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Blockchain-based sequential market-clearing platform for enabling energy trading in Interconnected Microgrids

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ABSTRACT

Interconnected Microgrids (IMGs) are considered a futuristic paradigm of power grids that offer modularity, resilience, and independence with energy exchangeability. In this context, each MG is accountable to its own citizens (i.e., generators or loads) and can participate in a market with its neighbours, if this enhances the benefits of its citizens. Thus, greedy behaviour is assumed to be rational for MGs participating in such a market. In this paper, a novel decentralized platform to facilitate energy trading between IMGs is developed. The platform would allow interested MGs to participate and gain benefits assuming self-benefit-driven (SBD) actions from participating MGs. The proposed platform provides a market-clearing approach based on sequential rounds. In each round, the MG with the cheapest energy price is privileged to export its surplus energy and maximize its own benefits. In order to identify the round champ, a decentralized ranking algorithm is developed to determine the MG with the cheapest energy price. The effectiveness of the proposed platform is validated using various case studies.

1. Introduction

IMG markets offer several advantages to all participants, including end-users and DG owners. The idea of energy management in IMG markets was first introduced in [1], where the authors proposed a distributed multi-agent structure to facilitate energy management. The authors in [2] modified the concept to develop self-adequate interconnected MGs with virtual boundaries. Energy management frameworks could be implemented within these boundaries to minimize computational time. The concept of looking at a system as a cluster of MGs rather than a bulk system evolved to include the operation introduced in [3].

2. Literature review

Energy management in an IMG can be categorized into two main structures: (1) centralized management, and (2) decentralized management. The main drawback of the centralized structure is the existence of a single central operator that collects the data from all participants and makes a centralized decision.

In [4,5], microgrid control centre is utilized to manage the transactions between IMGs. In [6], a model predictive control is proposed to provide a centralized energy exchanging model. Similarly, a centralized model designed to limit the information shared is proposed in [7]. Furthermore, a two-tier hierarchical model is proposed to enable an efficient energy exchanging framework [8–10].

A number of authors have recognized a method for limiting the information shared between the Energy Management Systems (EMSs) and the MGs. In [11,12], the author proposed a cooperated model that needs a central control unit to manage the transactions between the participating MGs. In [13], an anonymously based model is developed that can handle the transaction in a centralized framework while changing minimum information between the participants and Central controller.

Although the central operator has the ability to make an optimal decision according to pre-set objectives, the decentralized structure has the advantage of preserving the privacy of participants' data and improving reliability and independence by following a decentralized approach.

Several decentralized algorithms and platforms have been proposed and investigated toward optimal energy management in IMGs. Two main approaches have been examined by researchers to promote decentralized energy management structure: (1) optimization-based, where

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Nomenclature

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DSA	Double Signing Algorithm.
DSO	Distribution System Operator.
EMS	Energy Management System.
IMGs	Interconnected microgrids.
MCP	Market Clearing Price.
P2P	Peer to Peer.
P2S2P	Peer to System to Peer.
SBD	Self-Benefit Driven.
UMP	Uniform Marginal Price.

Parameters

$\gamma D^{i}_{s,m}$	Price of block m for demand s in microgrid i in $/kWh.
$\gamma E^{i}_{r,t}$	Price of block t for generator r in microgrid i in $/kWh.
$\gamma E^{j}_{r,t}$	Price of block t for generator r in microgrid j in $/kWh.
$\gamma G^{i}_{c,k}$	Price of block k for generator c in microgrid i in $/kWh.
λ^{i}_{max}	Maximum price in case of exporting for microgrid i.
$\overline{PD}^{i}_{s,m}$	Upper energy limit of block m for demand s in microgrid i in kWh.
$\overline{PE}^{i}_{r,t}$	Upper energy limit of block t for generator r in microgrid i in kWh.
$\overline{PG}^{i}_{c,k}$	Upper energy limit of block k for generator c in microgrid i in kWh.
L	Clustering ratio.
N_{max}	Total number of MGs participating in energy trading.
Q^{i}	Given number for microgrid i.
SW^{i}_{o}	Social welfare for microgrid i without trading in $.

Sets and Indices

A_i	Set of all microgrids connected to MG i.
c	Index identifying distributed generators.
D	Set of demand users.
D_s	Set of demand blocks.
G	Set of internal generators.
G_c	Set of internal generator blocks.
G_E	Set of Exporter generators.
G_r	Set of Exporter generator blocks.
i	Index identifying microgrid.
j	Index identifying microgrid.
k	Index identifying generator blocks.
m	Index identifying demand blocks.
r	Index identifying exporter distributed generators.
s	Index identifying demand participants.
t	Index identifying exporter generator blocks.

Variables

η^{i}_{new}	New internal price for microgrid i after participating in energy trading in $/kWh.
EB^{j}	Export benefit for microgrid i in $.
$PD^{i}_{s,m}$	Energy required from block m for demand s in microgrid i in kWh.
$PE^{i}_{c,k}$	Total Energy exported from block k for generator c in microgrid i in kWh.
$PE^{j}_{i_{r,t}}$	Energy exported from block t for generator r in microgrid i to microgrid j in kWh.
$PE^{i}_{j_{r,t}}$	Energy exported from block t for generator r in microgrid j to microgrid i in kWh.
$PG^{i}_{c,k}$	Energy generated from block k for generator c in microgrid i in kWh.
SWE^{i}	Effective Social welfare for microgrid i in $.

energy management is formulated as an optimization problem that is solved using decentralized techniques; and (2) Peer-to-Peer (P2P), where negotiations are organized directly between peers.

