

# Sharing Renewable Energy in a Network Sharing Context

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**Abstract**—This paper studies the performance gains resulting from the sharing of energy and network resources in the case of co-located base stations of different mobile network operators, powered by photovoltaic panels, and equipped with energy storage. Three configurations are considered for base station cooperation. The first one assumes two non-cooperating base stations, each one exploiting its own power system and serving its own customers, hence with no sharing. The second considers a shared power system, but no cooperation in customer service. The third looks at cooperation in both energy production and service provisioning, since only one base station handles all customers when traffic is low. Using an analytical modeling framework, we compute performance metrics for the three cases, and we show that significant gains are possible in the case of energy and network sharing.

**Index Terms**—Cellular networks, Network sharing, Renewable energy, Energy harvesting, Solar energy.

## I. INTRODUCTION

This is a period of important transformations for Mobile Network Operators (MNOs) and their networks.

First of all, the decrease in the fees charged to end users per unit data volume is putting great emphasis on the reduction of the network operation costs, and energy saving is a primary target. This has spurred a decade of intense research in energy-efficient communications and networks, with many large international cooperative research efforts, like [1]–[3]. These projects led on the one hand to the proposal of new network management approaches, mostly based on the introduction of sleep modes in periods of low traffic (see, e.g., [4]), and on the other hand to much more energy parsimonious equipment, Base Stations (BSs) in particular (see, e.g., [5]). Second, the need to bring cellular communications to areas of the world where the power grid is not developed, or not reliable, generated a great interest in standalone BSs, which can operate out of a local power unit. Given the high cost of operation of Diesel power generators, the drive for cost reduction, and the decreasing amount of energy necessary to run a BS, the use of Renewable Energy Sources (RES) has become a viable option, and is being applied in a growing number of cases [6]. The possible RES for a BS power system are mostly photovoltaic (PV) panels and wind turbines. The former is more common, due to the better predictability of the amount of generated energy, and to the reduced environmental impact.

Third, the more and more rapid succession of cellular network generations (5G is about to come, while MNOs are still

deploying their 4G networks) is creating investment problems to MNOs, that are considering the possibility of partnering with their competitors in the development of portions of their infrastructure, while still competing on service offerings. This makes the concept of network cooperation, or network sharing (in its various flavors, from mast sharing, to antenna sharing, to tower sharing, to full network sharing, and to network slicing in the near future of 5G), which the MNOs considered nonsense up to few years ago, a viable and economically attractive option. The benefits of network sharing in terms of energy saving can be significant, and were previously analysed in [7], [8]. Base station cooperation was also investigated in [9], looking at different levels of cooperation, as well as in [10], where the problem is tackled at the transmission level, and in [11], where fairness in energy sharing is discussed.

In this paper we explore the opportunities arising from the three aspects above, and we look at the possible performance gains resulting from the sharing of co-located base stations powered by a common PV panel, supplemented with energy storage. We compare three cases. The first one (the baseline case) assumes two non-cooperating BSs, each with its own power system. The second considers a shared power system, but non-cooperating BSs. The third looks at cooperation in both energy production and service provisioning. We analytically compute performance metrics for the three cases, and we show performance gains deriving from cooperation, by exploiting a performance analysis framework that was developed for PV powered BSs [12].

The rest of this paper is organized as follows. In Section II we provide a description of the system configurations that we analyze. In Section III we illustrate the stochastic model adopted in the performance study. In Section IV we discuss numerical results, and finally Section V concludes the paper.

## II. THE TWO BASE STATIONS

We consider a scenario where two BSs of two competing MNOs are co-located, and offer services over the same geographical area. Power is provided to the two BSs by a solar energy system. We study and compare three different configurations.

