be split into two segments: hardware and infrastructure. The first represents the expenses incurred by the purchase of inverters, panels and their respective installation kits. The second concerns the costs involved in the installation of the panels and inverters.

3. Photovoltaic System Design

This section presents the analytical models used to estimate the energy generated by using the photovoltaic system, as well as the models to compute both the overall CAPEX and end-user savings obtained by usage of photovoltaic energy. The design takes into account the energy consumption of different HetNets architectures proposed by Fiorani et al. [5].

3.1. Inverter-generated energy

The amount of energy generated by an inverter (E_{inv}) [kWh], can be calculated through the following equation:

$$E_{inv} = \eta_{inv} \cdot N^{P}_{inv} \cdot E_P, \quad (1)$$

where η_{inv} represents the efficiency of the inverter, expressed in the interval [0-1], whereas N_{inv}^{P} and E_P represent the number of solar panels that can be installed for each inverter and the energy generated by a single solar panel, respectively. The factor N_{inv}^{P} is given by Eq. (2):

$$N_{inv}^{P} = \left\lceil \frac{P_{inv}^{Input} \cdot t_{solar}}{E_p} \right\rceil, \tag{2}$$

where P_{inv}^{Input} and t_{solar} represent the nominal input power in kW and the mean time of sun exposure of the solar panel (hours) a day, respectively, while E_p, given in kWh, is obtained by Eq. (3):

$$E_p = A_p \cdot \eta_p \cdot r_s \cdot (1 - tx_{loss})^i, \tag{3}$$

where A_p, η_p, r_s, tx_{loss} and i represent the surface area of the solar panel (m^2), the percentage of solar irradiance converted into electrical power, the intensity of the solar irradianc (kWh/m^2/day), the percentage rate of power loss of the panel as a function of the time (i), in years, respectively.

3.2. Backhaul energy demand

The amount of energy required to keep under operating a backhaul architecture (E_{Min}) is given by the difference between the total energy consumption of a HetNet (Con_{total}) architecture minus the minimum energy consumption obtained from the conventional network ($N_{med} \cdot Con_{med}^{min}$). The formula is expressed by Eq. (4):

$$E_{min} = Con_{total} - (N_{med} \cdot Con_{med}^{min}), \tag{4}$$

where N_{med} and Con_{med}^{min} represent the number of electric power meters and the minimum daily consumption franchised from the grid electricity per meter [kWh], respectively.

3.3. Total Generated Energy and Savings per User

The total energy generated by the photovoltaic system (E_{gen}) is represented by Eq. (5):

$$E_{gen} = N_{inv} \cdot E_{inv}, \tag{5}$$

where N_{inv} represents the number of inverters needed to power the architecture and is given by $N_{inv} = \lceil \frac{Con_{total}}{E_{inv}} \rceil$. Furthermore, the extra amount of energy generated (E_{xtra}), which can be sold to the electric utility, can be described as $E_{xtra} = E_{gen} - E_{min}$. As a result, the money saved per user (AS_{user}), expressed in [BRL/user/year], can be calculated by means of Eq. (6):

$$AS_{user} = \frac{\left(E_{xtra} \cdot c_{sale}^{kWh} + Con_{total} \cdot c_{acquisition}^{kWh}\right) - CAPEX_{FV}}{\rho \cdot A}, \tag{6}$$

where c_{sale}^{kWh} and $c_{acquisition}^{kWh}$ represent the retail and acquisition prices of one kWh, respectively. Additionally, ρ represents the population density (users/km^2), A represents the size of the residential area (km^2) and $CAPEX_{FV}$ represents the Capital Expenditures of Photovoltaic System, as represented by Eq. (7).