In [14], the global optimization is reached in a coordinated decentralized approach in which all agents can negotiate together. A similar coordinated approach is proposed using the ADMM technique as in [15]. In [16] the central operator (i.e., DSO) was eliminated and the Alternating Direction Method of Multipliers (ADMM) was used to perform energy management. In [17], decentralized approach is developed based on dual decomposition technique. Further improvement was proposed in [18] to realize an online management scheme without forecasting the load data. In general, the aforementioned work focused on developing a mathematical model for energy management in IMGs rather than establishing an energy market. However, the different interests of the participants are not well-defined, and the internal demand interest is not carefully implemented.

Peer-to-peer methods were extensively investigated in the literature to handle negotiations between system peers. This research work can be grouped into two categories: auctioneer-based negotiations and direct negotiations. In a bilateral contract created based on an auctioneer-developed negotiation in [19], the auctioneer is designed to act fairly between prosumers and customers, while a load aggregator is proposed in [20] to communicate with a virtual intermediate auctioneer that settles the trading between the participating peers. In [21], a non-profitable tool is developed for energy management between energy buildings and consumers. In this work, direct negotiations are promoted for being completely decentralized and eliminating any third party.

In [22], the researchers proposed a peer-centric method to handle transactions between peers; the method was further improved in [23]. Despite the novelty of the proposed approach, the communication media required to facilitate these negotiations is massive and sophisticated, and thus it imposes significant computational overhead. In response to this challenge, one-to-one negotiation was proposed in [24], in which each peer negotiates and agrees on its contract. Similarly, a blockchain-based direct P2P negotiation model is proposed and practically tested in Brooklyn [25]. In [26], the author exercised the load management techniques under the blockchain-based energy trading model. The blockchain-based model is further utilized in [27] to provide P2P crowdsourcing-based framework considering network constraints.

Overall, the research gaps in the above-cited literature can be summarized as: a lack of end-user participation, a consideration of balancing demand and prosumers, and a limiting of the number of required communication links.

In [28], the authors presented a unique energy trading framework based on a Peer-to-System-to-Peer (P2S2P) concept. The proposed model succeeded in enabling energy trading between a large number of participants utilizing blockchain capabilities. In [29], the authors developed a decentralized market to act in the parallel and short-term pool-structured auction. The market in [29] is set for all customers which could be compared to authors previous work in [28]. However, the proposed paper tackles another problem regarding the exchange between self-benefit-driven MGs. Every MGs satisfy its internal customers first using the algorithm proposed in [28], then it bids with the aggregated excess in the market between the MGs. In addition, the market in [29] did not count for the power system losses, while this is counted in [28].

That being said, this paper proposes a platform that is capable of providing planned one-to-one energy negotiations, in which efficient settlements could be achieved in a completely decentralized fashion. The market focuses on the exchanges between the MGs keeping in mind the greedy actions of each MGs. In contrast, in [29] author focuses on developing an energy trading framework in a decentralized manner while not providing a framework for market settlements between IMGs. Using the UMP contradicts the rational assumption that MGs will act in a greedy way and would not participate unless their participation would be to their own benefit, regardless of how it would affect others. The main contributions of this paper can be summarized as follows:

- Proposing a new framework for energy trading in IMGs that is independent of the connectivity of the IMGs.
- Considering SBD behaviour from participating MGs that satisfies both demand and prosumers.
- Developing a decentralized energy trading platform using sequential settlements to ensure market fairness and promote cheaper energy.
- Adapting blockchain technology to handle the proposed market's transactions, which would provide a safe, reliable, and transparent monetary fund.

The rest of the paper is organized as follows. Section 3 discusses the decentralized energy trading structure. Section 4 presents the energy trading platform. The optimization model for the proposed energy trading platform is illustrated in Section 5. The effusiveness of the proposed framework is investigated through the case studies in Section 6. The monetary fund verification is presented in Section 7, and Section 8 draws the conclusion.

3. Decentralized energy trading structure

In this section, a decentralized framework is proposed assuming SBD action from participating MGs. The presented framework enables energy trading between interconnected MGs while preserving data privacy by communicating the data between neighbours only. The trading framework is designed to give MGs with the lowest energy prices the privilege of offering their surplus energy in the market first. Therefore, the MG with the lowest energy price will get the opportunity to export the available energy. Once this happens, this MG is eliminated from the next settlement rounds. Then the MG with the next lowest price (i.e., the lowest after eliminating the previous MG) is selected to export, and so on.

