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Household users cooperation to reduce cost in green mobile networks

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***Abstract*—The staggering mobile traffic growth is leading to a huge increase of operational costs for Mobile Operators (MOs) due to power supply. In a Smart Grid (SG) scenario, where Demand Response (DR) strategies are widely adopted to better balance the Demand-Supply mismatch, new opportunities arise for MOs, that can receive some monetary rewards for accomplishing the SG requests of periodically increasing or decreasing their energy consumption. This study considers a mobile network that exploits Renewable Energy (RE) to power the BSs and Resource on Demand (RoD) strategies to dynamically adapt the number of active radio resources to the varying traffic demand, in order to better react to the SG requests. On top of this, the purpose of this work is investigating the effects of the cooperation between Household Customers (HCs) engaged in the DR program and the mobile network. Based on a predefined agreement, HCs cooperate with the MO in order to increase its capability to accomplish the SG requests, receiving in return some benefits when stipulating the Internet provisioning contract with the MO. HCs can contribute to achieving the MO goals by means of two techniques. On the one hand, a fraction of the electric loads that are postponed by the HCs when the SG asks for a reduction of the energy consumption can be shifted on behalf of the mobile network, that will receive the corresponding monetary rewards (*HC Trade - HCT*). On the other hand, HCs can accept to handle some additional mobile traffic, that is moved to their own WiFi Access Points from the BSs, in order to reduce the energy load of the mobile network (*WiFi Offloading - WO*).**

Our results show that, although HCT alone provides limited saving in the energy bill due to the poor attitude of HCs to postpone their electric loads, up to 18% of cost saving can be achieved under full HCs cooperation when HCT is combined with WO. The effects of HCs cooperation can be further enhanced by installing larger sized RE generators, allowing to significantly reduce the energy bill up to more than 90%.

Keywords*— *Green Mobile Networks; Smart City; Smart Grid; Demand Response; Household users.

I. INTRODUCTION

Nowadays, Mobile Operators (MOs) are facing increasingly high operational cost due to power supply. In particular, the largest amount of energy consumed in cellular networks, accounting for 80% of the total demand, is required to operate the access network [1]. Considering that by 2021 each of us will own up to more than 12 Internet connected devices and that mobile data traffic will have increased by a factor seven in just a few years, denser mobile access networks are going to be extensively deployed [2]. Hence, the MOs energy bill is bound to further increase. Moreover, with the incoming 5G scenario, the energy cost issue is becoming even more relevant, since stricter constraints pose additional requirements for the new mobile access networks, determined by the need for huge capacity and higher speed rates capable to sustain ubiquitous Internet access, urban mobility, pervasive IoT services, and broadband connectivity. Hence, several research efforts are currently devoted to develop feasible solutions to cope with this problem, from the design of energy efficient hardware components, featuring more load proportional consumption profiles, to the application of Resource on Demand (RoD) strategies, up to the introduction of Renewable Energy (RE) to power Base Stations (BSs). The aforementioned approaches aim at reducing operational cost by decreasing the energy amount drawn from the electric grid. Nevertheless, with the affirmation of the Smart Grid (SG) paradigm, new opportunities arise for MOs to limit their operational expenditures. Demand Response (DR) policies are widely deployed by utility operators, with the purpose of balancing the mismatches between electricity demand and supply. Monetary incentives are provided by SG Operators (SGOs) to induce a shift of the power consumption from high to low peak periods. Indeed, MOs can become relevant players in this framework, since they can actively interact with the SG. By dynamically modulating their demand in accordance with the SG requests, MOs can significantly contribute to DR objectives, thus obtaining remarkable reductions of the electricity cost, besides providing Ancillary Services to the SG. In addition, in a Smart City environment, the interaction of mobile networks with the SG can be further enhanced by envisioning a cooperation between different types of SG customers that agree to collaborate to achieve predefined objectives and obtain mutual benefits.

