Energy Sharing and Trading in Multi-Operator Heterogeneous Network Deployments

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***Abstract*—With a view to the expected increased data traffic volume and energy consumption of the fifth generation networks, the use of renewable energy (RE) sources and infrastructure sharing have been embraced as energy and cost saving technologies. Aiming at reducing cost and grid energy consumption, in the present paper, we study RE exchange (REE) possibilities in late-trend network deployments of energy harvesting (EH) macrocell and small cell base stations (EH-MBSs, EH-SBSs) that use an EH system (EHS), an energy storage system (ESS) and the smart grid (SG) as energy procurement sources. On this basis, we study a two-tier network composed of EH-MBSs that are passively shared among a set of mobile network operators (MNOs), and EH-SBSs that are provided to MNOs by an infrastructure provider (InP). Taking into consideration the infrastructure location and the variety of stakeholders involved in the network deployment, we propose as REE approaches (i) a cooperative RE sharing, based on bankruptcy theory, for the shared EH-MBSs and (ii) a non-cooperative, aggregator-assisted RE trading, which uses double auctions to describe the REE acts among the InP provided EH-SBSs managed by different MNOs, after an initial internal REE among the ones managed by a single MNO. Our results display that our proposals outperform baseline approaches, providing considerable reduction in SG energy utilization and costs, with satisfaction of the participant parties.**

***Index Terms*—Network sharing, energy sharing, energy trading, Shapley Value, double auction.**

I. INTRODUCTION

A huge traffic increase is expected in the near future [1]. Unless countermeasures are taken, a global percentage equal to 51% and 23% of energy consumption and carbon dioxide (CO_2) emissions, respectively, is foreseen to be generated by Information and Communication Technology [2].

To address these challenging numbers in the era of the fifth generation networks (5G), different forms of network sharing are adopted, as the common use of entities leads to both energy and cost savings. Network sharing schemes among mobile network operators (MNOs) vary from passive sharing (i.e., mast, generator and tower sharing) and active sharing (i.e., sharing of entire radio access networks) to the roaming based one (i.e., an MNO roams its traffic to a rival one during a pre-defined period of time and over a pre-defined area) and the lease of third party infrastructure by MNOs [3]. When combined with other technologies, the prospects of increasing energy and cost savings are further improved.

In this context, despite the high capital expenditure they introduce, the adoption of renewable energy (RE) sources and RE distribution have been embraced as effective green cost-saving techniques for wireless networks [4]. On one hand, thanks to the production of low or no CO_2 emissions by RE sources, research has focused on the implementation of RE-supported macrocell and small cell base stations (MBSs, SBSs) [5], [6]. On the other hand, thanks to the technology revolution in smart grid (SG) networks [7], research on energy exchange (EE) between network elements with energy abundance and energy shortage becomes popular [8]–[13].

Despite their benefits, RE sources and EE raise issues over the network operation. RE shortage events due to RE generation unpredictability are a preoccupation for MNOs. Supporting energy storage systems (ESSs), consisted of battery series, are usually adopted as a countermeasure [14]. Their storage capacity though is upper limited. Moreover, both the RE and ESS equipment aggravate the space scarcity issues that MNOs face at their site installations [15]. The EE technique complements the use of an ESS, balancing the drawbacks of storage limitation and space scarcity. Energy can be exchanged at, adjustable to needs, volumes and with or without payment, which corresponds to energy trading and sharing, respectively. EE can be implemented using power lines [8], the SG [9]–[12], or with the aid of an aggregator [13], when the energy volume available for exchange is limited [16].

Only limited and recent works explore the implications of adopting RE source and EE in multi-operator environments. Collocation and ownership of networks affect the choice of an EE model. Multi-operator collaborative energy trading agreements with energy retailers and directly with the energy market are studied in [17] and [18], respectively. These works study the activity of multiple MNOs in the same area, leaving out however, space scarcity scenarios that oblige sharing of both network and energy harvesting (EH) infrastructure. In such cases, a fair allocation of RE volumes to the stakeholders involved in the sharing should be given careful consideration so as to cover their individual energy needs.

Fairness in energy sharing was studied only recently in [19] and with respect to the improvement of the communication service quality in the network. However, only collocated BSs of rival MNOs are assumed, while energy sharing is implemented via the SG. Thus, challenging EE prospects in multi-MNO scenarios are not explored. An indicative example

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is the use of private power lines among network elements of rival MNOs, which has been studied as a permanent solution only in single-MNO scenarios [8], [9]. Lastly, it leaves out popular multi-MNO architectures, e.g., with a third party [20], where the conflicting interests of stakeholders could hinder EE.

More are the challenges though in EE acts among multiple MNOs. Achieving energy neutrality with EE in a multi-tier wireless network is one of them. In detail, energy neutrality for MBSs is more challenging and expensive than for SBSs, since MBSs provide the umbrella coverage in an area and are more energy hungry. Moreover, rival MNOs often co-locate their MBSs in urban areas due to the high traffic load volumes and site regulations, whereas SBSs are overlaid all over a macrocell area. Thus, the encounter of a both permanent and unified solution for MBSs and SBSs is difficult. At the same time, for all stakeholders that participate in a sharing agreement, disclosure of private information and the extend to which they will do it, is a hot potato issue. Involving an impartial entity might be necessary when information disclosure is extensive.

Addressing all aforementioned issues with simple approaches, meanwhile ensuring fairness for the stakeholders that participate in a multi-operator EE act is a demanding task. In this paper, we go beyond the existing literature by exploring EE in late-trend multi-MNO heterogeneous network (HetNet) deployments that use EH as energy source, along with the SG. To this end, we study a scenario in which MNOs manage a two-tier wireless HetNet with an EH system (EHS) and an ESS available at each site. In our scenario, MNOs apply passive sharing for the macrocell tier of their network, due to network planning limitations and in order to address the high energy needs, CO_2 emissions and costs, of an MBS. The small cell tier infrastructure is composed of EH-SBSs, i.e., SBSs with respective EHSs and ESSs, and is provided by an InP. We aim at studying the EE prospects in both tiers, meanwhile addressing the challenges of a network sharing model that involves multiple stakeholders of different interests.

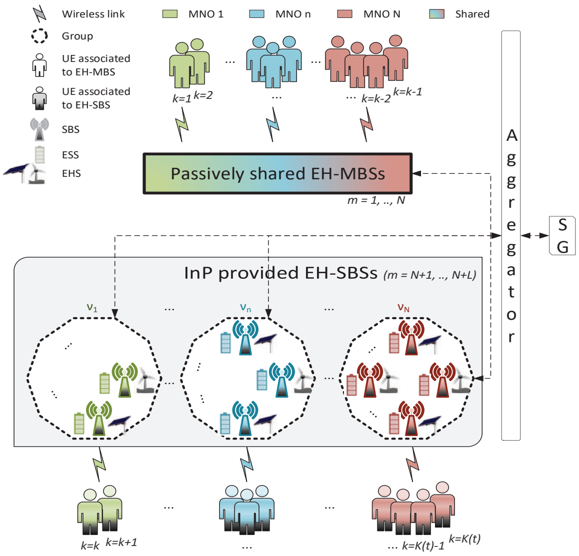
To this end, the contribution of this paper is described as

- a cooperative energy sharing scheme via power lines, applicable to passively shared EH-MBSs. Passive sharing is assumed as a sharing of the MBS infrastructure, the EHS and ESS. We propose an energy sharing scheme among EH-MBSs, or their owner MNOs in the case of one-to-one correspondence, that refers to the sharing of the RE that is harvested by the shared EHS and stored at the shared ESS. EE is carried out through power lines due to the passive sharing, which presumes collocated EH-MBSs that are unlikely to be relocated, even though they belong to rival MNOs. Short-lengthened power lines are assumed, which result in negligible losses on energy transfer and circumvent of additional costs due to the SG or an aggregator. We propose an energy sharing scheme that is cooperative, as, even though the MNOs of the passive sharing have rival interests, they have similar characteristics. Cooperative game theory increases the value of the total sharing effort, meanwhile preserving the individual benefits of players. On this basis, we describe the problem of allocating the harvested and stored RE to the cooperative MNOs as a bankruptcy game (BG). BGs refer to the allocation of a determined entity to a group of players who are interested in it [21]. RE volumes can be such an entity when they are insufficient to cover the individual MNO energy needs. Our proposal, namely RE BG (RE-BG), uses Shapley Value (SV) so that the cooperative act continues. SV ensures fairness in RE volume allocation among players MNOs, as it assesses their individual contribution to the obtained result [22].
- a non-cooperative aggregator-assisted energy trading of low complexity, applicable to InP provided EH-SBSs that are managed by rival MNOs. We propose an aggregator-assisted energy trading among the EH-SBSs of rival MNOs that follows after an aggregator-assisted EE within the network managed by one MNO. The aggregator ensures the exchange of low energy volumes of the EH-SBSs through the SG, given that they are randomly located within the macrocell area and cannot be connected with power lines. Moreover, the aggregator prevents extensive disclosure of private MNO information to rival ones, e.g., traffic levels of all their EH-SBSs. As the aggregator and MNOs have different characteristics and rival interests, we propose a non-cooperative RE double auction (DA) framework, namely RE-DA, for the RE trading. DA has been used extensively to describe resource allocation based on price regulations [23]–[26], resource allocation in combination with power allocation and interference control [27], e-markets [28], [29] and energy exchange among micro-grids [30]. A DA energy trading scheme is proposed in [11] for wireless networks, without making reference though to multi-MNO implications. Our RE-DA framework regulates trading of the harvested and stored RE at each EH-SBS of the different MNOs, after an initial internal REE has taken place among the EH-SBSs of the same MNO. Eventually, the EH-SBSs of an MNO apply DA either having only abundant or shortage in RE volume, thus acting only as seller or buyer players, respectively. It is noted that a seller EH-SBS enters the DA supplying the RE volume at the price that best fits its individual future needs. The aggregator acts as auctioneer, receiving a fit payoff.
- an evaluation of the schemes based on (i) the green energy utilization, (ii) the reduction of expenses on SG energy purchases and (iii) the satisfaction of all parties involved, as they are main aims of our proposed solutions.

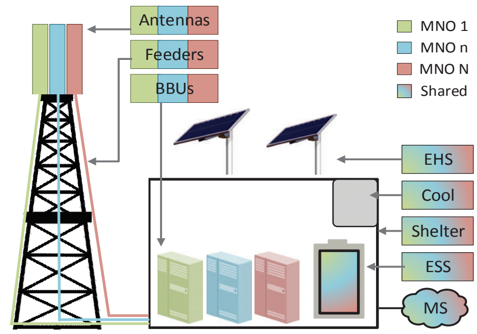
The rest of our paper is organized as follows: Section II provides the system model of our work and Section III refers to the challenges it reveals. Sections IV and V describe our EE proposals. Finally, Section VI presents the performance results of our proposals and Section VII concludes our paper.