As shown in Fig. 1(a), in centralized bargaining, all bargaining occurs simultaneously, whereas in the proposed sequential decentralized algorithm, bargaining is carried out in sequence. Using this approach, the following benefits are offered: (1) Maintaining MG privacy, (2) promoting cheap energy trading, and (3) considering SBD action from MGs while improving overall benefits. In order to realize the aforementioned sequential approach, all the MGs have to be ranked in a decentralized manner. Therefore, two sequential ranking algorithms are developed and proposed. The first algorithm, called the #1-focused ranking algorithm, finds the MG with the lowest price (#1) in a distributed fashion. This algorithm runs rounds of settlements and allows only the MGs with the cheapest energy price to export their energy in each round. The second algorithm is called the Price Range-focused (PR-focused) ranking approach. In this algorithm, MGs are clustered according to the range of their energy prices in a definite number of groups. Microgrids in the same group offer energy within a certain price range and are allowed to export energy at the same time.

As shown in Fig. 2, the information is exchanged only between directly-connected neighbours. It is worth mentioning that the proposed decentralized platform does not require a DSO to influence market settlements. Trading is based solely on offer and demand, with the advantage given to low-priced sellers.

4. Decentralized energy trading platform

This section describes the assumptions, algorithms, and problem formulation for the proposed decentralized energy trading framework among IMGs. The proposed framework is modelled to maintain privacy while assuming greedy action from all participants, as will be explained later. To satisfy each MG's self-interest, a unique objective function is defined from the basic principle of the UMP model. This objective function is defined in the next subsection.

4.1. Sequential market clearing methodology

The proposed sequential market starts by ranking the participating MGs according to their internal clearing price (λ_o). It is reasonable to assume that the MGs with the lowest λ_o and with their market cleared using UMP will have surplus energy at a lower price. However, if this is not the case, the other MGs have the freedom to reject the offered energy unless it is cheaper.

Ranking is done via the developed decentralized ranking algorithms, as explained in the next subsections. At any round, after ranking, the MG with rank #1 (or group#1) firms the offers it has, if any, and then sends export offers to all its neighbouring MGs. It should be noted that the MG (or group#1) with the lowest energy prices will not be interested in importing power from the high-priced MGs. The MG with rank#1 (or group#1) tries to maximize its export benefits from exporting any surplus energy to its directly connected MGs. Then, MGs that receive offers solve a UMP model internally to maximize their social welfare after including the offered generators' bidding from exporting MGs. The offer-taker MGs can accept or reject (firm) these offers when they are assigned to be rank#1 (or group#1).

Afterwards, the rank#1 (or group#1) MG is eliminated from the next rounds and the remaining MGs are re-ranked to find the current rank#1 (or group#1) MG to start over again. This sequence is repeated until all MGs are eliminated (i.e., given a chance to send export offers). It is worth noting that MGs are withholding offers if they are not rank#1 (or group#1). Once an MG is designated rank#1, it has to firm the withheld offers (accept/reject) from previous rounds before sending export offers to others.

4.2. Exporter MG objective function definition

In this subsection, the objective function for each participating MG is formulated following an SBD action. Assuming a non-cooperative game, each MG is looking to increase its benefits from exporting energy to its neighbours participating in the IMG market. Exporting MGs aim to maximize their generators' benefit by exporting surplus energy without affecting the energy prices offered to their local loads. Meanwhile, importing MGs act to secure cheaper energy for their loads.

Fig. 3 shows a general offer/bidding curve for the generator/load, which is used to find the market clearing price (λ_1: marginal price in case of isolated operation) that maximizes the social welfare (the area between the two curves). In case of export, an MG can offer its excess generation (i.e., after clearing the local market) in the IMG market. In this way, an MG can gain additional social welfare for its generators (i.e., export area A_E) without changing the local market price (λ_1) after achieving a new export price (λ_2: marginal price in case of exporting).

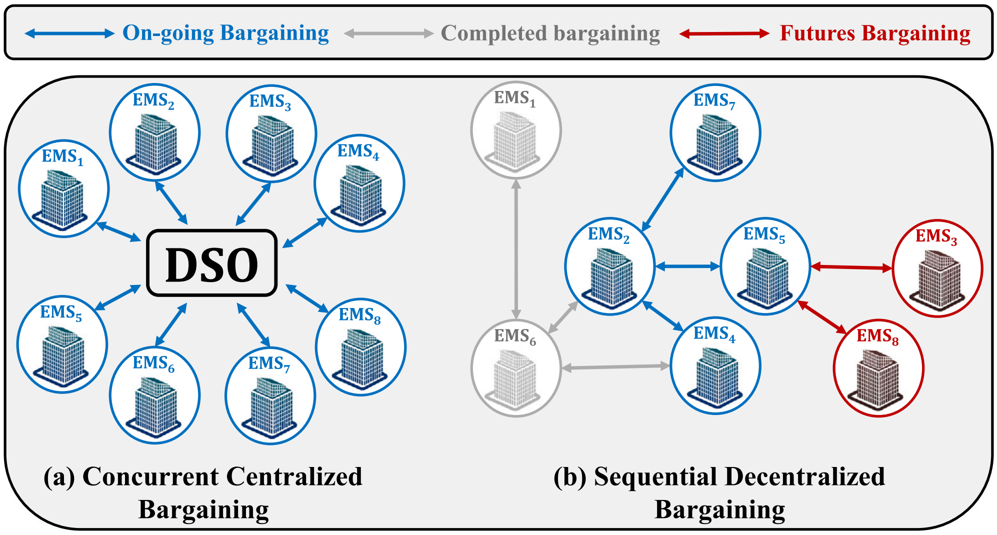


Fig. 1. Concurrent and sequential bargaining.