3.4. Acquisition Costs of the Photovoltaic System

This section presents the analytical models used to predict the cost of installing the photovoltaic system as a function of the energy needs of the heterogeneous network architectures outlined by Fiorani et al.[5]. Thus the CAPEX of the photovoltaic infrastructure ($CAPEX_{FV}$) can be described by Eq. (7):

$$CAPEX_{FV} = (1 + tx_{install}) \cdot C_{equip}, \tag{7}$$

where $tx_{install}$ and c_{equip} represent installation rate and the acquisition cost of the hardware, respectively. The acquisition cost of the hardware is given by Eq. (8):

$$c_{equip} = \sigma \cdot [N_P \cdot (c_P^{Unit} + c_{Kit}^{Unit}) + N_{inv} \cdot c_{inv}^{Unit}], \quad (8)$$

where N_P represents the number of solar panels, which is in turn given by: $N_P = N_{inv} \cdot N_{inv}^P$. Whereas, c_P^{Unit}, c_{Kit}^{Unit} and c_{inv}^{Unit}, represent the unitary cost of the panel, the unitary cost of the installation kit and the unitary cost of the inverter, respectively.

4. Case Study

We consider a 100 km^2 residential area with population density of 3.000 users per km^2 and 10,000 residential buildings uniformly distributed. To simplify the models, we assume the same number of floors and flats for each building, five floors with a total of 15 flats per block. In the present work, 80% of indoor users and 20% of outdoor users, which were based on estimates of predicted population growth in the next few years [16]. Furthermore, we assumed that the solar panels would be exposed to the sun for an average period of five hours [17].

With information about the total energy consumption of data architecture, it is possible to estimate the amount of energy that the photovoltaic system must generate. Some key parameters are shown in Table 1 to design and evaluate the technical and economic feasibility of a photovoltaic system, such as data about the solar panel, which is made of polycrystalline silicon and provides energy efficiency of 16.68%, with an annual performance loss of 0.5% [18,19]. In addition, the panel has a surface area of 1.91 m^2, a lifespan ranging from 25 to 30 years and 10-year warranty against factory defects. Its photovoltaic cells are protected by a tempered glass layer and under optimal solar irradiance conditions, produces 320W, 8.69A and 36.8V DC [19].

Table 1. Parameters of the photovoltaic system

Equipment	Nominal Power	Efficiency (%)	Surface (m)	Power loss	Installation rate (%)	Value (R$)
Inverter	60 kW	98.3	-	-	20	20,246.20
Solar panel (Polycrystalline Silicon - 70 cells)	320 W	16.68	1.918828	0.5%/year	20	659.77
Installation kit (Solar panel)	-	-	-	-	20	199.75

In Table 1, there is also information about the inverter, which has nominal output power of 60 kW, efficiency of 98.6% and 5-year warranty [20]. Table 1 also displays the input data for calculating the CAPEX of the photovoltaic system, such as the cost of the inverter, solar panel and installation kit for one solar panel, R$ 20,246.20 [20], R$ 659.77 [19] and R$ 199.75 [21] respectively. The installation cost of this equipment includes manpower and the engineering project, which correspond to 20% of the value of the product [22,23]. Additionally, the solar irradiation examined in this case study varied between 1.66 and 6.66 kWh/m^2/day, whereas the mean of daily sunlight in a one-year period was based on an interval from 3 to 10 hours a day, as is the case with Brazil [17].

The value of the hardware has a fixed 5% depreciation rate per year, limited to a 60% starting value [24]. With regard to the purchase and retail prices of one kWh of electric power from the utility, the former corresponds to R$ 0.64 with taxes [18], and the latter to R$ 0.47 without taxes [25,26,27], these values being the average for the year 2015. It should be noted that the availability cost of the electric system, for a consumer in group B, is 100kWh, for a three-phase electricity supply [28].

5. Results

In this section, we show the results obtained from the case study considering 15 years of analysis that comprises from 2016 to 2030. Also, we present the $CAPEX_{FV}$ that was calculated for all the HetNets architectures presented Section 2.1. The technical and economic feasibility of the approach adopted here can be demonstrated by making a comparison between the values, (in monetary terms of millions of Real – R$), of the energy consumption of the heterogeneous network architectures, with the purchase and installation costs of the photovoltaic system ($CAPEX_{FV}$).

The consumption of electric energy accumulated over a 15-year period of these architectures (kWh), without considering the use of photovoltaic systems and monetary corrections, can be seen in Table 2.