II. System Model

In Fig. 1, we provide our system model, while the basic notation of our paper can be found in Table I. In accordance to Fig. 1(a), we assume a set of MNOs $\mathcal{N} = \{1, .., n, .., N\}$ in a macrocell-sized area serving in time slot t a total set $\mathcal{K}(t) = \{1, .., k, .., K(t)\}$ of user equipment devices (UEs), uniformly distributed in space. Each MNO n operates a two-tier HetNet that is consisted of EH-BSs, i.e., BSs powered



(a) System model in a macrocell-sized area.



(b) Passively shared infrastructure.

Figure 1. Detailed system model.

by a hybrid use of an EHS, an ESS and the SG through an aggregator. The small cell tier is consisted of a total set $\mathcal{L} = \{1,..,l,..,L\}$ of EH-SBSs, uniformly distributed in the studied area and owned by an InP. Each MNO $n \in \mathcal{N}$ manages an ν_n percentage of $\mathcal{L}$. The macrocell tier of each MNO n is consisted of one EH-MBS, forming a total EH-MBS set that is equal to the MNO one, $\mathcal{N}$. The EH-MBSs are owned and passively shared by $\mathcal{N}$. As can be observed in Fig. 1(b), the passive sharing includes sharing of energy and expenses corresponding to the main supply, cooling system, shelter, ESS and EHS. The operation and expenses corresponding to the baseband unit, feeders and antennas are an individual and exclusive responsibility of each MNO. Let the total set of BSs be $\mathcal{M} = \{1.., N, (N+1), .., (N+L)\}$. If $m \leq N$, then $m \in \mathcal{M}$ is an EH-MBS, while if $N < m \leq (N+L)$, an EH-SBS. In case of RE shortage, all $m \in \mathcal{M}$ proceed to an aggregator-aided energy trade with the SG [16].

We focus on the downlink (DL) side of the network, where BS power consumption follows a linear model with regard to traffic load volumes [31] and where orthogonal frequency division multiple access is assumed, with transmission of information in physical resource blocks (RBs). On this basis, let $\chi(t)$ be a UE traffic pattern. The UE traffic load of an MNO $n \in \mathcal{N}$ can be described as $\chi_n(t) = \kappa_n \chi(t)$, where $\kappa_n \in \mathbb{R}_{++}$ for a slot t, forming a total UE set at t $\mathcal{K}(t)$, with cardinality $K(t) = \sum_{n=1}^{N} \chi_n(t)$. Each UE $k \in \mathcal{K}(t)$ connects to an $m \in \mathcal{M}$ that is owned or managed by its own provider MNO and with which it has the best signal-to-noise ratio, $SNR_{km}(t)$. We calculate $SNR_{km}(t)$ as [32]

$$SNR_{km}(t) = P_m^{tx,sub} + G_m^{tx} - PL_{km}(t) - FL_{km} - N_{th} - NF, \quad (1)$$

where $P_m^{tx,sub} = 10log_{10}\left(P_m^{tr} / \left(12TRX_m PRB_m\right)\right)$ represents the power allocated to each subcarrier of EH-BS m *(dBm)*, with P_m^{tr} being the maximum transmission power of m *(W)*, TRX_m being the number of transceiver chains at m and PRB_m being the number of allocated RBs[1] to m. Moreover, in eq. (1), G_m^{tx} denotes the antenna gain of m (including feeder losses *(dBi)*) and $PL_{km}(t)$ is the pathloss between UE k and BS m at t *(dB)*. Finally, FL_{km} represents the slow fading losses *(dB)* as a random variable of log-normal distribution, with zero mean deviation and a standard deviation σ_m, N_{th} is the thermal noise and NF is the noise figure.

The guaranteed bit rate demand, ϱ_k (Mb/s) of a UE $k \in \mathcal{K}(t)$, can be expressed in RBs as

$$w_{km}(t) = \sum_{k \ in \mathcal{K}} \zeta_{km}(t) \cdot \lceil \frac{\varrho_k}{W_m^{RB} f(SNR_{km}(t))} \rceil, \quad (2)$$

where W_m^{RB} is the bandwidth that corresponds to an RB pair of m and $f(SNR_{km}(t))$ is the spectral efficiency of the link

Table I
BASIC NOTATION

$\mathcal{N}$	Set of MNOs, Set of EH-MBSs, with cardinality N, indexed by n
$\mathcal{S}$	Set of cooperative MNOs, with cardinality S, indexed by s, $\mathcal{S} \subseteq \mathcal{N}$
t	Time slot with duration τ
$\mathcal{K}$	Set of UEs, with cardinality K, indexed by k
$\mathcal{L}$	Set of EH-SBSs provided by the InP, with cardinality L, indexed by l.
ν_n	Percentage of L managed by MNO n.
$\mathcal{M}$	Set of EH-BSs, MBS or SBS, with cardinality $M = N + L$, indexed by m $m \leq N$: EH-MBS, $N < m \leq (N+L)$: EH-SBS
P_m	Power needs of m, *(Watt)*
P_m^{out}	Output transmit power of m, *(Watt)*
P_m^{pass}	Shared power needs of m at min. non-zero P_m^{out}, *(Watt)*
P_m^{con}	Non-shared power needs of m at min. non-zero P_m^{out}, *(Watt)*
h_m	Harvested RE at m, *(Wh)*
z_m	Stored RE at ESS of m, *(Wh)*
c_b	Unit price of buying energy from the SG, *(€/Wh)*
c_s	Unit price for selling energy to the SG, *(€/Wh)*
c_a	Unit price for practicing initial interior REE, *(€/Wh)*
g_m^*	Max. RE volume exchanged by m with the SG, *(Wh)*
e_m^*	Max. RE volume exchanged by m via REE, *(Wh)*
B	Bankruptcy problem
V_B	Utility function for B
Ω	Sum of RE for allocation with bankruptcy
$\mathcal{X}$	Set of seller EH-SBSs, with cardinality X, indexed by x, $\mathcal{X} \subseteq \mathcal{L}$
$\mathcal{Y}$	Set of buyer EH-SBSs, with cardinality Y, indexed by y, $\mathcal{Y} \subseteq \mathcal{L}$
ϵ_r^-	RE supplied by indicated r, member of indicated set $\mathcal{R}$, via IndREE, *(Wh)*
ϵ_l^+	RE received by indicated r, member of indicated set $\mathcal{R}$, via IndREE, *(Wh)*
$E_r^{\mathcal{R}}$	Claim/Reservation RE of indicated r, member of indicated set $\mathcal{R}$, *(Wh)*
$\Phi_r^{\mathcal{R}}$	Reservation price of indicated r, member of indicated set $\mathcal{R}$
$e_r^{\mathcal{R}}$	Payoff RE volume of indicated r, member of indicated set $\mathcal{R}$, *(Wh)*
$\phi_r^{\mathcal{R}}$	Trading price of indicated r, member of indicated set $\mathcal{R}$
G	Critical point of trading with double auction
Q	Total RE volume traded with double auction, *(Wh)*
ADA	Payoff allocated to the auctioneer of double auction

[1]It is noted that 1 RB is equal to 12 subcarriers in the frequency domain and 0.5 ms in the time domain.

between k and m at slot t. Given that adaptive modulation and coding is adopted over any radio link, we map the requested data rate ϱ_k and $SNR_{km}(t)$ to a respective spectral efficiency as indicated in [33, Table A.2]. We also denote with $\zeta_{km}(t)$ the association state of k with m at t, which is equal to 1 when k is associated to m and 0 otherwise.

Based on [31], we model the power needs $P_m(t)$ of an EH-BS $m \in \mathcal{M}$ at slot t as

$$P_m(t) = TRX_m \left(P_m^{pass} + \Delta_m P_m^{out}(t)\right), \; P_m^{out}(t) = \frac{\sum_{k=1}^{K} w_{km}(t)}{W_m} P_m^{tr}, \quad (3)$$

where Δ_m is the slope of load-dependent power consumption and P_m^{out} is the output transmit power of BS m. P_m^{out} is described as the portion of the maximum transmit power of m, P_m^{tr}, as it is defined by the occupied RB number of m during t, i.e., $\sum_{k=1}^{K} w_{km}(t)$, and the total number of RBs, W_m, that is allocated to m by default. The consideration of the $\frac{\sum_{k=1}^{K} w_{km}(t)}{W_m}$ term was based on the assumption that P_m^{tr} is equally allocated to the each subcarrier and RB that are available by default at the BS. Finally, P_m^{pass} stands for the total power consumption of m at minimum non-zero output power. Based on [31], we consider that $P_m^{pass} = P_m^{con}/S$, where P_m^{con} represents the power needs of a non-shared BS m at the minimum non-zero output power, while S is the cardinality of the set $\mathcal{S} \subseteq \mathcal{N}$ of MNOs who participate in the passive sharing of m. When $m \leq |\mathcal{S}|$, i.e., when m is an MBS, then, apparently, $|\mathcal{S}| > 1$. Otherwise, $|\mathcal{S}| = 1$.

The energy procurement source of an EH-BS m $\in \mathcal{M}$ is controlled and changed accordingly by a charge control system (CCS) that is able to measure and arrange energy availability from each source. Aiming at achieving a purely green network operation with reduced operational expenses, we assume the hereafter described energy sources.

1) Energy harvesting (EH): It is the primary energy procurement source for the EH-BSs and is either solar (harvested with photovoltaic panels) or aeolian (harvested with wind turbines). Solar energy has been opted for the energy hungry MBSs, since its harvesting is periodic and reduces probability for energy outages. However, we assume both solar and wind RE source for SBSs to enhance chances of RE availability in the whole network. We calculate the amount of harvested RE $h_m(t)$ *(J)* at BS m for the duration τ of a slot t as [34], [35]

$$h_m(t) = \begin{cases} PV_m \cdot H_m \cdot \tau \cdot (1 - \eta_{sol,m}) \cdot sin(2\pi\tau/T_{RE}), & sun \\ \frac{1}{2} \cdot WN_m \cdot \rho \cdot A \cdot v^3 \cdot C_m \cdot \tau, & wind. \end{cases} \quad (4)$$

In the *sun* case of eq. (4), PV_m is the number of photovoltaic panels at BS m, H_m stands for the average solar generation of the panel at m and in the studied area $(Wh/m^2/hour)$, while $\eta_{sol,m} \in [0,1]$ is the percentage of panel RE losses due to temperature, cleanness and shading, mismatching operation of elements, wiring and aging [36]. Lastly, T_{RE} is the period of solar generation. In the *wind* case of eq. (4), WN_m is the number of wind turbines at m, ρ is the air density $\left(kg/m^3\right)$ and v is the wind velocity (m/s). $A = \pi b^2$ is the area swept by the turbine rotor blades $\left(m^2\right)$, where b corresponds to the rotor blade radius. Lastly, C_m is the power coefficient or rotor efficiency and is a function of tip speed ratio and pitch angle.