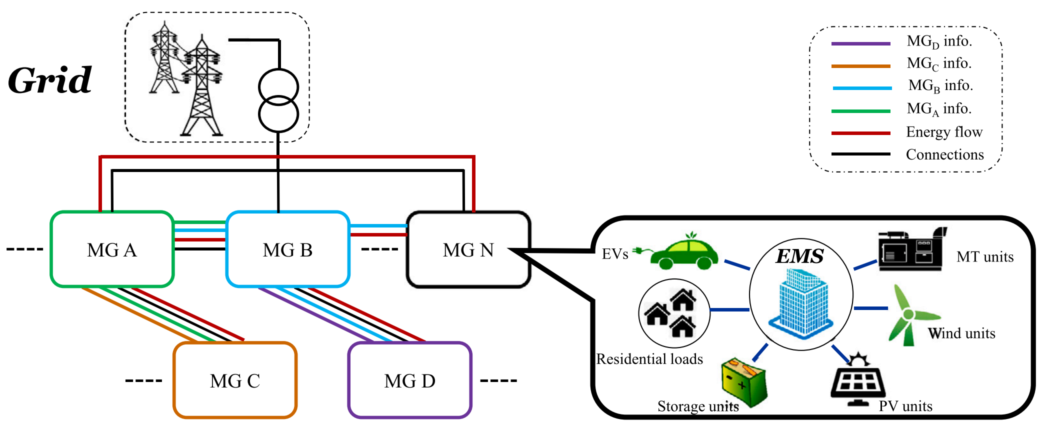


Fig. 2. IMG structure in decentralized framework.

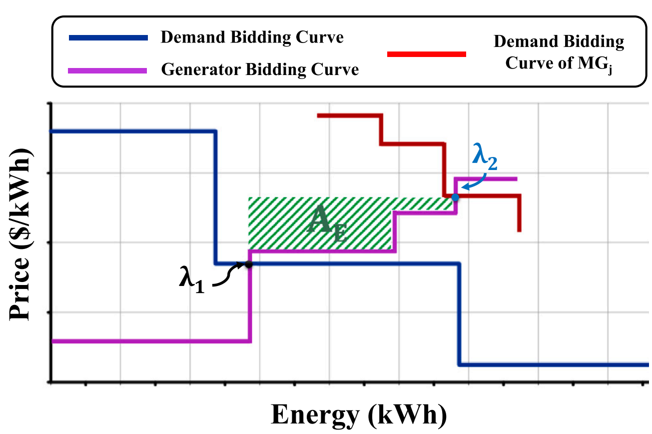


Fig. 3. Demand and generator with and without export.

This price (λ_2) in the receiving MG is higher than the internal MCP in the exporter MG and lower than the MCP in the importing MG.

The following assumptions are used in the proposed energy trading framework:

- Each MG is assigned only one mode of operation, either to export or to import through the same link.
- There are no restrictions on MGs' connections; they can be connected in series, parallel, or mesh.
- End-users and prosumers can submit their aggregated bidding and participate in their local market. The EMS of each MG can then use this data to bid in the IMGs' energy trading platform.
- Each MG can exchange data with its directly connected neighbours only.
- As greedy action from MGs is assumed, global equity of welfare is not guaranteed.

4.3. Sequential market settlements using #1-focused ranking algorithm

As mentioned in the previous subsection, the proposed decentralized energy trading algorithm is based on finding the MG with the lowest internal price (rank#1). Keep in mind that the information cannot be propagated more than one level (i.e., the MGs must be directly connected), for security and privacy concerns. A decentralized ranking algorithm is developed based on this assumption to identify rank#1 MG.

Considering a system with N microgrids, each microgrid MG_i solves the internal UMP market model to obtain its own uniform price (λ_i) and social welfare (SW_i). These data are broadcast to directly connected neighbours, along with the aggregated demand and generator biddings. The attribute-based rank r_{ij} is then calculated and broadcast, indicating the rank of MG_j as ranked by MG_i with respect to all MGs connected with MG_i. After receiving ranks r_{ij}, each MG can check its average rank to see if it is rank#1.

The pseudocode for the active thread at MG_i is shown in Fig. 4. Note that this thread exchanges information periodically. If the MG is rank#1, it executes a rank#1 passive thread. Otherwise, the MG has to wait for a pre-defined time T. This pre-defined time is set to allow exporter MGs to solve the optimization problem and send offers.

The rank#1 passive thread starts by deciding upon adopted and withhold offers. The feasible offers (i.e., those that improve the MG's social welfare) are committed, and the others are rejected. Afterwards, the MG runs the market-clearing optimization algorithm designed to maximize its export benefits. Finally, it sends offers to its neighbours and activates their offer-received flag (i.e., a flag to indicate if an MG has received offers).