The high penetration of RE sources to power mobile networks is attested by the huge number of papers related to this topic that can be found in the literature [3], [4]. Furthermore, RoD strategies based on BS sleep modes represent a common solution to improve the energy efficiency of mobile networks [3]–[5]. In recent years, various studies have become available about to the application of RoD strategies, based on BS on/off switching, in a scenario where the BSs are powered by RE [6]–

[9]. Only few recent studies focus on the possible interaction of a renewable powered mobile network with the SG in a DR framework, where BS sleep mode RoD techniques are employed to better react to the SG requests, hence obtaining energy cost reductions [10]–[13]. In these papers, the mobile network exploits the combined use of RE and various radio resource management techniques to provide a better accomplishment of the SG requests of increasing or decreasing its energy demand. In [12], [13], WiFi Offloading (WO) techniques are implemented to shift a fraction of the mobile traffic from BSs to nearby Access Points owned by the same mobile operator, with the purpose of reducing the traffic load and the energy consumption on the mobile network. Indeed, WO represents a commonly adopted solution that allows to migrate traffic from cellular networks to WiFi networks, in order to tackle the recent explosion of mobile data traffic [14], [15].

To our best knowledge, no study in the literature considers a possible cooperation between a green mobile network and household users to enhance the interaction with the Smart Grid. This paper aims at studying the cooperation of Household Consumers (HCs) with a green mobile network to respond to SG requests and, in particular, the work investigates the impact of this cooperation on the energy saving and bill reduction obtained by the MO. The cooperation of the HCs exploits two different methods, either based on the postponement of a fraction of their electric load on behalf of the mobile network or based on WiFi Offloading techniques.

The rest of the paper is organized as follows. Sec. II details the considered scenario. In Sec. III the adopted methodology is presented and the techniques of cooperation between the HCs and the green mobile network are described. Performance analysis results are presented in Sec. IV, where energy saving and cost reduction provided by the HCs' cooperation are evaluated under several configuration settings. Finally, Sec. V concludes the paper.

II. COOPERATION BETWEEN MOBILE NETWORK AND HOUSEHOLD USERS

This study considers a portion of an on-grid green mobile access network that participates in a DR program. The investigated scenario is represented in Fig. 1. A macro Long Term Evolution (LTE) BS provides baseline coverage in a residential area where a number of dwellings are present. Six micro BSs provide additional capacity in the same area to cope with peak mobile traffic demand. Besides the energy supply provided by the electric grid, the cluster of BSs is powered by photovoltaic (PV) panels, and a set of batteries is installed to store extra amounts of RE that are not immediately used. The DR program envisions that every day the SGO collects information from its customers about their hourly energy demand forecast the day ahead fro the current hour. Every hour the SG may ask its users to either increase, up request (U), or decrease, down request (D), their consumption with respect to the level predicted the day ahead. Monetary rewards or penalties are provided to the customers in case they are able to comply with or opposing the SG requests, respectively. Sometimes the SGO may not issue any specific requests (N). In order to timely react to SG requests, various techniques are implemented by the MO, that are based on local RE generation, RoD strategies, and Household Consumers cooperation. When the SG requests to reduce the grid energy consumption, the MO can exploit the local RE production to power BSs or it can draw the previously harvested energy from the storage. In addition, it can switch some BSs off during periods of low traffic load (RoD). In case the SGO requests for an increase in the consumption, the MO can draw some extra energy from the grid and store it into the battery. On top of this, a cooperation with the MO by HCs participating in the DR program is envisioned. Based on a predefined agreement, the MO may provide discounts on the pricing of communication services or additional benefits (e.g., higher speed Internet connection) when stipulating the Internet contract with the HCs willing to join the cooperation program. For their part, HCs accept to help the MO in accomplishing SG requests when a reduction of the energy consumption is requested, in case neither RE is currently available nor any BSs can be switched off due to high traffic load. Two different methods are exploited. On the one hand, a portion of the traffic volume can be offloaded from the mobile network to nearby Access Points owned by HCs (WiFi Offloading - WO), in order to decrease the mobile network consumption and, possibly, put some offloaded BSs in sleep mode. On the other hand, HCs, besides postponing some of their electric loads to their own advantage, can further reduce their consumption by an additional fraction on behalf of MO (HC Trade - HCT).