- **Configuration 1 - No Sharing** – The two BSs operate independently, each one using the power generated by a dedicated PV panel and stored in a dedicated battery. Two PV panels and two batteries are present, and no energy

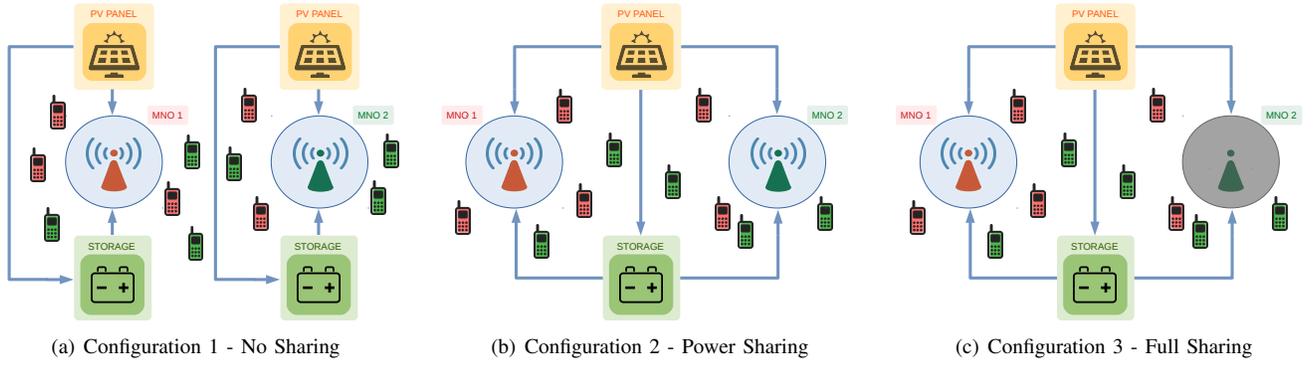


Fig. 1. The three different configurations of the two base stations and of the renewable energy generation system that we consider in this paper. a) The two BSs operate independently, each one using the power generated by a dedicated PV panel and stored in a dedicated battery. b) The two BSs operate independently, sharing the power generated by one PV panel and stored in a common battery. c) The two BSs cooperate, sharing the power generated by one PV panel and stored in a common battery.

sharing is possible. The two BSs are always on, as long as renewable energy is available, from either the PV panel or the battery. No network sharing is implemented. Each BS serves the customers of the corresponding MNO. This configuration is depicted in Figure 1.a.

- **Configuration 2 - Power Sharing** – The two BSs operate independently, sharing the power generated by one PV panel and stored in a common battery. One PV panel and one battery are present, and energy sharing is possible. The two BSs are always on, as long as renewable energy is available. No network sharing is implemented. Each BS serves the customers of the corresponding MNO. This configuration is depicted in Figure 1.b.
- **Configuration 3 - Full Sharing** – The two BSs cooperate, sharing the power generated by one PV panel and stored in a common battery. One PV panel and one battery are present, and energy sharing is possible. The two BSs are both on, when the total load exceeds the capacity of one BS, and energy is available. In this case, each BS serves the customers of the corresponding MNO. If the total load can be handled by just one BS, just one BS is active (as long as energy is available), and the other is set to sleep mode. In this case, the BS that is on serves the customers of both MNOs, as shown in Figure 1.c. Network sharing is implemented.

The three configurations are compared under the assumptions of similar load (the two BSs have daily traffic load patterns with identical shape, scaled according to different parameters  $\alpha$  and  $1 - \alpha$ ), equal total PV panel peak power (the total area of the available PV panels - one or two - is constant), and equal total battery capacity. In the case of no power sharing the two PV panels are identical, and so are the two battery capacities.

The performance metrics used for the comparison are the following.

- BS outage probability, i.e., probability that no energy is available (either from the PV panel or in the battery) to operate the two BSs, computed over all weather conditions and over all times of the day;

- BS outage probability as a function of time, computed over all weather conditions;
- Battery charge as a function of time, averaged over weather conditions.

### III. MARKOVIAN MODEL

We model the behavior of the two-BS system using the Markovian framework described in [12], which accounts for the dynamics of the power system energy production process, of the BS energy consumption process, and of the battery charge with time.

The model consists in a discrete-time Markov chain (DTMC) which evolves over time slots of duration  $\Delta T$  [h]. The DTMC state is defined by three variables:

$$\bar{s} = (W, T, S)$$

where  $W$  indicates the weather state;  $T$  represents the time of the day, and  $S$  corresponds to the current charge of the battery.