It is worth noting that exporter MGs set their prices to a very high value after sending offers, as shown in Fig. 4, in order to be excluded from the next ranking round. If the offer-received flag is activated, the MG has to execute the rank#2 thread, and the MG_i that received offers has to adopt the feasible offers and withhold the other offers for further investigation in subsequent rounds. The adopted offers are used to update the MG's price, social welfare, and the generators' biddings before entering subsequent rounds. However, these offers are not firmed yet, as this MG may receive better offers in the next rounds. The presented procedures run until all the MGs receive rank#1, at which point all deals are firmed and the MGs exchange contracts for their commitments. The handling of these transactions in the blockchain layer is discussed in subsection E.

4.4. Sequential market using PR-focused ranking algorithm

The #1-focused rank algorithm suffers from time limitations when solving a system with a large number of participating MGs. Therefore, a PR-focused algorithm is proposed to overcome the limitations while promoting cheap energy trading. In a PR-focused algorithm, all MGs are divided into a definite number of price range clusters based on their internal prices; the group with the lower price range is selected to send offers to their neighbours in order to maximize their export benefit. All MGs in the lowest price group will send offers to their neighbours, so the grouping is based on price, not the connectivity of the system.

The main advantage of this method is that it can handle a large number of MGs efficiently in terms of computational time. However, the lowest-priced MG is not given the privilege to sell first; instead, the group with the lowest price range will sell simultaneously. All of the aforementioned assumptions are used here.

In this ranking algorithm, each MG is pre-assigned a number Q $\subset(0,\ N_{max})$, thus enabling it to calculate a sequence for its directly connected MGs (i.e., r_{ij}) according to their preassigned number Q. After settling the internal market model, each MG_i will calculate the attribute sequence (i.e., price sequence) for each directly connected MG. At this stage, every MG has two sequences: one for the pre-defined numbers, and the other for the prices. Then each MG exchanges its rank with its neighbouring MG with the highest gain. The exchange is performed based on an indicator called $gain$. For each MG, the gain between this MG and all its neighbours can be calculated using Eq. (1) [30].

$$Gain_{ij} = a_{ii}\ r_{ij} + a_{ij}\ r_{ii} - a_{ij}\ r_{ij} \qquad \forall j \in A_i \tag{1}$$

Where; a_{ii} is the self rank of microgrid i according to its internal price, a_{ij} is the sequence of all connected microgrids according to their internal prices, and A_i is all microgrids directly connected to microgrid MG i.

Once the exchange MG is found (the microgrid selected to exchange the self number Q which has highest $gain_{ij}$), MG i will exchange its number Q_i (i.e. self pre-assigned number of MG i) with Q_j (i.e. self pre-assigned number of the exchange MG j). It should be noted that this $gain_{ij}$ calculation is repeated until Q_i is not changed for any MG $\in A_i$. The clustering ratio (L) is the reciprocal of the number of clusters selected based on the computational power of the trading engine and the time limitations. Afterwards, each MG that passes the condition given in Eq. (2) sets itself to be in group#1. In so doing, it executes the group#1 passive thread and sends offers to its neighbours. Otherwise, the MG has to wait a pre-defined time T before repeating the process again.

Note that this pre-defined time is set to allow exporter MGs to solve the exporting optimization problem that maximizes its export benefits. The resultant offers are then sent to neighbouring MGs. Furthermore, note that L will determine whether we can use the #1-focused or the PR-focused algorithm. If reciprocal(L) >= the number of participating MGs, the #1-focused can be used; otherwise, the PR-focused has to be used.

$$Q_i \leq L\ N_{max} \tag{2}$$

For further illustration, the pseudocode for the active and passive threads are shown in Fig. 5.

4.5. Decentralized energy-trading monetary fund

In the authors' previous work [28], an adapted blockchain is used for establishing an energy-trading platform. However, a mandatory modification on the blockchain must be developed in order to handle the transactions in the proposed decentralized sequential trading platform. The main difference between centralized and decentralized trading is as follows:

- In the centralized platform, the offers sent by the central operator are firm and the global welfare equity is preserved. Thus, the MGs cannot reject any firmed offers.
- In the decentralized platform, as mentioned earlier, the MGs have the ability to accept/reject the withheld offers when it is their turn to export.

Therefore, the Double Signing Algorithm (DSA) is adopted in this paper to accurately log the transactions of the actual offers into the blockchain. This DSA requests the sender MG and recipient MG to sign on the transaction to ensure full acceptance of the offer and eliminate any third party. Any MG can participate in IMG energy trading simply by opening an MG wallet.

The main modification will be in creating unconfirmed transactions. So, any MG can send offers, and these offers will be listed as offered transactions and are signed by the sender MG only. Eventually, the recipient MG will approve a part or all of these transactions. The approved transaction will be listed as an unconfirmed transaction, later to be signed by both the sender and recipient (i.e., DSA). It is worth emphasizing that, similar to the approach in [28], the miners are the only authorized group that can approve these unconfirmed transactions. The process for creating these transactions is further explained using pseudocode in Fig. 6.