2) ESS: Its utility is described as the storage of abundant harvested RE, i.e., $max\left\{h_m(t) - \tau P_m(t), 0\right\}$, as a provision for RE shortage events. Therefore, it is the second energy procurement source for the EH-BS. The RE volume that is stored in the ESS during slot t is $max\left\{(h_m(t-1) - \tau P_m(t-1)) \cdot (1 - \eta_{ESS,m}), 0\right\}$, where $\eta_{ESS,m} \in [0,1]$ is an energy loss factor due to battery deficiencies [37]. However, if $z_m(t)$ is the energy available at the ESS of m at the beginning of slot t, $z_m(t)$ has an upper and lower bound. $z_m(t)$ is upper bounded by the maximum storage capacity Z_m at m. It is $Z_m = \Psi_m V_m I_m$, where Ψ_m is the total number of batteries composing the ESS (in serial connection) of BS m, while V_m and I_m is the nominal voltage and capacity, respectively, of each battery. Each ESS battery is also characterized by its depth of discharge, DOD, which prevents the degradation of its health. Thus, $z_m(t)$ is both upper and lower bounded with: $(1 - DOD) \cdot Z_m \leq z_m(t) \leq Z_m$.

3) Aggregator and Smart grid (SG): SG connection via an aggregator is assumed for every BS $m \in \mathcal{M}$ as the last energy procurement source, as a countermeasure against RE outages and so that MNOs can trade with the SG. EH-BSs trade an energy amount g_m either as a purchase from the SG at a price c_b *(€/Wh)* or as a sale to the SG at a price c_s *(€/Wh)*, with $c_s \leq c_b$. The maximum absolute value of g_m is

$$|g_m^*(t)| = \left|h_m(t) + z_m(t^-) - \tau P_m(t)\right|, \quad (5)$$

where $z_m(t^-) = max\left\{(h_m(t-1) - \tau P_m(t-1)) \cdot (1 - \eta_{ESS,m}), 0\right\}$ represents the ESS energy that BS m has at the beginning of slot t, before any energy procurement takes place from it.

III. RE EXCHANGE (REE) AND CHALLENGES

Aiming at extending the prospects of cost and energy saving in the multi-stakeholder deployment of our system model, we suggest the inclusion of REE acts among the EH-BSs of each tier, before a possible trade with the SG. In detail, we suggest that REE acts occur if the sum of stored and abundant RE is

- sufficient to cover the energy needs of EH-BS $m \in \mathcal{M}$, i.e., $\tau P_m(t) \leq h_m(t) + z_m(t^-)$.
- insufficient to cover the energy needs of EH-BS $m \in \mathcal{M}$, i.e., $\tau P_m(t) > h_m(t) + z_m(t^-)$.

Let $e_m(t)$ *(Wh)* be the RE volume that m exchanges through REE acts for slot t. The highest absolute value of $e_m(t)$ is

$$|e_m^*(t)| = \left|h_m(t) + z_m(t^-) - \tau P_m(t)\right|, \quad (6)$$

while energy volume traded with the SG of eq. (5) becomes

$$|g_m^*(t)| = \left|h_m(t) + z_m(t^-) \pm e_m^*(t) - \tau P_m(t)\right|. \quad (7)$$

Challenges are found on the extraction of the $e_m(t)$ RE volumes with an REE scheme that is, firstly, applicable to multi-MNO and multi-tier network architectures, and, secondly, fairly regulates REE among the stakeholders. In order to address this challenge, we study the REE prospects in our system model as a two-branched case described as *(i)* the passively shared EH-MBSs and *(ii)* the InP provided EH-SBSs.

For the first case, we formulate REE as a cooperative energy sharing scheme via power lines for the energy transfer that addresses fairness issues. The passively shared EH-MBSs have the fundamental role of providing seamless umbrella coverage, while doing a green and economic energy management of the utmost fairness for the owner MNOs. Thus, fairness in sharing the harvested and stored RE volumes of the site's EHS and ESS, respectively, is a critical issue, as both group and individual MNO profits have to be protected. Simple strategies, such as equal allocation of the total RE volume or allocation with demand magnitude priority could be easy solutions to adopt and ultimately extract the $e_m(t)$ RE volumes. However, such strategies may result into a distribution that could be not only energy and cost inefficient, but also unfair to some MNOs. MNOs have to overcome any arisen inefficiency and fairness issues and seek an energy neutral EH-MBS operation.

For the second case, we formulate REE as a non-cooperative aggregator-assisted energy trading scheme of low complexity. The EH-SBSs are overlaid in the whole macrocell area and an REE act among them demands public reveal of information on the individual MNO activity. However, MNOs may prefer to keep this information private, especially when sharing of the macrocell tier already reveals some of their characteristics. MNOs could negotiate directly amongst them for the encounter of a solution and the extraction of the $e_m(t)$ RE volumes. However, this can lead to strategy exposure and hazard both their individual future energy planning and profits, while multiple negotiations for multiple network elements with energy needs increase the complexity of negotiations.

Fig. 2 describes our proposed energy procurement strategy for the EH-MBSs and EH-SBSs. As can be observed, for the passively shared EH-MBSs, we propose an approach, namely RE-BG, that treats the abundant and stored RE as a predefined entity that has to be completely allocated in $e_m(t)$ RE volumes to the passively shared EH-MBSs. RE-BG is executed at the CCS on site. After the application of RE-BG, EH-MBSs can trade energy with the SG, via the aggregator. For the InP provided EH-SBSs, we propose an aggregator-assisted approach, namely RE-DA, that runs in parallel with the RE-BG scheme. RE-DA can be applied by EH-SBSs of the different MNOs after the EH-SBSs have procured RE, firstly, from the EHS and secondly, from the ESS of the site. Moreover, for an inter-MNO REE to occur, we assume that an initial interior REE, which is based on the least difference in the abundant and lacked RE volume at the EH-SBSs of the same MNO, is preceded. Thus, with RE-DA, MNOs carefully extract at the CCS the information pieces they reveal to rival MNOs, i.e., the abundant or lacked RE at their site and respective unit prices, which they communicate to the impartial aggregator. For a decision, they take into consideration current and future energy needs, as well as the profitability of their options. The latter then extracts the traded multi-MNO $e_m(t)$ RE volumes and respective trading prices. After the application of RE-DA, EH-SBSs can trade energy with the SG, via the aggregator.

IV. Energy sharing among EH-MBSs

As a result of the adopted passive sharing, MNOs share an EHS, composed of solar panels, and an ESS along with the equipment of their collocated MBSs. Then, the EH-MBSs apply an REE scheme of sharing the harvested and stored RE

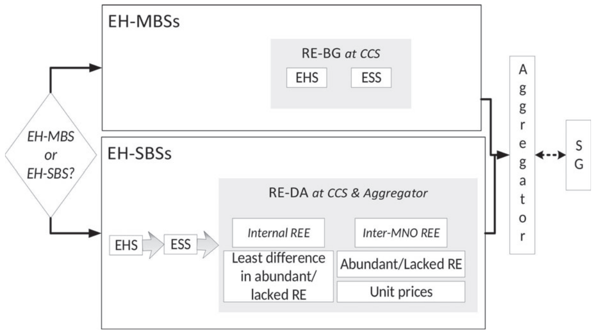


Figure 2. Suggested energy procurement order.

in order to ultimately achieve energy neutrality before trading energy with the SG. RE transfer is implemented via power lines that have been installed by the MNOs, with negligible energy losses thanks to the short length of the power lines.

During daylight, when solar energy generation varies, and at the beginning of a slot t, each shared EH-MBS makes an estimation of its expected energy needs for the duration τ of t. During night-time though, when solar EH is zero[2], a decision for the REE act is made based only on the stored RE. Therefore, each shared EH-MBS estimates its energy needs during a slot t', which corresponds to a set of slots t [3]. Based on the extracted estimation for the daylight and night-time, the shared CCS makes the energy management of the shared EH-MBSs for the duration τ of t and τ' of t', respectively.

We model the energy sharing problem among the shared EH-MBSs, using cooperative game theory. In detail, we use a bankruptcy game, according to which a specific *entity* needs to be completely allocated among a specific group of *players* [21]. Each player makes a *claim* on the entity. A *utility function* is set for the game, which eventually allocates to each player a part of the entity, i.e., the *payoff*.

Regarding the considered scenario, this entity, let $\Omega(t)$, is the sum of *(i)* $h(t)$, i.e., the RE that is collected from the shared EHS and *(ii)* the available stored RE $z(t^-)$ at the shared ESS, when the sum is either over-sufficient or insufficient to cover the power needs $P(t)$ of the passively shared EH-MBSs for the duration τ of a slot t, i.e., $\tau P(t) \leq h(t) + z(t^-) = \Omega(t)$ and $\tau P(t) > h(t) + z(t^-) = \Omega(t)$, respectively. Entity $\Omega(t)$ has to be fairly and completely provided to the EH-MBSs that are passively shared by a set of MNOs $\mathcal{S} \subseteq \mathcal{N}$. The EH-MBSs, or, as there is a one-to-one correspondence, their owner MNO, of coalition $\mathcal{S}$ can be portrayed as the players of the game. Each player $s \in \mathcal{S}$ claims an amount $E_s(t) = \tau P_s(t)$ of the entity $\Omega(t)$ so as to achieve an purely green operation of its EH-MBS, s, with $P_s(t)$ being defined as in eq. (3).

Thus, we have a bankruptcy problem, $B(t)$ modeled as

$$B(t) = \left\{ \left(\Omega(t),\ E_s(t) \in \mathbb{R}_{++} \times \mathbb{R}_{+}^{|\mathcal{S}|}\right) : \Omega(t) \leq \textstyle\sum_{s=1}^{|\mathcal{S}|} E_s(t) \right\}. \tag{8}$$

[2]It is noted that, in terms of simplicity, for periods of non-existent solar energy generation, solar energy harvesting is zero.

[3]In terms of simplicity and without loss of generality, we continue the analysis in the present section making reference to slot t.

We define the utility function of the bankruptcy game, $V_{B(t)}$, $V_{B(t)}\ :\ 2^N \times \mathbb{R}$, which evaluates the bankruptcy problem $B(t)$ and associates it to a real value, as

$$V_{B(t)}\left(\mathcal{S}\right) = \begin{cases} min\left\{E_{s\in\mathcal{S}}(t), \Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right\} & ,\mathcal{S} = \{s\} \\ min\left\{\sum_{s\in\mathcal{S}} V_{B(t)}\left(s\right), \Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right\} & ,\mathcal{S} \neq \{s\} \end{cases}. \tag{9}$$

Eq. (9) practically represents the amount of RE that can be allocated, after the non-participants in coalition $\mathcal{S}$ have received their claim. Thus, in an individual act of MNO, i.e., $\mathcal{S} = \{s\}$, the game value $V_{B(t)}\left(s\right)$ is equal to either the total amount of its claim, $E_s(t)$, or the remaining amount of $\Omega(t)$, after non-participant MNOs in $\mathcal{S}$ have taken their share. Similarly, in a coalition with more than one participants, i.e., $\mathcal{S} \neq \{s\}$, the game value $V_{B(t)}\left(\mathcal{S}\right)$ can be either the sum of individual act values $V_{B(t)}\left(s\right)$ or the remaining $\Omega(t)$, after non-participant MNOs in $\mathcal{S}$ have satisfied their needs.