According to the findings in [12], the time granularity  $\Delta T$  is set equal to one hour. Hence, the DTMC state jumps from a state with  $T = i, i \in \{0, 1, \dots, 23\}$  to a state with  $T = (i + 1 \bmod 24)$ .

The value of the weather variable  $W$  defines the level of energy production in the day. According to the findings in [12], we use 5 different levels of weather condition in the DTMC model, and the quantization is obtained by constructing a histogram with bins of equal size. The value of  $W$  changes only at the beginning of a new day. The weather histogram as well as the probabilities with which a day of weather level  $j$  follows a day of weather level  $i$  are obtained from long-term (20 years) historical data about the daily solar irradiance [13]. The actual energy production in a given time slot depends on both  $W$  and the time slot: for any value of  $W$ , at night the energy production is zero. The amount of solar irradiance in individual time slots is derived from fine-grained short-term (2 years) solar irradiance historical data [13]. We look at the geographical location of Torino in Italy, and we consider only the three winter months, that correspond to the lowest energy

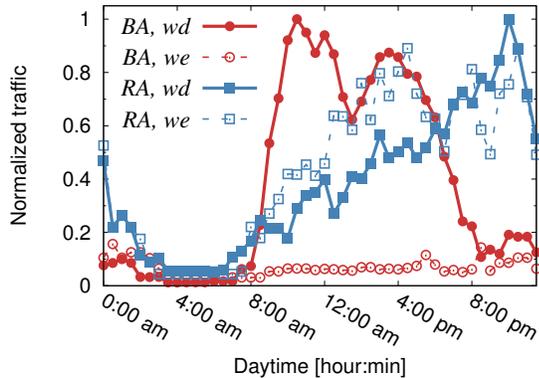


Fig. 2. Week-day (wd) and week-end (we) traffic loads in a business (BA) and residential (RA) area.

production, and thus provide a pessimistic example.

The state variable  $S$  represents the battery charge level. Denoting with  $C_B$  the battery capacity in kWh, we define a quantization step  $Q_s$  which is set to 100 Wh for battery capacity of 25 kWh, and equal to 50 Wh for battery capacity of 12.5 kWh. At every state transition, the energy level in the battery at the beginning of the next slot is computed as the rounded sum of the energy in the battery at the beginning of the current slot, plus the energy produced during the time slot, minus the energy consumed in the same time slot.

The cardinality of the DTMC state space in the worst case is equal to  $24 \times 5 \times 250 = 30000$ , and the steady-state probabilities are computed using the TANGRAM-II tool [14]. In order to compute the BS power consumption we use the model defined in the FP7 project EARTH [1]. The power needed to operate a macro BS can be expressed as:

$$P_{in} = N_{TX} \cdot (P_0 + \Delta_p \cdot P_{out}), \quad 0 < P_{out} < P_{max} \quad (1)$$

where  $N_{TX}$  is the number of BS transceivers,  $P_{max}$  represents the maximum radio frequency output power at full load for one transceiver,  $P_0$  corresponds to the fixed power consumption for one transceiver when the radio frequency output power is null, and  $\Delta_p$  is the slope of the load-dependent power consumption.  $P_{out}$  is derived as:

$$P_{out} = \rho \cdot P_{max}, \quad 0 \leq \rho \leq 1 \quad (2)$$

where  $\rho$  denotes the instantaneous normalized BS load.

The power consumption of a LTE macro BS without Remote Radio Unit (RRU) has been derived considering the standard EARTH BS, and the forecast consumption of BSs in year 2020 [5]. In the first case, the typical minimum and maximum values of the power consumption  $P_{in}$  are 780 W and 1344 W, respectively. In the latter case, the typical minimum and maximum values of the power consumption  $P_{in}$  are 139 W and 742 W, respectively. The daily variation of the parameter  $\rho$  is defined by the BS traffic profiles. We use real traces provided by one of the Italian mobile network operators [15]. The daily traffic patterns measured in a cell in a business area (BA) and in a cell in a residential area (RA), during week-day (wd) and week-end (we), are provided in Figure 2, setting the maximum

observed load equal to the maximum load that can be carried by the BS (i.e.,  $\rho = 1$ ). The three different BS configurations can be handled by the Markovian modeling framework we just described, which must be however used in three different ways. In the case of No Sharing, the model must be run twice, independently for the two BSs. Instead, in the case of Power Sharing and Full Sharing, the model is run just once, using the total energy consumption of the two BSs, which is lower in the case of Full Sharing in the periods when just one BS is active.