5. Decentralized platform optimization model

This section explains the mathematical formulation of the proposed energy trading framework. As mentioned earlier, the objective of the exporter MG is to maximize the Export Benefit (EB). This EB is defined by Eq. (3).

$$EB^i = \sum_{j}^{A_i} \sum_{r}^{G_E} \sum_{t}^{G_r} [PE^j_{i_{r,t}}\ (\lambda^i_{max} - \gamma E^i_{r,t})] \tag{3}$$

The objective function is subjected to the following constraints:

Pseudo-Code for active thread at MG_i

```
1  : Broadcast Di, Gi, λi, SWi      \\ Di , Gi denotes self aggregated demands' and generators' biddings
                                    \\ λi , SWi denotes internal uniform price and social welfare
2  : Read Dj, Gj, λj, SWj           \\ j denotes interconnected microgrids
3  : Rank rij                       ∀ j∈ Ai  \\ rij denotes rank of microgrid j that is ranked by microgrid I
4  : Broadcast ranks rij            ∀ j∈ Ai
5  : Receive ranks rji              ∀ j∈ Ai  \\ rji denotes rank of microgrid i that is ranked by microgrid j
6  : Average rank = Σj rji / Σj     ∀ j∈ Ai  \\ Ai denotes set of connected microgrids with Microgid I
7  : if  Average rank=1;
8         Execute rank#1 thread
9  : else
10 :      wait (T)                  \\ T denotes predefined waiting time
11 : end if
12 : if offer_receivedi =1          \\ offer_received denotes a flag for receiving offers
13 : Excute rank#2 thread
14 : end if
15 : Counter= counter+1
16 : if Counter = Nmax              \\ Nmax denotes maximum number of MGs
17 :      Reset
18 : end if
```

Pseudo-Code for Rank #1 thread at MG_i

```
1  : for l=1:k
2  :      for s=1:j
3  :           if offerls feasible
4  :                Commit offerls
5  :           else
6  :                Reject offerls
7  :           end if
8  :      end for
9  : end for
10 : Run P2
11 : Generate and broadcast offersmj'
12 : Send offer_receivedj' =1
13 : Set price = 1000
14 : Go to line 12 in active thread
```

Pseudo-Code for Rank #2 thread at MG_i

```
1  : read offersmj           \\ offersmj denotes block m
                                offered from microgrid j
2  :      for k=1: m
3  :           if offerkj feasible
4  :                Accept offerkj
5  :           else
6  :                Withhold offerkj
7  :           end if
8  :      end for
9  : Update (Gi, λi, SWi)
10 : set offer_received =0
```

Fig. 4. Pseudocode for sequential market clearing approach.

- Power balance constraint:
  This constraint ensures that demand and supply are balanced in each MG.

$$\sum_{s}^{D}\sum_{m}^{D_s} PD^i_{s,m} = \sum_{c}^{G}\sum_{k}^{G_c} PG^i_{c,k} + \sum_{j}^{A_i}\sum_{r}^{G_E}\sum_{t}^{G_r} PE^i_{j_{r,t}} \tag{4}$$

  The first term represents the internal demand of MG_i, the second term represents the internal generation, and the third term represents the imported energy from all the neighbouring MGs.
- Clearing constraints:
  These constraints ensure that the cleared demand and generation for each MG do not exceed their upper limits according to the bidding blocks.

$$0 \le PD^i_{s,m} \le \overline{PD}^i_{s,m} \tag{5}$$

$$0 \le PG^i_{c,k} \le \overline{PG}^i_{c,k} \tag{6}$$

The cleared exported energy from each MG does not exceed its upper limits assigned from the EMS of each MG.

$$0 \le PE^i_{r,t} \le \overline{PE}^i_{r,t} \tag{7}$$

The cleared exported energy is defined as the sum of all exported energy to the neighbouring MGs,

$$PE^i_{r,t} = \sum_{j}^{A_i} PE^j_{i_{r,t}} \tag{8}$$

The exported energy is set to zero if the block's price exceeds the imported MG internal price

$$\gamma E^i_{r,t} > \lambda^j_o \quad \rightarrow \quad PE^j_{i_{r,t}} = 0 \tag{9}$$

- Social welfare improvement constraint:
  This constraint reflects the greedy participation of MGs, as mentioned earlier. Each MG participates in the interconnected market if this will improve its own benefit, regardless of how it affects the others. Hence, the demand of each MG should not obtain a higher

Pseudo-Code for active thread at MG_i

Initialization at each MG_i

```
1  : Each MG participate has a pre-known Number Q ⊂ (0,N_max]
2  : Calculate sequence rij        \rij donates ordering of all connected microgirds according to their Q
```