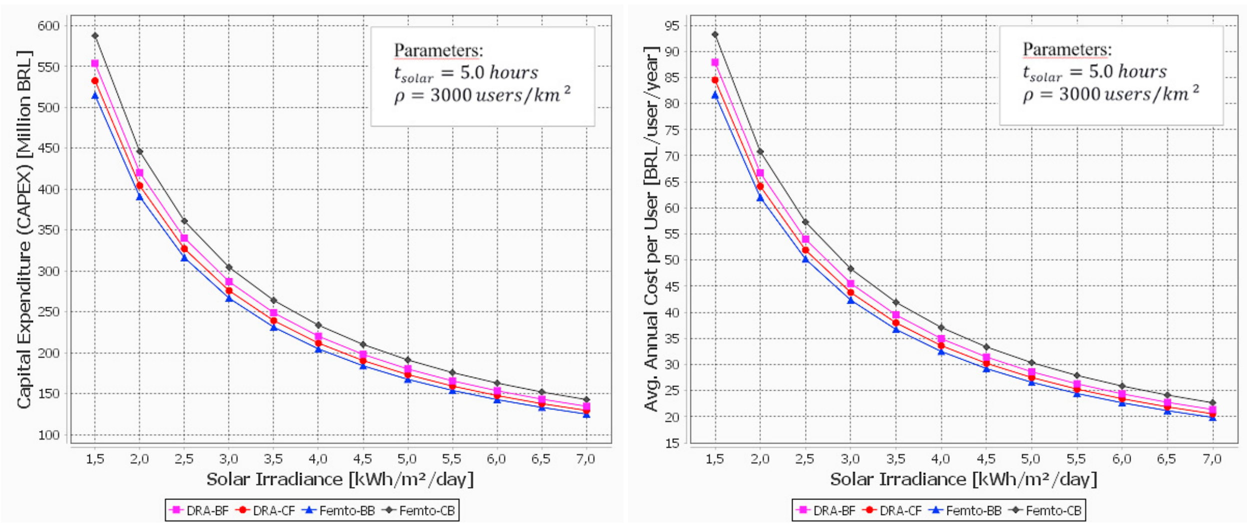
Table 2. Reference values for energy consumption without the use of photovoltaic systems.

HetNet architecture	Value (Millions of R$)	Total consumption (MWh)
Macro+DRA-CF	383.66	571,112.07
Macro+DRA-BF	419.54	619,677.58
Macro+Femto-CB	419.99	697,174.73
Macro+Femto-BB	361.20	533,514.22

To ensure that the project is economically viable (compared with the acquisition of electricity from the utility), the expenses involved in the acquisition and installation of the photovoltaic systems ($CAPEX_{FV}$) must be below the reference values shown in Table 2. Thus, the cost of the photovoltaic system associated with the energy consumption of heterogeneous mobile network architectures should be lower than the range of R$ 361.20 to R$ 471.99 million, to be economically feasible.

Fig. 2 (a) shows the photovoltaic structure as a function of the solar irradiation intensity during the daytime. It can be observed that when the solar irradiance is above 2.5 kWh/m2/day, the acquisition and installation costs of the photovoltaic system lie below the range of R$ 361.20 to R$ 471.99 million, which yields promising results, since this solar irradiation rate matches that of a temperate climate (parts of Europe, North America, etc), where solar availability is lower than tropical climate regions (Mexico, Brazil, Singapore, etc).

Fig. 2 (b) supplements the analysis, by showing how the installation and acquisition costs of the photovoltaic system are spread among the users of the HetNet. There is a steady decline in the curve of the graph, which shows that the installation cost per user tends to fall if the solar irradiation is more intense, since a smaller amount of hardware is needed to generate the same amount of energy.