#### IV. NUMERICAL RESULTS

We look at the case of two BSs, which provide service over the same area, carrying respectively 60% and 40% of the total traffic. In Figure 3 we report the BS outage probability (i.e., the probability that the battery is empty) versus the PV panel size, for the three considered configurations, under both the EARTH and the 2020 energy consumption models, and for both the residential and the business traffic profiles. The results for Configuration 1 refer to the BS carrying 60% of the total traffic. We can note that the difference between the outage probabilities of Configurations 1 and 2 is limited, because of no network sharing, and because the total power consumption of the two BSs is almost equivalent, since the total traffic to be served is the same, and both BSs remain always on. Instead, important performance gains are achieved by allowing one of the two BSs to go to sleep mode when the total amount of traffic is such that just one BS is sufficient to carry it. It must be noted that the outage probabilities resulting from the 2020 power consumption model are smaller than those resulting from the EARTH model, even at half the size of the PV panel.

In order to better appreciate the differences between the results obtained with the EARTH and 2020 power consumption models, we plot results for the two cases with equal PV panel size in Figure 4. The outage probability obtained with the 2020 model is remarkably smaller. Also, in order to visualize the differences between the results obtained with the residential and business traffic profiles, we plot results for the two traffic patterns with equal PV panel size in Figure 5. The outage probability obtained with the business traffic profile becomes higher when the PV panel size is too small, so that outage probabilities are unacceptably high.

We now take a more detailed look at the outage probability, considering individual time slots. In Figure 6 we compare the outage probability versus time, under the EARTH energy consumption model, for the residential area traffic profile, respectively for Configurations 2 and 3, with battery capacity 25 kWh. We can clearly see that when the PV panel size is too small (20 kWp), the benefit of network sharing is limited, since the outage probability in the early morning hours remains close to 1. This happens because of the long period of no energy production during winter nights, that leads to the battery depletion if energy is scarce. On the contrary, for adequate sizes of the PV panel, the peaks in outage probability that are observed in the early morning are