Active thread at MG_i

```
1  : Broadcast D_i, G_i, λ_i, SW_i     \\ D_i , G_i denotes self aggregated demands' and generators' biddings
                                      \\ λ_i , SW_i denotes internal uniform price and social welfare
2  : Read D_j, G_j, λ_j, SW_j          \\ j denotes interconnected microgrids
3  : Calculate attribute based sequence aij  \\aij denotes sequence for all connected microgrids
                                              according to their prices
4  : Broadcast sequences r_ij and a_ij    ∀ j∈ A_i
5  : Receive sequences  r_ji  and a_j     ∀ j∈ A_i   \\ r_ji denotes rank of microgrid i that is ranked by
                                                        microgrid j
6  : Set gain_max to 0.
6  : for j ∈ A_i
7  : calculate gain_j
8  :      if gain_j > gain_max
9  :      gain_max ← gain_j
10 :      MG*_j ← MG_j
11 : end for
12 : Check if (a_i-a_j) (Q_i-Q_j) <0  for MG*_j
13 :            Q_i ← Q_j
14 : else if Q∈(1,2)& price =1000 ∀ j∈ Ai
15 :      Q_i ← Q_j (Guaranteed Swap)
16 : Set Guaranted swap flag_j =1
17 : end if
18 : Send(a_i,Q_i) to MG_j
19 : Execute passive thread Microgrid j
20 : if Q_i < L N_max
21 :        Set MG_i as seller MG.
22 :        Execute group#1 thread
23 : else
24 :        Set MG_i as buyer MG
25 :        if offer_received_i =1
26 :        Execute group#2 thread
27 :        else wait time = predefined_2
28 :        end if
```

Passive thread at MG_i

```
1  : Receive (a_j,Q_j) from MG_j
2  : Check if (a_i-a_j) (Q_i-Q_ij) <0 or
          Guaranteed swap flag_i =1
3  :          Q_i ← Q_j
4  : end if
5  : Go to line 1 in the active thread
```

Pseudo-Code for Group#1 thread at MG_i

```
1  : for l=1:k
2  :      for s=1:j
3  :               if offer_ls feasible
4  :                        Commit offer_ls
5  :               else
6  :                        Reject offer_ls
7  :               end if
8  :      end for
9  : end for
10 : Run Sequential Market Clearing mathematical algorithm
11 : Generate and broadcast offers_mj'
12 : Send offer_received_j' =1
13 : Set price = 1000
14 : Go to line 1 in active thread
```

Pseudo-Code for Group#2 thread at MG_i

```
1  : read offers_mj                 \\ offers_mj denotes block m
                                      offered from microgrid j
2  :      for k=1: m
3  :               if offer_kj feasible
4  :                        Accept offer_kj
5  :               else
6  :                        Withhold offer_kj
7  :               end if
8  :      end for
9  : Update (G_i, λ_i, SW_i)
10 : set offer_received =0
```

Fig. 5. Pseudocode for sequential PR-focused ranking algorithm.

price or receive less energy at the same price as its MCP after participating in the market. As the demand bidding curve of each MG is known, the price will be reduced or the demand covered will be increased if the social welfare of the MG after trading is greater than the social welfare calculated before trading.

$$SWE^i = \sum_{s}^{D}\sum_{m}^{D_i}[PD^i_{s,m}\,\gamma^i_{D_{s,m}}] - \sum_{c}^{G}\sum_{k}^{G_c}[PG^i_{c,k}\,\gamma^i_{G_{c,k}}] - \sum_{j}^{A_i}\sum_{r}^{G_E}\sum_{t}^{G_r}[PE^i_{j_{r,t}}\,\gamma E_{j_{r,t}}] \tag{10}$$

$$SWE^i \geq SW^i_o \tag{11}$$

- Trading conditions check:
Each importer MG applies this trading check in order to ensure that the MG is getting benefits from these offers. In order to pass this condition, the social welfare of the demand in addition to the social welfare of the internal generators should be higher than the social welfare before trading. This approach assumes that MGs do not favour any parties, generators or loads over each other.

$$SW^i_{D_{new}} + SW^i_{G_{new}} \geq SW^i_o \tag{12}$$

$$SW^i_{D_{new}} = \sum_{s}^{D}\sum_{m}^{D_i}[PD^i_{s,m}\,(\gamma^i_{D_{s,m}} - \gamma^i_{new})] \tag{13}$$

$$SW^i_{G_{new}} = \sum_{c}^{G}\sum_{k}^{G_c}[PG^i_{c,k}\,(\gamma^i_{new} - \gamma^i_{G_{c,k}})] \tag{14}$$

6. Case studies

The proposed energy trading platforms were implemented and tested assuming a number of IMGs with different generators and demand biddings. Each MG is assumed to have the layout of the IEEE 906 European low-voltage test system with 55 loads and 4 generators.

Table 1
Internal Data for MGs.

	MG-T1	MG-T2	MG-T3	MG-T4
Uniform Price (\$/kWh)	0.065	0.0285	0.1047	0.1024
Social Welfare (\$)	19.3084	26.905	1.903	2.02628
Demand Covered (kWh)	218	428.032	69.734	68.518

Pseudo-Code for Creating unconfirmed transactions

```
: Receive request for creating transaction
: if      Sender's ID & Recipient's ID ϵ MG wallet's ID
:         initiate Check#1
:         if check#1 = 0
:                   break
:         else if check#1=1
:                   create offered transactions
:         else if check#1=2
:                   create unconfirmed transactions
:         end if
:end if
```

Pseudo-Code for check#1 thread

```
: if transactions ⊂ offered transaction
:         if transaction double signed
:         return 2
:         else
:         return 0
: else if transactions ⊄ offered transaction
:         if sender signed
:         return 1
:         else
:         return 0
: end if
```

Fig. 6. Psuedocode for creating unconfirmed transactions.