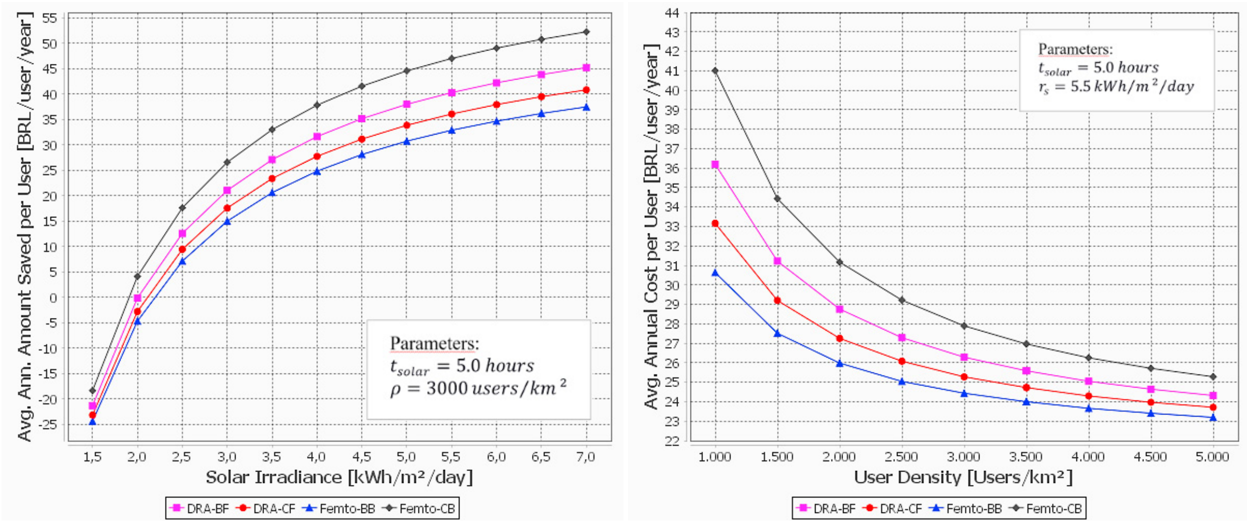


(a) (b)

Fig. 2. (a) Photovoltaic CAPEX (R$) as a function of solar irradiance (kWh/m^2/day). (b) Average annual cost per user (R$) as a function of solar irradiance (kWh/m^2/day).

Fig. 3 (a) shows the mean value saved per user as a function of the solar irradiation (kWh/m^2/day), when the extra volume of electric power produced by the photovoltaic system is taken into account, as defined by Eq. (7). Notice the ascending line of the curve, which indicates that the users' savings tend to increase as the solar irradiance becomes more intense. In other words, the acquisition cost of the photovoltaic system can be subtracted from the value of the total amount of energy generated. This difference corresponds to the amount the user would pay for the utility.

In addition, Fig. 3 (b) shows the average annual cost per user as a function of the user density. An analysis of this graph, makes clear that the mean cost per user tends to decrease as the user density increases, thus indicating that the energy consumption of HetNets architectures do not follow the linear growth rate of the user density. The larger the size of the population of a certain area, the more users of the HetNets will share the costs. This can explain why the acquisition and installation costs tend to become smaller as the user density grows.



(a) (b)

Fig. 3. (a) Average value saved per user (R$) as a function of solar irradiance (kWh/m^2/day). (b) Average annual cost per user (R$) as a function of user density (users/km^2).

6. Conclusion

This work has examined the technical and financial factors involved in the adoption of a photovoltaic system within heterogeneous mobile networks (HetNets) and the results show that this is a promising alternative for reducing CO_2 emissions. In addition to ensuring sustainability, the acquisition and installation costs of the photovoltaic system ($CAPEX_{FV}$) are lower than the acquisition costs of energy from the utility, which suggests there are financial benefits from adopting photovoltaic systems, apart from the fact that they lead to a significant reduction of CO_2 emissions. In this work, it was found to be economically viable to invest in the installation of photovoltaic infrastructures in regions with solar irradiation above 2.5 kWh/m^2/day.

The real-life case study shows that capital expenditure and average annual cost per user are reduced in proportion to the increase of solar radiance intensity. Also, the energy consumption does not follow the linear growth rate of the user density.

Finally, in future work we plan to extend this study taking into account the operational and maintenance (O&M) costs of the photovoltaic structure, to provide the mathematical models with a greater degree of realism. Items such as maintenance of the hardware throughout its lifetime, the rental costs of places to install the panels, etc, are essential factors when designing photovoltaic systems that operate in long-lasting optimal conditions. In addition, factors such as uncertainties of sunlight availability when considering climate, planet region or season or even the impact of spatiotemporal variation of users on the energy demand of HetNets architectures should be considered in future works.

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