However, if $V_{B(t)}\left(\mathcal{S}\right) < \left(\Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right)$, then $V_{B(t)}\left(\mathcal{S}\right) = 0$. This is due to the fact that entity $\Omega(t)$ needs to be totally allocated to the cooperative MNOs [21]. Consequently, when $V_{B(t)}\left(\mathcal{S}\right) < \left(\Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right)$, $\Omega(t)$ is insufficient to cover the energy needs of the total shared system and the value of that game is 0.

In order to ensure a viable solution for the bankruptcy game, the energy amounts that will be allocated to the participants in a coalition $\mathcal{S}$, i.e., the extracted payoffs, need to fulfill certain constraints. Let $e_s(V_{B(t)}(\mathcal{S}))$ be the payoff of player $s \in \mathcal{S}$ for participating in the $B(t)$ with the utility function $V_{B(t)}$. Then, $e_s(V_{B(t)}(\mathcal{S}))$ is the volume of $\Omega(t)$ that is allocated to a player $s \in \mathcal{S}$ and is subjected to the following constraints:

- The sum of allocated payoffs should equal $V_{B(t)}(\mathcal{S})$: $\sum_{s\in\mathcal{S}} e_s(V_{B(t)}(\mathcal{S})) = V_{B(t)}(\mathcal{S})$.
- The payoff of a player s in a coalition $\mathcal{S}$ should be at least equal to the payoff of its stand-alone action: $e_s(V_{B(t)}(\{s\})) \leq e_s(V_{B(t)}(\mathcal{S}))$.
- A player s cannot receive a higher payoff than its claim, so that fairness is preserved: $0 \leq e_s(V_{B(t)}(\mathcal{S})) \leq E_s(t)$.

We use Shapley Value (SV) to solve the problem, i.e., to calculate the payoffs $e_s(V_{B(t)}(\mathcal{S}))$ of the described bankruptcy game [22]. SV rewards a player $s \in \mathcal{S}$ with the SV payoff that portrays its marginal contribution to the coalition value, based on the utility function of the game. In the present case, SV payoffs $e_s(V_{B(t)}(\mathcal{S}))$ represent the contribution in generating $\Omega(t)$, when an $\mathcal{S}$ is formed and based on the utility function $V_{B(t)}(\mathcal{S})$ of eq. (9). SV has four basic axioms [22]:

- Efficiency axiom: $\sum_{s\in\mathcal{S}} e_s(V_{B(t)}(\mathcal{S})) = V_{B(t)}\left(\mathcal{S}\right)$.
- Dummy axiom: If a player s is such that $V_{B(t)}\left(\mathcal{S}\right) = V_{B(t)}\left(\mathcal{S} \cup \{s\}\right)$, then for $\forall\mathcal{S}'$, $\mathcal{S}' = \mathcal{S} - \{s\}$, it is $e_s(V_{B(t)}(\mathcal{S}')) = 0$.
- Symmetry axiom: If two players s_1 and s_2 are such that $V_{B(t)}\left(\mathcal{S} \cup \{s_1\}\right) = V_{B(t)}\left(\mathcal{S} \cup \{s_2\}\right)$, then for $\forall\mathcal{S}'$, $\mathcal{S}' = \mathcal{S} \cup \{s_1, s_2\}$ it is $e_{s_1}(V_{B(t)}(\mathcal{S}')) = e_{s_2}(V_{B(t)}(\mathcal{S}'))$.
- Additivity axiom: If V_1 and V_2 are characteristic functions, then $e\left(V_1 + V_2\right) = e\left(V_1 + V_2\right) = e\left(V_1\right) + e\left(V_2\right)$.

For the bankruptcy game, the efficiency axiom of SV remains valid when the game is defined by the player set, i.e., coalition S. The remaining axioms remain valid for the proposed game.

SV has an impact as a solution to the described problem since it displays a player's worth in the studied game, when the player joins coalition $\mathcal{S}$. Thus, we calculate the payoff of each player $s \in \mathcal{S}$ via the canonical definition of the SV payoff, which, based on the utility function V_B of eq. (9), is

$$e_s\left(V_{B(t)}\left(\mathcal{S}\right)\right) = \sum_{\mathcal{S}\subseteq\mathcal{N}\setminus\{s\}} \frac{|\mathcal{S}|!\left(|\mathcal{N}| - |\mathcal{S}| - 1\right)!}{|\mathcal{N}|!}\left[V_{B(t)}\left(S \cup \{s\}\right) - V_{B(t)}\left(\mathcal{S}\right)\right]. \tag{10}$$

Due to the different coalition forms of $\mathcal{N}$ EH-MBSs examined, the computational complexity of our scheme RE-BG is $\mathcal{O}(2^N)$ [38]. Given a large $|\mathcal{N}|$, the scheme's complexity increases tremendously. In this case though, it is acceptable as the number of collocated EH-MBSs, N cannot be too high.

V. Energy trading among EH-SBSs

MNOs lease from an InP EH-SBSs that are connected to the SG via an aggregator. MNOs adopt an REE scheme of aggregator-assisted energy trading among their EH-SBSs, so as to achieve energy neutrality before any trades with the SG.

At the beginning of a slot t, each EH-SBS estimates its expected energy needs and harvested RE for the duration τ of t. Taking into account the available stored RE at the ESS at the beginning of t, the CCS of the site calculates the RE volume that the EH-SBS is able to supply or demand at a trade. The impartial aggregator gets the information and arranges an initial interior REE among the EH-SBSs managed by the same MNO. Buyer EH-SBSs are matched to the seller ones with the least difference in requested and supplied RE volume, at the cost of the same price $c_a \leq c_b$ *(€/Wh)*, until there are no remains of requested or supplied RE. After the initial interior REE, the CCS calculates the RE volume that the EH-SBS supplies or demands for a trade with EH-SBSs of other MNOs, along with a respective price. This information is communicated to the impartial aggregator, who extracts the energy trading volume and price for each EH-SBS and for slot t, and its own payoff. Payments are executed through monetary transactions among the involved parties. We assume that the energy transfer is managed by the aggregator on a cloud level and that the SG delivers RE volumes to recipient EH-SBSs with energy shortage having negligible energy losses.

We model the energy trading problem of the EH-SBSs managed by various MNOs using non-cooperative game theory. In detail, we use the concept of double auction (DA), which is applicable to cases where multiple *sellers* and *buyers* are active [22]. In a DA, each seller and each buyer supplies and demands, respectively, a number of *items*. All sellers report a price for the item, i.e., the *asking price*, while all buyers propose another price, i.e., the *bidding price*. A *trading point* among sellers and buyers is eventually determined based on the demanded and supplied quantities of the traded item, as well as from the asking and bidding prices. The DA can be executed in a distributed manner or centrally by an *auctioneer*.

Regarding the considered scenario, we simulate as DA an aggregator-assisted energy trading among EH-SBSs that are managed by different MNOs. We set the harvested and stored RE, as well as the RE volumes exchanged with initial interior REE, as the trade item of DA, the EH-SBSs as the DA buyers and sellers and the aggregator as the DA auctioneer. The total set of EH-SBSs, $\mathcal{L} = 1, .., l, .., L$, is consisted of

- EH-SBSs with abundant RE in comparison to their energy needs $\tau P_l(t)$, i.e., $\tau P_l(t) \leq h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t)$,
- EH-SBSs with RE shortage in comparison to their energy needs $\tau P_l(t)$, i.e., $\tau P_l(t) > h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t)$),

where $\epsilon_l^-(t)$ and $\epsilon_l^+(t)$ are the RE volumes provided and received with the initial interior REE, respectively.

The RE volume $E_l(t)$ that each EH-SBSs l has in abundance or shortage corresponds to the reservation RE volume that the EH-SBS wants to supply or demand, respectively, with

$$E_l(t) = h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t) - \tau P_l(t). \quad (11)$$

Based on $E_l(t)$, the auctioneer-aggregator separates $\mathcal{L}$ to ordered sets of seller and buyer EH-SBSs, $\mathcal{X}$ and $\mathcal{Y}$, respectively:

- If $E_l(t) \geq 0$, then EH-SBS l is a seller and $l \in \mathcal{X}$. We will hereafter refer to the $E_l(t)$ of a seller as $E_l^{\mathcal{X}}(t) = E_l(t)$.
- If $E_l(t) < 0$, then EH-SBS l is a buyer and $l \in \mathcal{Y}$. We will hereafter refer to the $E_l(t)$ of a buyer as $E_l^{\mathcal{Y}}(t) = |E_l(t)|$.

Along with $E_l(t)$, each EH-SBS $l \in \mathcal{L}$ communicates to the auctioneer-aggregator as well its asking or bidding price (€/Wh) to reserve its participation in the DA. Let $\Phi_l^{\mathcal{X}}$ be the reservation asking price of a seller $l \in \mathcal{X}$ and $\Phi_l^{\mathcal{Y}}$ the reservation bidding price of a buyer $l \in \mathcal{Y}$. Let us note that none of the buyers or sellers splits its volume so as to ask different reservation price for each category. Values of $\Phi_l^{\mathcal{X}}$ and $\Phi_l^{\mathcal{Y}}$ are extracted based on a different strategy.