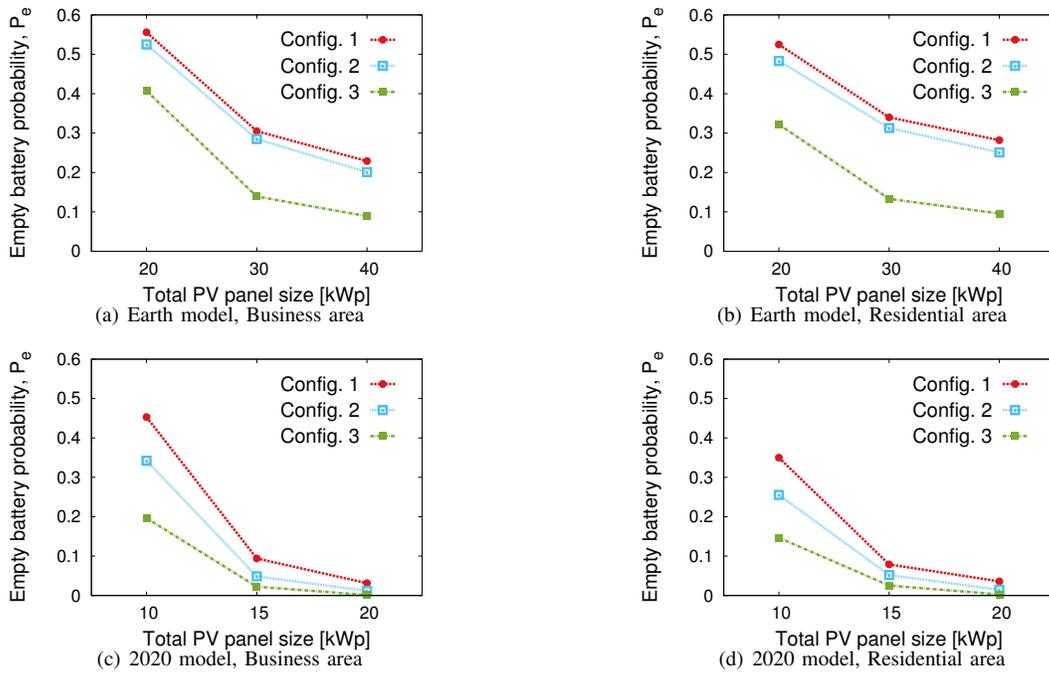


Fig. 3. BS outage probability (empty battery probability), under EARTH and 2020 power consumption models, in the business (Bus) and residential (Res) area, for Configurations 1, 2 and 3. Total battery capacity 25 kWh, and variable energy quantum (50 Wh for Configuration 1 and 100 Wh for Configurations 2-3).

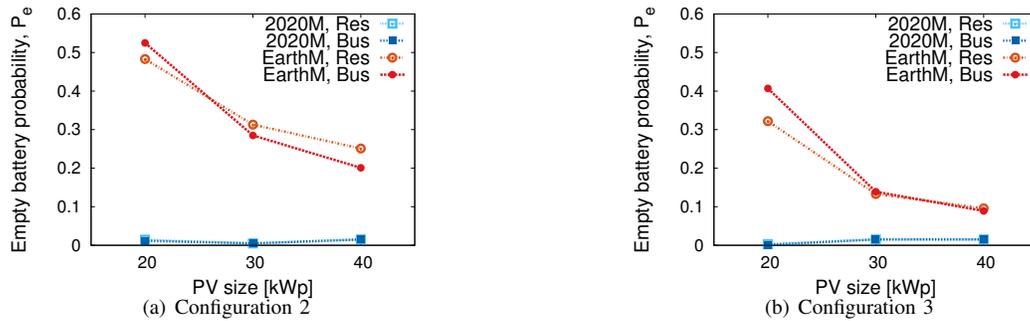


Fig. 4. BS outage probability (empty battery probability), under EARTH and 2020 power consumption models, for Configurations 2 and 3. Total battery capacity 25 kWh, and energy quantum 100 Wh.

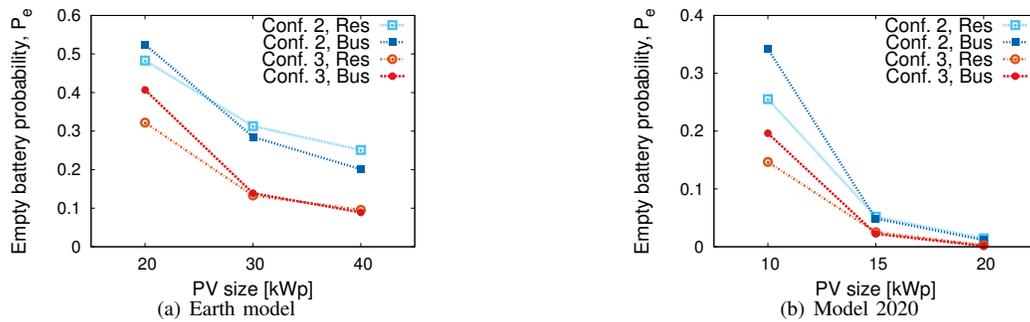


Fig. 5. BS outage probability (empty battery probability), in the business (Bus) and residential (Res) area, for Configurations 2 and 3. Total battery capacity 25 kWh, and energy quantum 100 Wh.

significantly reduced by the choice of putting one BS to sleep and using the other to provide service. This is due to the combined effect of a full battery at the end of the energy

production period, and a reduced energy consumption at night, due to only one active BS. In Figure 7 we compare the outage