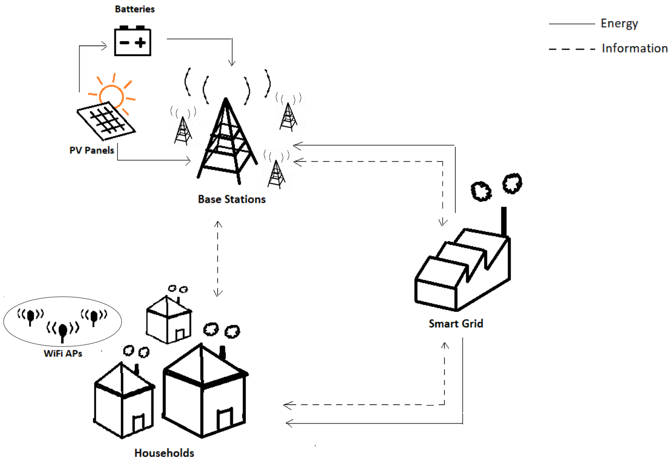


Fig. 1: Scenario

III. METHODOLOGY

Real traces of mobile data traffic, renewable energy production, household load profiles, energy pricing, and SG requests have been used to investigate the described scenario. Mobile traffic profiles during weekdays and weekends in a residential area are obtained from an Italian mobile operator [11]. Traffic peaks are observed during the evening hours. Based on this information, the BS energy consumption is computed according to the power model proposed in [1]. Real data about RE production are derived from the tool PVWatts [16], that provides the daily profiles of solar power generation from PV panels during the Typical Meteorological Year in a given location. Household electricity consumption profiles are derived from a study carried out in Italy considering 1000 dwellings [17] and they are reported in Fig. 2, showing the load patterns during the Winter and the Summer. A huge additional consumption component is due to air conditioning in Summer. Winter heating is not taken into account since in Italy it still strongly depends on natural gas rather than electric sources. The SG request patterns are obtained by mapping the energy prices obtained from the Italian energy market into three categories, corresponding to the requests of type U, D and N, obtained by properly setting thresholds on the energy price values. Denoting α the probability of issuing a request of type N, the probability of receiving a request of type U (or D) is $\frac{1-\alpha}{2}$. Data about monetary rewards provided by the SG for satisfying its requests are taken from a real electricity transmission system operator [18].

The cluster of BSs is equipped with a set of PV panels with nominal capacity denoted S_{PV} and expressed in kWp. Moreover, the energy storage is composed by a number, that we denote B, of lead-acid battery units, each with capacity 200 Ah and voltage 12 V. Charging/discharging losses of 25% are considered. The maximum allowed Depth of Discharge is 70%, whereas the constraint on the maximum charging/discharging rate is assumed to be $\frac{1}{10}$ of the total battery capacity per hour.

The Mobile Network participates in the DR program. According to the strategy proposed in [19], in order to accomplish the requests of type D from the SG, hence receiving the corresponding reward, BSs are powered by the RE that is currently produced or by the energy previously harvested in the storage. Furthermore, the RoD proposed in [6] is exploited to switch off some micro BSs when the traffic is low, while their traffic is moved to the macro BS, with the purpose of reducing the consumption with respect to the predicted demand. Micro BSs are put into sleep mode if their traffic load falls below a predefined optimal threshold and if the macro BS has still enough capacity to handle the additional traffic [6]. In case of U request, an extra amount of energy is drawn from the SG and stored into the battery units. In addition, the accomplishment of the requests from the SG is achieved by exploiting the Household users cooperation as detailed hereafter.

A. Household cooperation

The MO may perform some kind of agreement with HCs that participate to the same DR program and that are willing to contribute to the achievement of the MO goals, for instance by modulating their own energy demand to the advantage of the mobile network. As a return, HCs receive some benefits from the MO, in terms of discounts or free additional services when stipulating a contract with the MO for the Internet access provisioning.