A. Sellers

Each seller EH-SBS $l \in \mathcal{X}$ is characterized by a utility function, $U_l^{\mathcal{X}}(t)$, which values the significance of its $E_l(t)$ in relation to its own energy needs. We set

$$U_l^{\mathcal{X}}(t) = \delta_l^{\mathcal{X}}(t) \cdot ln\left(1 + E_l^{\mathcal{X}}(t)\right) + \Phi_l^{\mathcal{X}}(t) \cdot \left(h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t) - E_l^{\mathcal{X}}(t)\right), \quad (12)$$

where $\delta_l^{\mathcal{X}}(t) = \frac{\frac{\tau P_l(t+1)}{h_l(t)+z_l(t^- - \epsilon_l^-(t)+\epsilon_l^+(t))+h_l(t+1)}}{\frac{\tau P_l(t)}{h_l(t)+z_l(t^- - \epsilon_l^-(t)+\epsilon_l^+(t))}} > 0$ is a preference value, which indicates the value of $E_l^{\mathcal{X}}(t)$ for the current and next slot, t and $(t+1)$, respectively. Thus, the first part of eq. (12) represents the value of $E_l^{\mathcal{X}}(t)$ for a future private use by seller $l \in \mathcal{X}$. The second part of eq. (12) corresponds to the revenues that $l \in \mathcal{X}$ can obtain during slot t by selling $E_l^{\mathcal{X}}(t)$ at a price $\Phi_l^{\mathcal{X}}(t)$. $U_l^{\mathcal{X}}(t)$ is strictly concave, i.e., $\frac{\partial^2 U_l^{\mathcal{X}}(t)(E_l^{\mathcal{X}}(t))}{\partial\left(E_l^{\mathcal{X}}(t)\right)^2} < 0$ and has a unique optimal that maximizes its value. Hence, for a strictly defined $\Phi_l^{\mathcal{X}}(t)$ and a $\delta_l^{\mathcal{X}}(t)$, there is a one-to-one correspondence between the best values of $E_l^{\mathcal{X}}(t)$ and $\Phi_l^{\mathcal{X}}(t)$, $E_l^{\mathcal{X},*}(t)$ and $\Phi_l^{\mathcal{X},*}(t)$, respectively. In eq. (11), we calculated $E_l^{\mathcal{X},*}(t)$. Given the $E_l^{\mathcal{X},*}(t)$, $\Phi_l^{\mathcal{X},*}(t)$ can be found for seller l when $\frac{\partial U_l^{\mathcal{X}}(t)(E_l^{\mathcal{X}}(t))}{\partial E_l^{\mathcal{X}}(t)} = 0$, with

$$\Phi_l^{\mathcal{X},*}(t) = \frac{\delta_l^{\mathcal{X}}(t)}{1 + E_l^{\mathcal{X},*}(t)}. \quad (13)$$

B. Buyers

Each buyer EH-SBSs $l \in \mathcal{Y}$ makes a reservation to buy an RE volume $E_l(t)^{\mathcal{Y}}$ for slot t to ensure energy neutrality for t.

We assume that each buyer $l \in \mathcal{Y}$ extracts a random value for its reservation bidding price $\Phi_l^{\mathcal{Y}}$. However, we assume that $c_s \leq \Phi_l^{\mathcal{Y}}(t) \leq \Phi_l^{\mathcal{Y}}(t) \leq c_b$. The restriction implies that the bidding price of the buyer must be higher than the offered prices by the sellers and the SG and, at the same time, lower that the price c_b at the cost of which it can buy SG energy.

C. Auctioneer-aggregator

As the DA auctioneer, the aggregator extracts the sets of seller and buyer EH-SBSs, after applying first the initial interior REE among the EH-SBSs of one MNO, as described in Section V. The aggregator then extracts the seller and buyer sets, $\mathcal{X}$ and $\mathcal{Y}$, respectively, based on their reservation RE volumes, $E_l^{\mathcal{X}}(t)$ and $E_l^{\mathcal{Y}}(t)$, and prices, $\Phi_l^{\mathcal{X}}(t)$ and $\Phi_l^{\mathcal{Y}}(t)$. We assume that $E_l^{\mathcal{X}}(t)$, $E_l^{\mathcal{Y}}(t)$, $\Phi_l^{\mathcal{X}}(t)$ and $\Phi_l^{\mathcal{Y}}(t)$ are static, i.e., sellers buyers cannot change their values, once they announce them to the aggregator. Based on the above, the aim of the aggregator is to determine for slot t

- the set of winner seller EH-SBSs, the final RE volumes they have to supply, $e_l^{\mathcal{X}}(t)$, as well as the trading selling price, $\phi_l^{\mathcal{X}}(t)$, at the cost of which they have to sell $e_l^{\mathcal{X}}(t)$.
- the set of winner buyer EH-SBSs, the final RE volumes they will purchase, $e_l^{\mathcal{Y}}(t)$, as well as the trading selling price, $\phi_l^{\mathcal{Y}}(t)$, at the cost of which they have to buy $e_l^{\mathcal{Y}}(t)$.

The aggregator takes into account the following restrictions

- $\sum_{l \in \mathcal{X}} e_l^{\mathcal{X}}(t) \leq E_l^{\mathcal{X}}(t), \ \forall l \in \mathcal{X}$, which ensures that none of the sellers sells more energy than it supplies,
- $\sum_{l \in \mathcal{Y}} e_l^{\mathcal{Y}}(t) \leq E_l^{\mathcal{Y}}(t), \ \forall l \in \mathcal{Y}$, which ensures that none of the buyers buys more energy than it demands,
- $e_l^{\mathcal{X}}(t), e_l^{\mathcal{Y}}(t) \geq 0, \ \forall l \in \mathcal{L}$, which reassures the exchange of a non-zero energy volume,
- $c_s \leq \phi_l^{\mathcal{X}}(t) \leq \phi_l^{\mathcal{Y}}(t) \leq c_b$, which ensures the profitability of the DA trades in relation to ones with the SG.

D. The auction

For the extraction of the aggregator's final decision, our proposed scheme, namely RE-DA, fulfills the presented aims and restrictions through the hereafter described procedure.

1) Step 1: The aggregator applies a Vickrey-like auction on each market side, so that buyers and sellers report their reservation prices [22], [28]. Without loss of generality and with the same prices being randomly sorted, the aggregator sorts the reservation prices of sellers $\forall l \in \mathcal{X}$ and buyers $\forall l \in \mathcal{Y}$ in ascending and descending order, respectively. Let X and Y be the cardinalities of sets $\mathcal{X}$ and $\mathcal{Y}$, respectively, and j and i the indices for the ordered $\mathcal{X}$ and $\mathcal{Y}$, respectively. It is

$$\Phi_{j=1}^{\mathcal{X}}(t) \leq ... \leq \Phi_j^{\mathcal{X}}(t) \leq \Phi_{j=X}^{\mathcal{X}}(t), \quad (14)$$

and

$$\Phi_{i=1}^{\mathcal{Y}}(t) \geq ... \geq \Phi_i^{\mathcal{Y}}(t) \geq \Phi_{i=Y}^{\mathcal{Y}}(t). \quad (15)$$

The reservation prices with the corresponding RE volumes are organized as in Fig. 3. The intersection point of the RE volumes and prices of seller and buyer EH-SBSs indicates the critical point of trading G. The G is the intersection point of the j_{th} seller and the i_{th} buyer EH-SBS. In accordance with the Vickrey auction rules, $(j-1)$ are the winner sellers that trade with $(i-1)$ winner buyers. Two cases are discriminated that can reassure the existence of G:

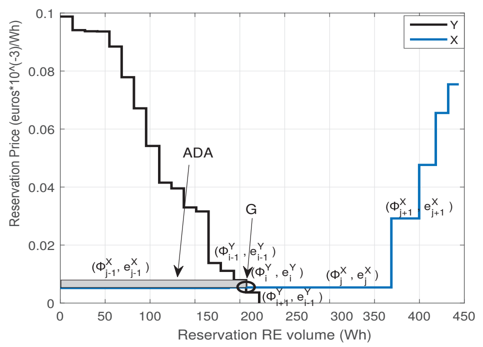


Figure 3. Typical DA case between the ordered sets of buyer EH-SBSs, $\mathcal{Y}$ and seller EH-SBSs, $\mathcal{X}$, with display of their DA reservation RE volumes and prices, the critical trade point G and the DA payoff of the aggregator, ADA.

- Asking and bidding prices satisfy $\Phi_{i+1}^{\mathcal{Y}}(t) \leq \Phi_{j}^{\mathcal{X}}(t) \leq \Phi_{i}^{\mathcal{Y}}(t)$ and aggregate energy supply and demand satisfy $\sum_{j=1}^{j=j-1} E_j^{\mathcal{X}}(t) \leq \sum_{i=1}^{i=i} E_i^{\mathcal{Y}}(t) \leq \sum_{j=1}^{j=j} E_j^{\mathcal{X}}(t)$.
- Asking and bidding prices satisfy $\Phi_{j}^{\mathcal{X}}(t) \leq \Phi_{i}^{\mathcal{Y}}(t) \leq \Phi_{j+1}^{\mathcal{X}}(t)$ and aggregate energy supply and demand satisfy $\sum_{i=1}^{i=i-1} E_i^{\mathcal{Y}}(t) \leq \sum_{j=1}^{j=j} E_j^{\mathcal{X}}(t) \leq \sum_{i=1}^{i=i} E_i^{\mathcal{Y}}(t)$.

In both cases, the market is cleared.

2) Step 2: The cleared prices of winner sellers and buyers for t, $\phi_{j'}^{\mathcal{X}}(t)$ with $j' = 1, .., j-1$ and $\phi_{i'}^{\mathcal{Y}}(t)$ with $i' = 1, .., i-1$, respectively are set by the auctioneer-aggregator as

$$\begin{cases} \phi_{j'}^{\mathcal{X}}(t) = \Phi_{j}^{\mathcal{X}}(t), \\ \phi_{i'}^{\mathcal{Y}}(t) = \Phi_{i}^{\mathcal{Y}}(t). \end{cases} \tag{16}$$

The cleared RE volume is defined differently for each seller and buyer EH-SBS for t based on the sum of reservation RE volumes until G. Two cases are extracted:

- **Case Overdemand** $\left(\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) \geq \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)\right)$, where the aggregated demanded RE from winner buyers exceeds the supplied by winner sellers RE sum. In this case, all winner sellers sell their total supplied RE volume, i.e., $e_{j'}^{\mathcal{X}}(t) = E_{j'}^{\mathcal{X}}(t)$, $j' = 1, .., j-1$, at the cleared seller price $\phi_{j'}^{\mathcal{X}}(t)$ of eq. (16). However, all winner buyers with indices $i' = 1, .., i-1$ buy at the cleared buyer price $\phi_{i'}^{\mathcal{Y}}(t)$ of eq. (16) an RE volume $e_{i'}^{\mathcal{Y}}(t)$ with

$$e_{i'}^{\mathcal{Y}}(t) = E_{i'}^{\mathcal{Y}}(t) - \frac{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) - \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)}{i-1}. \tag{17}$$

  In the case that $E_{i'}^{\mathcal{Y}}(t) < \frac{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) - \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)}{i-1}$, winner buyer i' pays for a winning traded entity $e_{i'}^{\mathcal{Y}}(t) = E_{i'}^{\mathcal{Y}}(t)$, while the remaining RE, $\frac{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) - \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)}{i-1} - E_{i'}^{\mathcal{Y}}(t)$ is allocated and bought equally by the remaining winner buyer EH-SBSs.
- **Case Oversupply** $\left(\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) \leq \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)\right)$, where the aggregated supplied RE from winner seller EH-SBSs exceeds the demanded by winner buyer EH-SBSs RE sum. In this case, all winner buyer EH-SBSs buy their total demanded RE volume, i.e., $e_{i'}^{\mathcal{Y}}(t) = E_{i'}^{\mathcal{Y}}(t)$, $i' = 1, .., i-1$, at the cleared buyer price $\phi_{i'}^{\mathcal{Y}}(t)$ of eq. (16). However, all winner seller EH-SBSs with indices $j' = 1, .., j-1$ sell at the cleared seller price $\phi_{j'}^{\mathcal{X}}(t)$ of eq. (16) an RE volume $e_{j'}^{\mathcal{X}}(t)$ with

$$e_{j'}^{\mathcal{X}}(t) = E_{j'}^{\mathcal{X}}(t) - \frac{\sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t) - \sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)}{j-1}. \tag{18}$$

  In the case that $E_{j'}^{\mathcal{X}}(t) < \frac{\sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t) - \sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)}{j-1}$, winner seller j' sells a winning traded entity $e_{j'}^{\mathcal{X}}(t) = E_{j'}^{\mathcal{X}}(t)$, while the remaining RE, $\frac{\sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t) - \sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)}{j-1} - E_{j'}^{\mathcal{X}}(t)$ is allocated and sold equally by the remaining winner seller EH-SBSs.