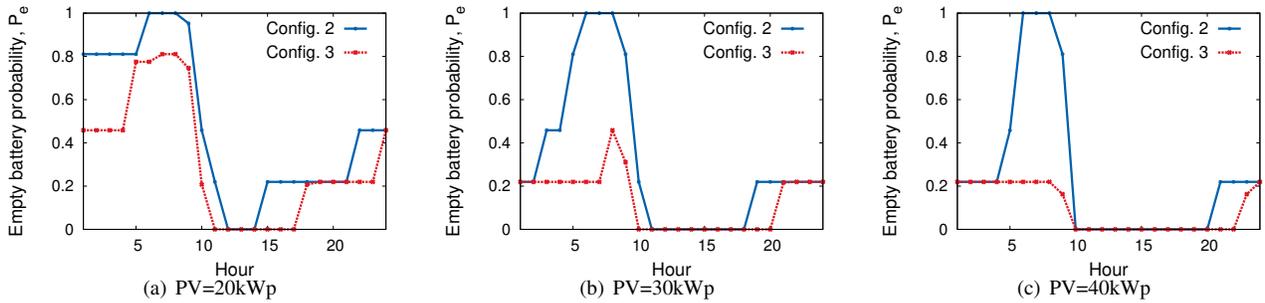


Fig. 6. Outage probability versus time, under the EARTH model, for various PV panel sizes, with storage capacity 25 kWh and energy quantum 100 Wh, in the residential area, for Configurations 2 and 3.

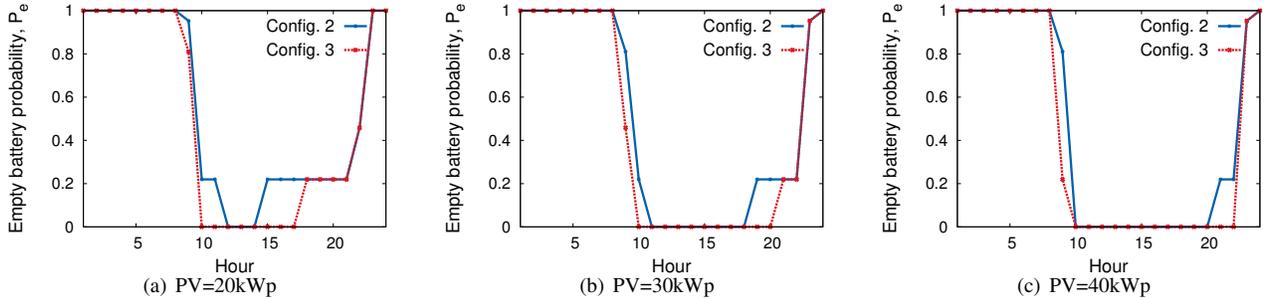


Fig. 7. Outage probability versus time, under the EARTH model, for various PV panel sizes, with storage capacity 12.5 kWh and energy quantum 50 Wh, in the residential area, for Configurations 2 and 3.

TABLE I  
AVERAGE EMERGENCY ENERGY

PV Size	Configuration 2	Configuration 3
20kWp	782Wh	370Wh
30kWp	403Wh	130Wh
40kWp	263Wh	75Wh

probability versus time, in the same conditions as before, but for the battery capacity, that is now 12.5 kWh. In this case we see that differences are much smaller, because the limited battery capacity does not extend significantly the BS operation interval, after the end of the renewable energy production period. The comparison of the results in Figures 6 and 7 shows the importance of a correct dimensioning of both the PV panel size and the battery capacity for sharing to be effective.

Finally, we look at the average battery charge as a function of time. In Figures 8 and 9 we plot the average battery charge level versus time, under the EARTH model, for various PV panel sizes, in the business area, for Configurations 2 and 3, and for different types of day, i.e., for different weather conditions (remember that we use 5 levels of weather conditions, hence 5 types of day). Once more, we observe that when the PV panel size is too small, the advantage of network sharing is small. However, for correctly dimensioned PV panel sizes, the network sharing approach significantly improves the battery charge level, especially for days of type 1 (those with lowest irradiance). By comparing the curves for days of type 1 in Figures 8 c) and 9 c) we see that the adoption of network sharing avoids empty battery conditions (outage) in the early

morning and during the night, which are instead present in the case of Configuration 2.