TABLE I: Household users characterization

	Class 1	Class 2	Class 3	Class 4	Class 5
f	0	0.6	0.9	0.4	0.1
w [h]	-	4	2	6	2

On the one hand, in case of D request, HCs can reduce their consumption for their own benefit by postponing a fraction x_H of their load with probability f for a timeout window w. When the timeout window w has expired, the load is executed. Based on the HC load characterization performed in [20], the maximum value of x_H, representing the fraction of loads of flexible appliances that can be postponed without affecting the consumer comfort, is set to 40%. Furthermore, when some load is shifted, HCs can devote a portion of the maximum value of x_H, denoted x_M, to the advantage of the MN with the same probability p_D, such that $x_M + x_H = 40\%$. The probability of providing a contribution to the Mobile Network in case of D request is hence $f \cdot p_D$. Households show different habits and lifestyles, hence their energy consumption patterns do not follow a unique profile. Furthermore, not all the customers are interested in participating in the DR program. In order to represent the consumption diversity, HCs are divided into five classes (reported in Table I), depending on their consumption profiles, their flexibility to postpone loads (represented by the probability f) and their time window constraints.

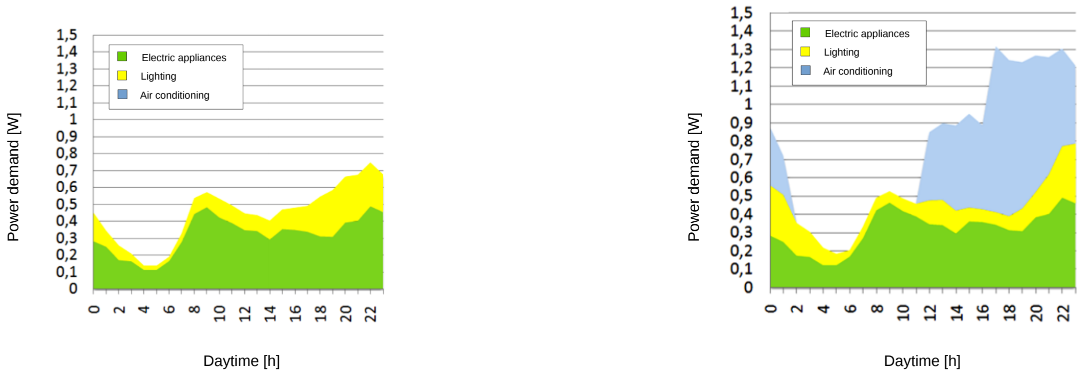
On the other hand, the cooperation of HCs may consist in performing Wifi Offloading. HCs involved in the preset agreement with the MO accept to handle 10-20% of the mobile traffic [13], that is transferred from the mobile network to nearby APs, owned by the HCs. In case of D requests, WO can always be performed by HCs, since the increased energy consumption due to the additional traffic load and the reduction in the WiFi available bandwidth can be assumed negligible. The application of WO allows the MO to switch off some more micro BSs, in order to further reduce the energy demand from the grid.

IV. PERFORMANCE ANALYSIS

In order to evaluate the effects of the HC cooperation on the energy saving and its benefits in terms of energy bill reduction for the MO, the system performance has been evaluated via simulation under several different configuration settings, in terms of SG requests distribution (different values of α), availability of HCs to cooperate with the MO (different values of p_D), and percentage levels of energy amounts that HCs accept to postpone on behalf of the MO (different values of x_M). Simulations are run with a time granularity of half an hour.

A. Impact of household user cooperation

Fig. 3 reports the yearly energy demand from the grid and the yearly energy cost for different combinations of strategies that can be applied to react to the SG requests, assuming



(a) Winter

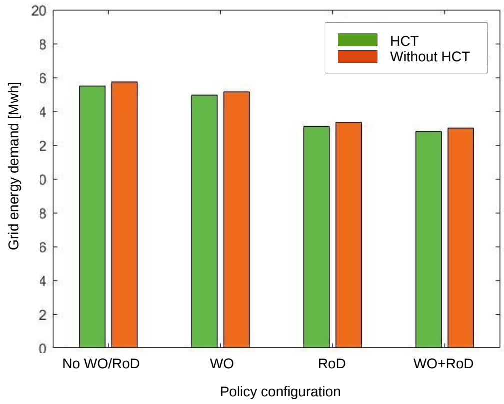
(b) Summer

Fig. 2: Daily electricity consumption profiles of a geographical area hosting 1000 dwellings in Italy [17].