3) Step 3: The payoff compensation of the auctioneer-aggregator, $ADA(t)$ is then calculated based on the total traded RE volume $Q(t)$ among the winner EH-SBSs, with

$$Q(t) = min\left(\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t), \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)\right). \tag{19}$$

Thus, we define the $ADA(t)$ at each DA event equal to

$$ADA(t) = \left(\Phi_{i}^{\mathcal{Y}}(t) - \Phi_{j}^{\mathcal{X}}(t)\right) \cdot Q(t), \tag{20}$$

where $\Phi_{j}^{\mathcal{X}}(t)$ and $\Phi_{i}^{\mathcal{Y}}(t)$ are determined at G. Practically, in order to extract $ADA(t)$, we consider the difference between the *(i)* trading prices, $\Phi_{j}^{\mathcal{X}}(t)$ and $\Phi_{i}^{\mathcal{Y}}(t)$, at critical point G, and *(ii)* the sum of reservation energies of seller and buyer EH-SBSs until G and winner seller and buyer EH-SBSs.

4) Step 4: After the extraction of the payoff RE volumes and prices, the values are returned to the winner seller and buyer EH-SBSs. Payments are then implemented through monetary transactions among MNOs and aggregator, while the latter proceeds to energy transfer through the SG.

The complexity of RE-DA is $O(L^2)$. With RE-DA, the aggregator firstly executes the initial internal REE for each MNO. In the worst case, this is a greedy scheme of consecutive quick-sort procedures and matchings for $\forall l \in \mathcal{L}$ with complexity $O(L^2)$. Then, each EH-SBS locally calculates its reservation RE volume and price, while the auctioneer-aggregator quick-sorts the seller set $\mathcal{X}$ and the buyer set $\mathcal{Y}$. The local calculation at the EH-SBSs is of negligible complexity. The quick-sort complexity is $O(nlog(n))$, with $n = L$, i.e., the maximum cardinality of $\mathcal{X}$ or $\mathcal{Y}$. Finally, the encounter of G and the final payoff extraction that follow are both characterized by an $O(n)$ complexity, with $n = \frac{L}{2}$ in the worst case scenario. Therefore, the complexity of RE-DA is $O(L^2)$.

E. Analysis on RE-DA

The presents section investigates the properties of the proposed RE-DA scheme, in terms of the adopted DA.

Proposition 1: RE-DA is strategy proof with respect to reservation prices.

Proof: We will show that none of the players has a reason to misreport their reservation prices to EH-SBSs of rival MNOs.

A seller EH-SBS may *(i)* misreport its reservation price asking one higher than $\Phi_{j}^{\mathcal{X}}(t)$, *(ii)* misreport its reservation price asking one lower than $\Phi_{j}^{\mathcal{X}}(t)$, or *(iii)* supply a reservation RE volume lower than $E_{j}^{\mathcal{X}}(t)$. In the first case, the seller risks its participation in the DA, as its asking price may be a lot higher than the bidding ones of the buyers. Also, the trading price might be determined by another seller, while the seller itself cannot have knowledge of other players' private reservation prices so as to ask the ideally high price. In any case, the seller asks the best price for its supplied RE volume, based on its utility function. Thus, the seller has no reason to ask a price higher than $\Phi_j^{\mathcal{X}}(t)$. In the case that a seller under-reports its reservation price, it does not value sufficiently the RE volume it is willing to supply. This is proved by its concave utility function of eq. (12). Thus, the seller has no reason to ask a price lower than $\Phi_j^{\mathcal{X}}(t)$. In the last case, the seller does not have a clear vision if under-reporting its reservation RE volume is a more beneficial decision, as the set of winner EH-SBSs is determined by another BS. Therefore, the seller has no reason to under-report its reservation RE volume.

A buyer EH-SBS may *(i)* overbid its reservation price asking one higher than $\Phi_j^{\mathcal{Y}}(t)$, *(ii)* underbid its reservation price asking one lower than $\Phi_j^{\mathcal{X}}(t)$, or *(iii)* request a higher than $E_i^{\mathcal{Y}}(t)$ reservation RE volume. Regarding the two first cases, buyer EH-SBSs cannot over- or under- estimate their bidding price, as bidding prices are extracted randomly. However, a buyer may overestimate the demanded RE volume, as no restriction is preserved from our scheme. This decision does not affect the sellers though, as they value appropriately their supplied RE volumes. Based on the above, our proposed scheme is strategy proof with respect to reservation prices.

Proposition 2: RE-DA is weakly budget balanced.
Proof: A DA scheme is weakly budget balanced if the sum of sellers' and buyers' payments is a non-negative number. In RE-DA, buyers and sellers are ordered in descending and ascending order, respectively, until G is encountered. Thus, buyer EH-SBSs of RE-DA trade at price $\phi_{i'}^{\mathcal{Y}(t)}$ which is always higher than the one of sellers, i.e., $\phi_{j'}^{\mathcal{X}(t)}$. The difference between them though is used in eq. (20) for the extraction of the payoff compensation of the auctioneer-aggregator, $ADA(t)$. $ADA(t)$ is always non-negative and equal to the difference of the buyers' payment and sellers' compensation. Based on the above, RE-DA is weakly budget balanced.

Proposition 3: RE-DA is individually rational.
Proof: A DA is characterized as individually rational when individual agents are attracted to voluntarily participate in it, because they expect non-negative ex-ante profits. A seller EH-SBS is willing to supply an RE volume $E_j^{\mathcal{X}}(t)$ at the cost of a $\Phi_j^{\mathcal{X}}(t)$, provided that it does not affect negatively its future activity. However, this is taken into consideration by the seller EH-SBS when it extracts $\Phi_j^{\mathcal{X}}(t)$ for a specific RE volume that maximizes its utility function (eq. (12)). In addition, the cleared trading price is always higher than the reservation one, $\Phi_j^{\mathcal{X}}(t)$ thanks to the sorting. Thus, the seller's profitability is ensured. Finally, a seller EH-SBS participates in the DA if and only if its asking price is higher than the one it can ask from the SG market, i.e., $\Phi_j^{\mathcal{X}}(t) \geq c_s$. Thus, seller's profitability is ensured again. A buyer EH-SBS demands an RE volume $E_i^{\mathcal{Y}}(t)$ at the cost of a bidding price $\Phi_i^{\mathcal{Y}}(t)$, which is not necessarily the best one possible for them. A buyer EH-SBS though cannot participate in the DA unless its $\Phi_i^{\mathcal{Y}}(t)$ is lower than the one it trades with the SG, i.e., $\Phi_i^{\mathcal{Y}}(t) \geq c_b$. This ensures the profitability of its action. Finally, no seller and buyer EH-SBS is burdened with any cost so as to participate in the DA, as the auctioneer-aggregator receives its payoff from the auction act. Based on the above, no seller or buyer EH-SBS has a negative profit by participating in the DA. Hence, RE-DA is individually rational for the EH-SBSs.

Proposition 4: RE-DA is asymptotically efficient with respect to the number of players.
Proof: For buyers and sellers, the DA payoff to the auctioneer-aggregator, $ADA(t)$ is perceived as the total efficiency loss in a DA transaction. However, the auctioneer-aggregator may have specific requests with regard to the payoff it wishes to receive. Therefore, we evaluate the efficiency of the method from both perspectives in Section VI-B. In order to do that, we use an efficiency indicator of the game, $ef(t)$, defined as:

$$ef(t) = \left(\frac{ADA(t)}{F_1 + F_2 + F_3}\right)^{-1} \tag{21a}$$

where
$$F_1 = \sum_{i'=1}^{i'=i-1} \left(\phi_{i'}^{\mathcal{Y}}(t) - \Phi_i^{\mathcal{Y}}(t)\right) \cdot E_{i'}^{\mathcal{Y}}(t), \tag{21b}$$

$$F_2 = \sum_{j'=1}^{j'=j-1} \left(\phi_{j'}^{\mathcal{X}}(t) - \Phi_j^{\mathcal{X}}(t)\right) \cdot E_{j'}^{\mathcal{X}}(t), \tag{21c}$$

$$F_3 = ADA(t). \tag{21d}$$

In eq. (21a), the denominator of eq. (21a) represents the total DA market value, with the consideration of all trading entities, i.e., the reservation and trading RE volumes and prices of winner sellers and buyers in eqs. (21b) and (21c), as well as the payoff of the auctioneer-aggregator in eq. (21d). From the players' perspective, RE-DA is favored when $ef(t)$ diverges from 0. However, from the perspective of the auctioneer-aggregator, an RE-DA trade is efficient when $ef(t)$ has a value close to 0, while its payoff from the DA is over a certain percentage $\lambda(t) = \frac{ADA(t)}{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)\phi_{i'}^{\mathcal{Y}}(t)}$. In Fig. 9 of the following section, we display that RE-DA becomes more efficient when more players participate in it. However, the efficiency is upper bounded by $\lambda(t)$.

VI. Performance Evaluation

In the present section, we introduce in Section VI-A the parameters we used for building our simulation scenario and for evaluating the performance of our proposals, while in Section VI-B, we present the relative extracted results.

A. Simulation scenario

We study a macrocell-sized urban area in Barcelona, Spain, where $N = 3$ MNOs are active with a HetNet as in Fig. 1(a). Each MNO owns 1 EH-MBS and passively shares it with the other MNOs. MNO $n = 1, 2, 3$ manages the operation of 2, 10 and 13 InP provided EH-SBSs ($L = 25$), respectively. A 10 MHz bandwidth and $SNR_{th} = -10$ dB are used [33]. We use $\kappa_n = 0.3, 1.0, 1.3$ for $n = 1, 2, 3$, respectively, unless otherwise stated, and a $\chi(t)$ of users as in [31]. A UE k has a random bit rate demand $\varrho_k = \{1024, 512, 256\}$ kb/s.