In Table I we report the average amount of energy that would be needed from an emergency Diesel generator (we refer to it as emergency energy) to allow service to continue when renewable energy is not available, in the six cases of Figures 8 and 9, i.e., Configurations 2 and 3, and PV panel size equal to 20, 30, and 40 kWp. From the results in Table I we see that, for all PV panel sizes, Configuration 2 requires at least twice as much emergency energy than Configuration 3, and in the most advantageous case (PV panel size = 40 kWp), Configuration 3 spends 3.5 times less emergency energy than Configuration 2.

## V. CONCLUSIONS

In this paper we investigated the gains resulting from the sharing of energy and network resources in the case of two solar-powered co-located BSs of two different MNOs. Three configurations were considered: No Sharing, Power Sharing, and Full Sharing, where the first assumes non-cooperating BSs, each one exploiting its own power system and serving its own customers, the second considers a shared power system, but no cooperation in customer service, and the third looks at cooperation in both energy production and service provisioning. Performance metrics computed with a Markovian model of the system show that significant gains are possible in the case of Full Sharing. In addition, they show that much smaller solar panels will be necessary with the coming generations of

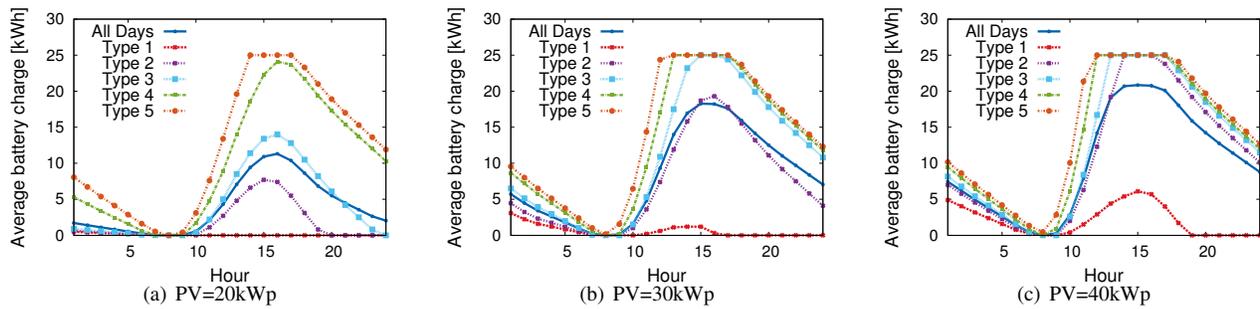


Fig. 8. Average battery charge level versus time, under the EARTH model, for various PV panel sizes, with storage capacity 25 kWh and energy quantum 100 Wh, in the business area, for Configuration 2.

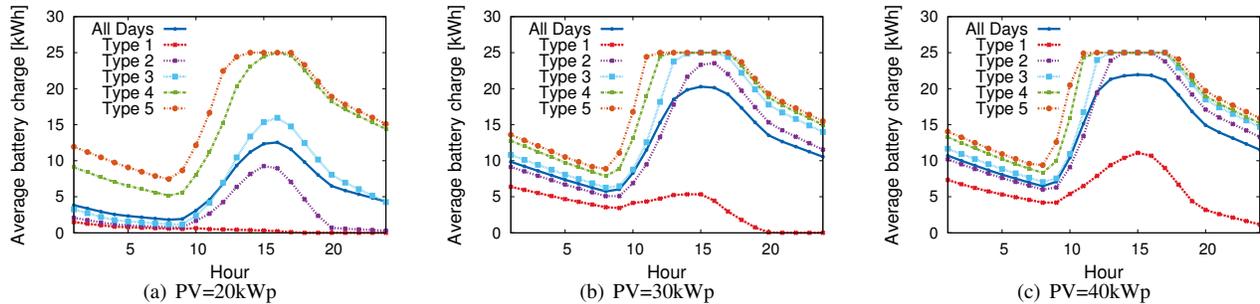


Fig. 9. Average battery charge level versus time, under the EARTH model, for various PV panel sizes, with storage capacity 25 kWh and energy quantum 100 Wh, in the business area, for Configuration 3.

BSs, which will however make sharing of lesser importance, due to an increased proportionality between traffic load and energy consumption (sharing, as well as sleep modes, become ineffective in the case of full proportionality).

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