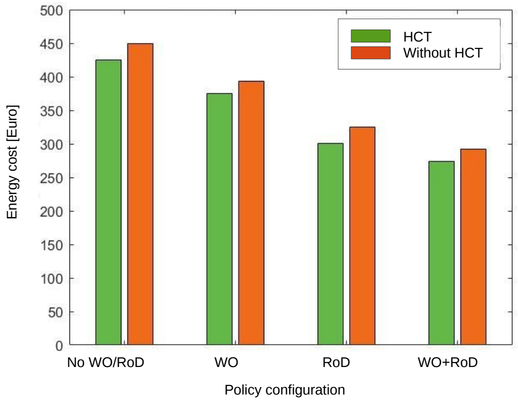
$\alpha = 1$, $S_{PV} = 1$ kWp, $B = 5$, x_M=5%, and $p_D = f$. We assume that in the baseline scenario, represented by the orange bars, the Mobile Network accomplishes the SG requests by exploiting the local RE production and the energy harvested in the battery, but no contribution from the HCs is envisioned. Conversely, the green bars represent the case in which the cooperation of the HCs is envisioned by means of the application of the HCT strategy. No additional policy (either RoD or WO) is active in the *No WO/RoD* configuration. On top of this, MO may decide to apply RoD to better react to D requests from the SG (*RoD*) and/or to include the application of WO in the preset agreement with the HCs (*WO* and *RoD+WO*).

As it can be evinced from Fig. 3a, the energy saving due to the Household cooperation by means of HCT only is limited, about 1.5% with respect to the case in which it is not applied. This low reduction may be caused by the low fraction of loads that the HCs accept to postpone on behalf of the Mobile Network. Furthermore, it may also be influenced by the inclination of HCs to reduce their consumptions for the Mobile Network, i.e. by the value of p_D. Indeed, when the Mobile Network needs Households support, it is obtained only 30% of the time. WO provides an only slightly higher contribution in reducing the energy consumption. A more relevant reduction of the energy consumption by up to about 15% is provided by the application of RoD.

The application of HCs cooperation strategies in green mobile networks interacting with the SG hence does not reduce significantly the yearly amount of energy drawn from the electric grid. Nevertheless, despite a grid energy saving amounting to less than 3% at most when HCT and WO are jointly applied, a more relevant impact is observed on operational cost, as shown in Fig. 3b. Indeed, under local RE production, HCT technique allows to decrease cost by up to 6%, whereas up to 18% cost reduction is achieved when HCT



(a) Grid energy demand



(b) Energy cost

Fig. 3: Yearly energy demand from the grid and yearly energy cost under different policy configurations, either with or without the cooperation of household users, assuming $\alpha = 0.1$.

is combined with WO. When a RoD strategy is applied, HCT alone results more effective, achieving up to 9% cost reduction. When HCT is combined with WO, the cost is decreased by up to 16%. It is more convenient to jointly apply HCT and WO to improve the system performance. In case only one of the two techniques can be adopted, WO outperforms HCT with more than 40% higher cost saving, unless a RoD strategy is implemented, in which case they result equally effective.