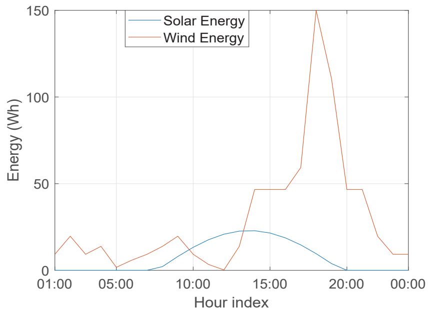


Figure 4. RE Generation vs. Time, June 21st, Barcelona, Spain.

Table II
SYSTEM PARAMETER VALUES

Parameter	Value	
N_{th}	-174 dBm	
NF	5 dB	
$Solar\ radiation$	5.14 $kWh/m^2/day$, BCN, Jun.	
$\eta_{sol,m}$	14%	
T_{RE}	24 h	
ρ	1.1849 kg/m^3	
b	0.5 m	
DOD	0.8	
c_b	0.10 €/kWh	
c_s	$c_b/100$	
c_a	$c_b/100$	
	$m \leq N$	$N < m \leq M$
P_m^{tr}	20 W	0.13 W
TRX_m	6	2
G_m^{tx}	15 dBi	5 dBi
$PL_{k,m}$	128.1+37.6log$D_{k,m}$	140+36.7log$D_{k,m}$
Δ_m	4.7	4
P_m^{con}	130 W	6.8 W
PV_m	6	1
WN_m	0	1
Ψ_m	3	1
V_m	48 V	12 V
I_m	150 Ah	28 Ah
$\eta_{ESS,m}$	15%	15%

EH- MBSs and SBSs use solar panels of 4 kW and 100 W, respectively. EH-SBSs are solar powered to a $\beta = 0.6$ ratio for each $n \in \mathcal{N}$, unless otherwise stated. Each remaining EH-SBS m uses an 100 W wind turbine, with power coefficient $C_m \in [0.38, 0.45]$ [35]. Statistical data are used for the wind velocity value v [39]. All ESSs are consisted of lithium batteries with initial charge around the $(1 - DOD)$ level.

We study the best day of the year in terms of solar insolation (June 21st). For RE-BG, we focus on a period slot τ' between 20:00-07:00, when no solar RE is generated. For RE-DA, we assume slots of $\tau = 1\ h$ throughout the day, with EH-SBS having RE harvesting profiles of Fig. 4. The remaining simulation parameters are portrayed in Table II [31], [33], [36].

We compare the proposed RE-BG with *(i)* Equal allocation (EQ), where each EH-MBS $n \in \mathcal{N}$ gets an equal share of the shared RE and *(ii)* Prioritized-claim allocation (PC), where EH-MBSs receive their complete claim of RE in a descending order. We assess the methods based on the ensured hours of SG independence $(hours)$ and their fairness in energy allocation based on the Jain's fairness index J. With α_n defined as the ratio of bought SG energy to each EH-MBS's claim, it is

$$J = \frac{\left(\sum_{n\in\mathcal{N}} \alpha_n\right)^2}{|\mathcal{N}| \sum_{n\in\mathcal{N}} \alpha_n^2}. \qquad (22)$$

We compare the proposed RE-DA to the cases when the set $\mathcal{L}$ of EH-SBSs is powered by (i) the SG only (SG-only), (ii) its individual EHS, ESS and the SG (NoREE), while no REE scheme is applied, and (iii) its individual EHS, ESS, an REE act in the form of RE-DA, without the initial internal REE, among a single-MNO managed infrastructure and the SG (IndREE). We use for the comparison an indicator

$$\gamma(t) = \frac{\sum_{m=N}^{m=N+L} g_m(t)|_{studied\ scheme}}{\sum_{m=N}^{m=N+L} g_m(t)|_{SG-only}} \qquad (23)$$

to estimate the SG energy procurements. Thus, γ represents the ratio of SG energy procurements in each studied scheme, $g_m|_{studied\ scheme}$, to the ones in the SG-only case, $g_m(t)|_{SG-only}$. We also assess the normalized payoff distribution produced for the winner sellers and the auctioneer-aggregator and evaluate RE-DA's efficiency based on $ef(t)$.

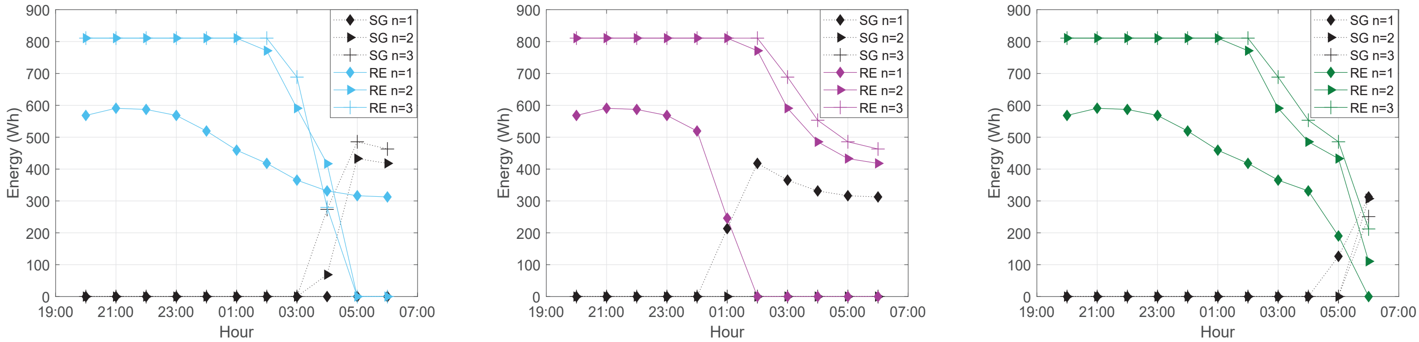
Finally, the profitability of each MNO individually from the proposed schemes is evaluated in terms of the created costs.

B. Performance results

In order to display the energy benefits of MNOs with RE-BG, in Fig. 5 we evaluate the hours of SG-independence an EH-MBS n has with the $e_n\left(V_{B(t)}\left(\mathcal{N}\right)\right)$ payoff it receives from the shared ESS. Figs. 5(a), 5(b) and 5(c) depict and compare the performance of EQ, PC and proposed RE-BG, respectively[4]. According to Fig. 5(a), $n = 2$ and 3 use their RE payoff for 8 h, while during the $9th$ hour, they need the SG to continue operating. $n = 1$ though is SG-independent during all night hours, while a part of its RE remains unused. This occurs because $n = 1$ gets the same amount of RE as $n = 2$ and 3, even though its traffic volume is lower. For fairness issues though, the stored RE should be exploited to the maximum by all EH-MBSs sharing the ESS. This does not comply with the performance of neither EQ, nor PC, as can be observed for the latter in Fig. 5(b). In detail, with PC, $n = 2, 3$ procure energy from the ESS all night long, since they have the biggest claim and, thus, are awarded with their total RE claim. $n = 1$ is at disadvantage, since its payoff corresponds to no more than 5 h of SG-independence. Unlike EQ and PC, RE-BG allocation offers a satisfying number of SG-independent hours to all cooperative EH-MBSs. According to Fig. 5(c), when RE-BG is applied, between 20:00-07:00, it ensures to all EH-MBSs SG-independence for 9 h. They then use the remains of their allocated RE payoff and obtain their energy deficits from the SG. In total, RE-BG offers a more balanced period of green network operation to all MNOs, since it considers both their cumulative energy needs and their marginal contribution to completely allocate the stored RE.

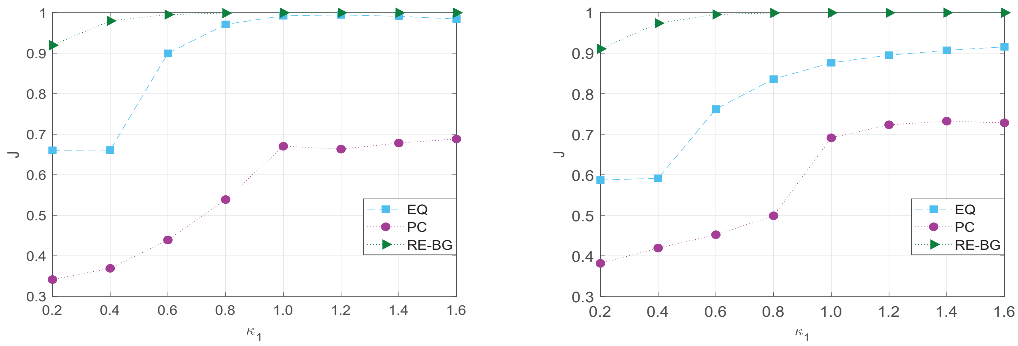
In Fig. 6 we see the effects of MNO traffic volumes on each allocation method's fairness, based on their Jain's fairness

[4]Harvested RE from the shared EHS during daylight was sufficient for the individual EH-MBSs needs and thus has not been included in the figures.



(a) Equal allocation (EQ) (b) Prioritised-claim allocation (PC) (c) RE bankruptcy game (RE-BG)

Figure 5. Monitoring of energy for different energy sharing methods.



(a) Same traffic load peaks for $n = 1$ and $n = 2, 3$. (b) Different traffic load peaks for $n = 1$ and $n = 2, 3$.

Figure 6. Jain's fairness index, J, *(i)* for the studied energy sharing methods, EQ, PC and RE-BG, *(ii)* for varied traffic loads, κ_1 and *(iii)* peaks of $n = 1$.

index, J. In detail, we vary traffic load factor κ_1, while κ_2 and κ_3 remain unchanged. We also consider similar and different traffic load peaks of MNOs $n = 1$ and $n = 2, 3$ in Fig. 6(a) and Fig. 6(b), respectively. We notice that J of RE-BG remains close to 1 irrespective of traffic load volumes or peak differentiations in both figures, since it considers each player's contribution to storing RE. Also, compared to its counterparts, RE-BG performs better. EQ performs closer to RE-BG when traffic load peaks are similar in Fig. 6(a), mainly for $\kappa_1 > 1$. This is when MNO traffic volumes become more similar and all allocated RE payoffs are consumed during the night. However, when peaks are different in Fig. 6(b), fairness of EQ deteriorates since traffic load differences among MNOs are intensified. Lastly, PC allocation is far below EQ and RE-BG in both figures, as there is always an EH-MBS in the need of SG energy. PC though performs better when traffic peaks are different in Fig. 6(b). This is because, when EH-MBS $n = 1$ receives its payoff for its high peak traffic load, MNOs $n = 2, 3$ are in their low peak traffic load and thus, their EH-MBSs use RE to a high degree. In the reverse case that MNO $n = 1$ is in its low peak traffic load and thus has lower needs in RE than $n = 2, 3$, the EH-MBSs of the latter have more remaining RE to share for their RE needs.

We display the benefits of MNOs with RE-DA, in Fig. 7 using the indicator $\gamma(t)$ of eq. (23) for the comparison of NoREE, IndREE our RE-DA to the SG-only operation of EH-SBSs in $\mathcal{L}$, during a day. Between 07:00-14:00, the EH-SBSs consume their harvested and stored RE and then use SG energy in all study cases. However, SG purchases are still considerably reduced, up to 80% at 11:00 when $\gamma = 2$. When $\gamma = 0$ between 14:00-19:00, in all cases, EH-SBSs consume only harvested RE and store some in their ESSs. After 19:00, IndREE coincides with NoREE until 22:00 consuming SG energy as well. With NoREE, the EH-SBSs cannot exchange RE amongst themselves. With IndREE, despite the fact that ESSs of both solar and aeolian EH-SBSs have abundant stored RE, no REE acts take place as MNO traffic load volumes are still considerable, making EH-SBSs reserved towards selling RE. Nevertheless, IndREE acts then become more intense, especially after 23:00, when traffic load volumes are low and there are EH-SBSs with abundant harvested (mainly aeolian) and stored RE. In contrast to its counterparts, RE-DA ensures SG independence for the system after 19:00 and until 04:00. RE-DA overcomes any reservation towards selling energy with the initial interior REE among the EH-SBSs of the same MNO. Trades with EH-SBSs of rival MNOs further reduce SG expenses, especially when MNO traffic load volumes are low. In the course of a day, NoREE, IndREE and RE-DA reduce significantly the sum of SG energy purchases, reaching a 34%, 31% and 12% of the SG-only case, respectively, while a further 63% and 60% reduction is achieved by RE-DA in comparison to NoREE and IndREE, respectively.

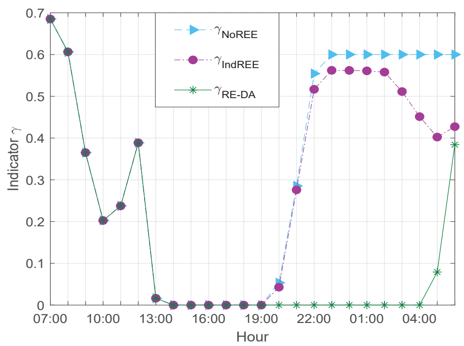


Figure 7. 24-hour evaluation of SG energy purchases based on ratio $\gamma(t)$ for the (i) NoREE, (ii) IndREE and (iii) RE-DA energy procurement schemes.

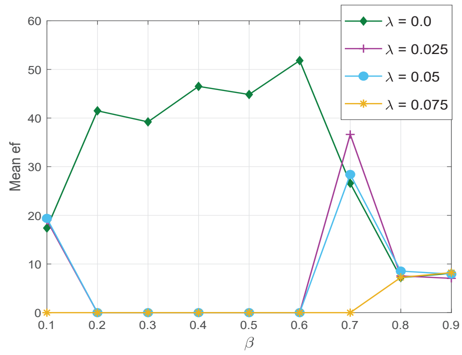


Figure 9. Efficiency of RE-DA trades based on mean ef vs. ratio β.

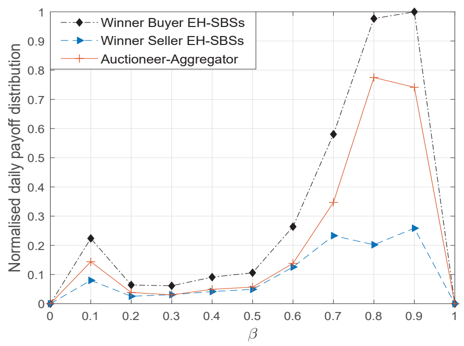


Figure 8. Normalised total daily DA *(i)* cost for winner buyer EH-SBSs, *(ii)* payoff of winner seller EH-SBSs, and *(iii)* payoff of the auctioneer-aggregator, vs. the ratio of solar powered SBSs, β.

The percentage β of solar EH-SBSs affects RE availability at EH-SBSs and, thus, RE-DA profitability for the stakeholders. Thus, in Fig. 8, we display the total normalized daily DA payoff (i.e., cost) $\sum_{t=1}^{t=T_{RE}} \sum_{i'=1}^{i'=i-1} e_{i'}^{\mathcal{Y}}(t)\phi_{i'}^{\mathcal{Y}}(t)$ of winner buyer EH-SBSs, the total normalized daily DA payoff $\sum_{t=1}^{t=T_{RE}} \sum_{j'=1}^{j'=j-1} e_{j'}^{\mathcal{X}}(t)\phi_{j'}^{\mathcal{X}}(t)$ of winner seller EH-SBSs and the total normalized daily DA payoff $\sum_{t=1}^{t=T_{RE}} ADA(t)$ of the auctioneer-aggregator, for varying β. As can be observed, no profits or costs are created with RE-DA when $\beta = 0$ and $\beta = 1$, as EH-SBSs have homogeneous EH profiles for these β values. Hence, no RE-DA trades take place. For $\beta \neq \{0, 1\}$ though, RE-DA is applied, with the payoff distribution among winner seller EH-SBSs and auctioneer-aggregator being intensely uneven occasionally. When $\beta \leq 0.5$, the trades among EH-SBSs of rival MNOs are considerably fewer in comparison to the case $\beta > 0.5$. For $\beta \leq 0.5$, the majority of EH-SBSs are wind-powered and therefore, during the night, power the solar ones, primarily with an initial internal REE. In daylight, the reverse happens. RE-DA trades with EH-SBSs of other MNOs take place in the early morning hours, when some ESSs may not be charged. The remaining seller EH-SBSs though, have enough abundant energy and, based on eq. (13), propose not considerably high asking prices. Thus, in Fig. 8, a similar distribution of the buyers' expenses is mostly encountered between the seller EH-SBSs and the auctioneer-aggregator. When $\beta > 0.5$, the majority of EH-SBSs are solar powered and EH is distributed throughout the day. At the same time, there are aeolian EH-SBSs to supply RE when solar EH is low or non-available and to allow more frequent RE-DA trades among EH-SBSs of rival MNOs. This explains the higher expenses of buyer EH-SBSs when $\beta = 0.7, 0.8$ and 0.9. RE-DA trades occur mainly during low-traffic hours, when aeolian RE compensates energy deficits of solar EH-SBSs. However, seller reservation prices are lower than the average buyer ones, creating thus the vast gap noticed in the figure for $\beta = 0.8,\ 0.9$. It can be said that mediocre β values allows REE with RE-DA, reducing the SG expenses with satisfying payoff for the auctioneer-aggregator.

As β affects the number of winner sellers and buyers, in Fig. 9, we study its effect on the efficiency of RE-DA, based on the mean ef value of eq. (21a). Our method's efficiency is also evaluated in relation to threshold values $\lambda(t)$ that the auctioneer-aggregator may impose so as to execute RE-DA. In Fig. 9, when no limitation is imposed by the aggregator, i.e., $\lambda = 0$, the method is more efficient for $0.2 \leq \beta \leq 0.6$. This means that, for $\lambda = 0$, the more diverse the RE sources at the EH-SBSs are, the more equal the payoff distribution among seller EH-SBSs and the auctioneer-aggregator is. Thus, the mean ef diverges from 0, i.e., RE-DA becomes more efficient. ef has the highest value for $\beta = 0.6$, since for this β value, more players participate in and eventually trade with RE-DA. Therefore, for this case, the method is asymptotically efficient with respect to the number of RE-DA players. However, our method's efficiency is limited by thresholds $\lambda(t)$ of higher values. In order to satisfy the requests of the auctioneer-aggregator for high $\lambda(t)$, either considerably wind- or solar-powered dominated infrastructure is needed. In these cases, there are periods of time during a day, when available RE at seller EH-SBSs is enough to over-cover the energy needs of their MNO's network and trade energy with EH-SBSs of rival MNOs with large profit margin for the auctioneer-aggregator. Otherwise, the requests of the latter cannot be satisfied and RE-DA is totally prevented. Once again though, when RE-DA is allowed, its efficiency is higher when more players participate in and eventually trade with it. As a conclusion, low λ thresholds are important for RE-DA, while player EH-SBSs need diverse RE-sources to achieve trades.

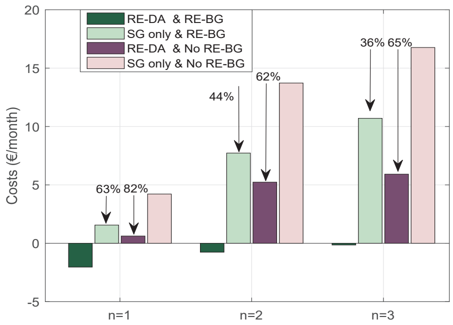


Figure 10. Monthly MNO costs created by the proposed and traditional methods.

In Fig. 10, we show the monthly costs created by our proposed approaches' individual and combined application in the studied area and compare them with the adoption or not of passive sharing and with the SG-only case. In the figure, green shades represent the application of both passive sharing and RE-BG at the EH-MBS site. Red shades correspond to the case when no passive sharing is applied to the EH-MBSs, i.e., when MNOs cannot apply the RE-BG scheme (No RE-BG). Dark shades indicate the application of RE-DA, while the light ones stand for the use of SG-only energy for the EH-SBSs. As can be observed, both individual and combined use of our proposals in the studied area induces significantly lower costs to all MNOs, n = 1, 2, 3. According to the figure, all MNOs are significantly benefited by both RE-BG (green-red comparison) and RE-DA (dark-light shades comparison), even resulting in an elimination of the created costs. In comparison to the SG-only case, MNOs n = 1,2, 3 achieve a 63%, 44%, 36% reduction of expenses, respectively, thanks to RE-BG and an 82%, 62% and 65% one, respectively thanks to RE-DA.

VII. Conclusions

In this paper, we studied the problem of REE in late-trend multi-MNO networks. We proposed REE methods (i) among collocated and passively shared EH-MBSs with an RE sharing approach, RE-BG, which is based on cooperative bankruptcy games and (ii) an aggregator-assisted RE trading approach, RE-DA, that applies an initial internal REE followed by a double auction among the InP provided EH-SBSs managed by the same and different MNOs, respectively. In the first case, we showed that RE-BG allows at least 9 hours of SG energy independence for all EH-MBSs of the MNOs during non-solar hours and a fairer RE allocation in comparison to baseline schemes. In the second case, we showed that RE-DA reduces SG energy consumption to a 12% of the one resulted with a SG-only operation. Combined use of solar and wind powered EH-SBSs at a mediocre analogy indicated more efficient use of RE, with the allocation of sufficient payoffs to both players and the auctioneer-aggregator. Careful consideration though should be given to the limitations imposed by the auctioneer-aggregator. Finally, our proposals considerably reduce individual MNO costs, resulting even to an elimination of MNO expenses on SG purchases in their combined application.

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