Note that these results refer to a scenario representing a limited portion of a mobile access network, consisting of a cluster of one macro BS and few micro BSs. Although the absolute values of the cost saving that can be obtained may look small, it should be considered that the number of BSs typically deployed by a mobile operator is really huge, counting thousands of BS sites over its coverage area. For instance, the operational expenditure faced by the main mobile operator in Italy due to power supply could be as high as almost 5 million € per year, with more than 11,000 BS sites deployed over the whole country[1]. Considering the staggering increase of the mobile traffic that is leading to the deployment of denser and denser mobile access network, the operational cost are bound to further increase in the future. Furthermore, as the access segment in mobile network is responsible of up the 80% of the total network energy consumption, the most relevant component of the expenditures for a mobile operator is represented by the energy bill. According to our results, by combining RoD with the full cooperation of HCs (HCT+WO), up to almost 40% of cost saving can be achieved with respect to the case in which none of these strategies are applied. This translates into remarkable cost saving amounting up to 2 million € per year.

B. Effect of Smart Grid requests distribution

The varying SG request distributions may affect the cost saving that can be obtained by the MO. Fig. 4 reports the energy cost under different policy configurations for different values of α. The differences of cost saving under various values of α result limited, especially when no RoD is applied and no HCs cooperation is envisioned. However, when HCT and WO are applied along with RoD, a slightly better performance in terms of energy bill reduction is obtained when requests of type N are less likely to occur, i.e., with $\alpha = 0.1$.

C. Varying the contribution of household users

The energy reduction and cost saving figures presented above under HCT are obtained assuming that HCs are willing to postpone 5% of their loads on behalf of MOs, when needed. Fig. 5 reports the yearly grid energy demand and the yearly energy cost for different values of x_M, compared against the case in which no HCT cooperation is envisioned (green bars), under different policy configurations. The effect of increasing values of x_M on the energy saving (Fig. 5b) is negligible. On the contrary, Fig. 5b shows that by increasing this fraction to 10% the cost saving is almost doubled only when HC cooperation is applied alone. Higher values of this fraction, besides being unlikely, do not provide significant further benefit in terms of energy bill reduction, resulting 11%.

D. Role of the probability of HCs acting on behalf of the MO

Regarding the proposed HCT technique, it is to be noted that D requests are satisfied by each HC with a probability f that depends on the contract type and on the loads that can be postponed, i.e. on the class to which household users belong. HCs will therefore accomplish only a fraction f of D requests, by reducing, hence postponing, part of their current load. Furthermore, given that HCs satisfy a D request to their own advantage, we assume they accept to postpone an additional fraction of load on behalf of the MO with probability p_D. Fig. 6 displays the variations of the yearly energy demand from the grid and the yearly energy cost for increasing values of p_D: $p_D = f$; $p_D = min(1, f + 0.1)$; $p_D = min(f + 0.5)$. As it can be observed from Fig. 6a, varying the value of p_D does not impact significantly on the amount of energy drawn from the grid. Similarly, focusing on energy cost, Fig. 6b highlights how no relevant difference is observed in terms of cost saving between different attitudes to contribute to the MO interaction with the SG, i.e. between different values of p_D. In our scenario, values of p_D as high as f provide cost saving that cannot be improved by further increasing the value of p_D. This behavior can be explained by the fact that, in order to devolve some energy to the Mobile Network, HCs have first to reduce their consumption with probability f. Hence, even if the probability p_D increases, a high dependency on the probability f is observed. Furthermore, considering that the fraction of load that is shifted, corresponding to x_M, is anyway limited, no significant improvement may occur.

These observations indicate that when HCT alone is adopted as a form of HCs cooperation, the cost reduction that can be obtained by the Mobile Network remains low, especially if household users are not properly involved or their willingness to participate in the DR program is low. In order to improve the cooperation of HCs with the Mobile Network and to increase the cost saving, the engagement of HCs to DR programs that envision mutual benefits deriving from the cooperation between MO and HCs still have to be enhanced and incentivized. Furthermore, the introduction of WO as a form of HCs cooperation may provide a remarkable contribution to this extent, since it allows to achieve cost reduction as high as 40% when combined with HCT.

E. System sizing

The results presented so far are evaluated considering small sizes both for the PV panel ($S_{PV} = 1\ kWp$) and for the battery bank ($B = 5$). We now evaluate the effect of RE system dimensioning on cost saving that can be achieved when the cooperation between HCs and the mobile network is envisioned.

We consider the case in which no RoD is implemented by the Mobile Network. From the HCs' side, we assume that only

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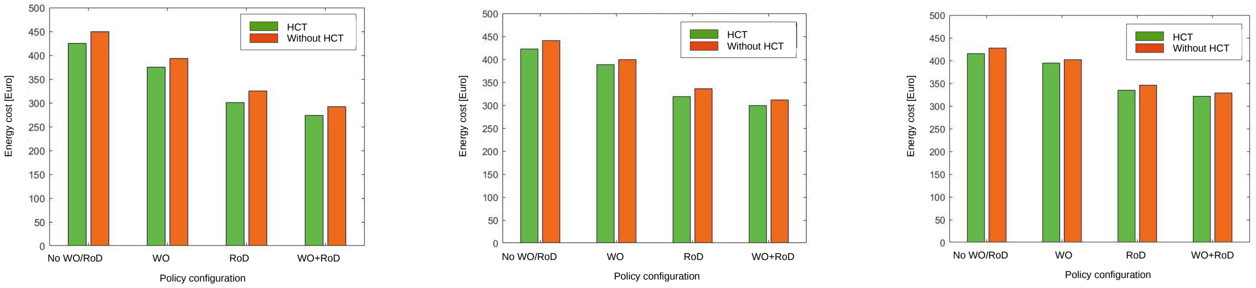
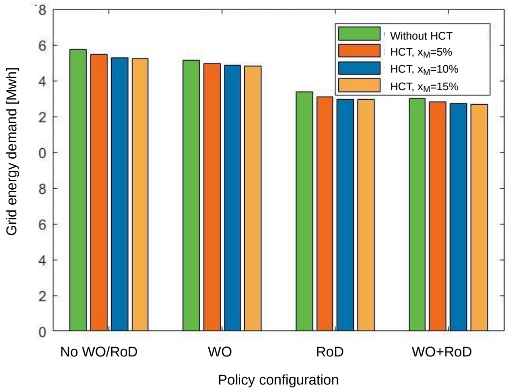
[1] Data provided by INWIT, an Italian company operating in the field of mobile communication infrastructures - *www.inwit.it/en/about-us/company-profile*.

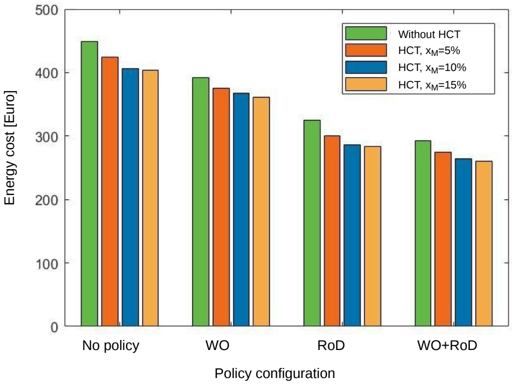


(a) $\alpha = 1$ (b) $\alpha = 0.2$ (c) $\alpha = 0.4$

Fig. 4: Yearly energy cost under different policy configurations, either with or without the cooperation of household users, for different values of α.

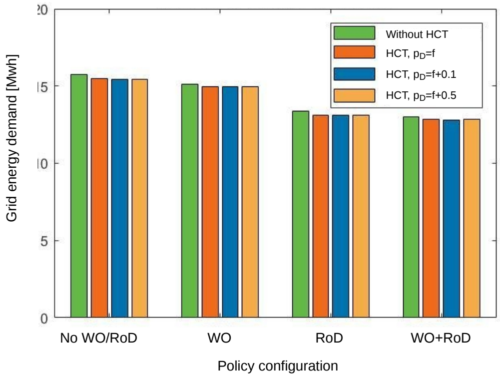


(a) Grid energy demand

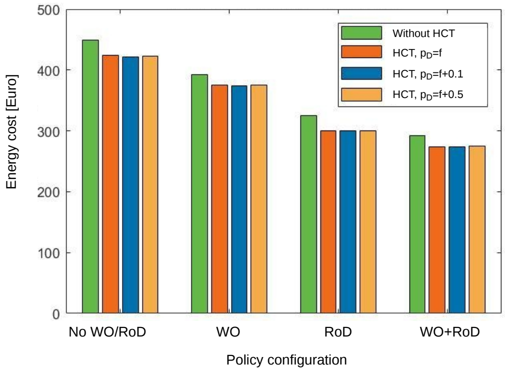


(b) Energy cost

Fig. 5: Yearly energy demand from the grid and yearly energy cost under different policy configurations, for different values of x_M, assuming $\alpha = 0.1$.



(a) Grid energy demand



(b) Energy cost

Fig. 6: Yearly energy demand from the grid and yearly energy cost under different policy configurations, for different values of p_D, assuming $\alpha = 0.1$.

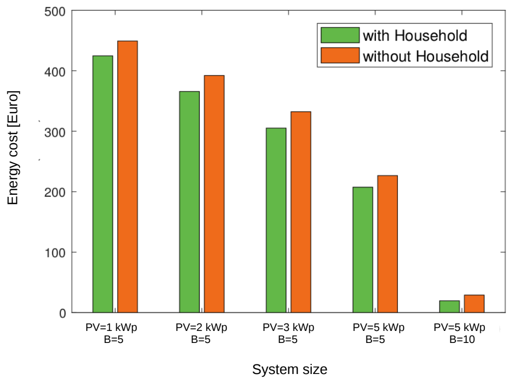


Fig. 7: Effect of RE system dimensioning on cost.

HCT is applied in case of HCs cooperation. Fig. 7 shows that as the RE system size increases, energy cost decreases to lower values. In particular, by increasing the PV panel size, up to more than 50% of energy cost can be saved. In addition, for fixed PV panel capacity of 5 kWp, by doubling the battery size cost saving can be further reduced by 86%. This huge saving is due to the fact that a larger battery not only allows to better accomplish D requests, since higher amounts of RE can be harvested for future usage, but it also permits to better react to U request, providing more capacity for storing extra amounts of energy drawn from the grid.

It should be observed that the cost saving obtained under larger RE system dimensioning can be as high as more than 90% with respect to the case with the smallest RE system size, although the maximum energy saving that can be obtained even under the largest RE generator is only slightly more than 40%. This means that in a DR framework a timely reaction to the SG requests plays a key role, resulting more relevant than the overall reduction of the energy amount drawn from the grid in order to achieve a remarkable energy bill reduction.

V. CONCLUSION

Our work demonstrates that HCs cooperation is effective in reducing the operational cost of a renewable powered mobile network in a DR framework, especially when combining different cooperation techniques. The MOs energy bill can be reduced by up to almost 18%. Cost reduction partly depends on the SG request profiles. In our scenario, the highest gains are obtained when N requests occur with a frequency as low as 10%, whereas as this value grows higher the gains tend to decrease.

The proposed approach could be similarly applied in a Real-Time Pricing framework of the energy market. Indeed, high electricity prices enforce users to reduce their consumption, whereas they are induced to buy more energy when prices are lower. Noticeably, the proposed techniques (HCT and WO), that provide remarkable cost saving by improving the interaction of the green mobile network with the SG, do not operate by reducing the overall grid energy consumption, but by timely reacting to the SG requests. The contribution of HCT in reducing cost is limited with respect to WO in the investigated scenarios, due to the little fraction of electric load that HCs accept to postpone to the MOs advantage. Furthermore, the effect of HCT contribution is not improved by increasing the probability of postponing HCs loads on behalf of MO, when the SG requests for an energy consumption reduction. However, the impact of HCT alone can be enhanced by applying a RoD strategy to the green mobile network, allowing to reduce cost by up to almost 40%.

Finally, a proper sizing of the RE generator allows to further increase the cost saving. By raising the PV panel size and the battery capacity to larger, still feasible, values, up to more than 90% of the energy bill can be saved. Scaling up the obtained gains to the dense mobile access networks managed by MOs, counting thousands of BSs, these figures translates into huge amounts of money that can be curtailed from the MO energy bill.

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