Two case studies are proposed in this section. In the first case, four interconnected MGs are considered to participate in energy trading using #1-focused sequential clearing approach. In the second case study, eight MGs are admitted to participate in the framework using the PR-focused sequential clearing approach. The proposed framework is assumed to be solved on an hourly basis.

Table 1 shows the solution for the UMP model inside each MG assuming isolated operation, i.e., no trading, in order to highlight the differences between these MGs and to be a benchmark for comparisons and discussions. The table presents their internal uniform price, social welfare, and total demand covered at this price. The generator and load bidding for each MG is given as three different blocks of price/power pairs (i.e., B1, B2, and B3).

6.1. #1-Focused sequential market clearing

The MGs presented in Table 1 are considered for applying the proposed sequential market clearing. In this model, we define two processes: (1) Ranking, in which the ranking algorithm mentioned above is used to find the rank#1 MG that will be exporting to its neighbours and firming any withheld or adopted offers and (2) Offers, in which the rank#1 MG solves an optimization problem to maximize its export benefits and send offers to neighbouring MGs. These processes of Ranking and Offers are run in rounds, with the rank#1 MG selected as the exporter. After each round, the selected MG is eliminated, and the ranking algorithm is run to select the next exporter. In this case study, a fully-connected network is assumed, with each MG assumed to have a connection with all other MGs. The objective function for the exporter MG is modelled as maximizing the export benefit according to the following problem:

$$\max(EB^i)$$
$$s.t.$$
$$Eqn.(4)-(11)$$

Note that the exporter MG has to run the trading condition check modelled by Eq. (12) in order to accept or reject the withheld offers.

6.1.1. First round

The #1-focused ranking algorithm is performed to identify the rank#1 MG. Based on the prices shown in Table 1, MG-T2 is selected to export. The optimization problem solution shows that each MG will import from MG-T2. Then each MG runs its own UMP model to adopt or withheld offers. However, no offers are rejected from round 1, as shown in Table 2.

Although the price of the MG-T1 remains constant after round#1, the total demand covered with the same price increased by 62%. For MG-T3 and MG-T4, the price and the total demand covered remain constant, but the effective social welfare increased. This indicates that the exporter generators offered lower prices compared to the importer's internal generators; therefore, these offers are being withheld. After this stage, MG-T2 is eliminated from the platform and the ranking algorithm is re-run. MG-T1 is selected as rank#1 to export in the next round, as shown in Table 2.

6.1.2. Second round

In round 2, MG-T3 and MG-T4 are found to be importers of energy from MG-T1. However, both MGs have rejected infeasible offers from the offered energy, as indicated in Table 2. Moreover, the price of energy in both MGs is reduced and the total demand covered is increased, so at this stage MG-T1 is eliminated from the subsequent rounds. Finally, MG-T3 is selected to be rank#1 after running the ranking algorithm.

6.1.3. Third round

MG-T4 was found to be importing energy in round 3, as demonstrated in Table 2. However, MG-T4 rejected offers received from MG-T3 after running the internal UMP model.

6.1.4. Fourth round

In round 4, although MG-T4 is rank#1, no feasible export can be found because other MGs already have lower prices, as shown in Table 2.

6.2. PR-focused sequential market clearing

The energy trading framework has been further tested using the proposed PR-focused clearing approach. The same MG types shown in Table 1 have been adopted in this case study. However, the connectivity of the MGs is different, with eight MGs assumed to be connected according to the connection shown in Fig. 7. In addition, the same definitions for offers and ranking processes are used in this case study. The proposed sequential market using a PR-focused algorithm has been executed assuming clustering of the participating MGs into four clusters (i.e., L = 0.25).

Table 2
Sequential Market Clearing Results Using #1-Focused.

		MG T1	MG T2	MG T3	MG T4
Round #1	Price	0.065 $/kW	0.0285 $/kW	0.1047 $/kW	0.1024 $/kW
Round #1	Social welfare	19.3084	26.90522	1.903386	2.02628
Round #1	Total Demand covered	218 kW	428.032 kW	69.734 kW	68.518 kW
Round #1	Rank #1		x		
Offers #1	Available offers from Rank #1	135.816	N/A	61.077	21.102
Offers #1	MG Eliminated		x		
Round #2	Price	0.065 $/kW	Eliminated	0.1047 $/kW	0.1024 $/kW
Round #2	SWE	23.257	Eliminated	2.145	3.428
Round #2	Total Demand Covered	353.816 kW	Eliminated	69.734 kW	68.518 kW
Round #2	Trading Condition	Pass	Eliminated	Fail	Fail
Round #2	Offers	Accepted	Eliminated	Withhold	Withhold
Round #2	Rank #1	x	Eliminated		
Offers #2	Available offers from Rank #1	N/A	N/A	345.163	273.837
Offers #2	MG Eliminated	x			
		MG T1	**MG T2**	**MG T3**	**MG T4**
Round #3	Price	Eliminated	Eliminated	0.081 $/kW	0.088 $/kW
Round #3	SWE	Eliminated	Eliminated	7.059	6.577
Round #3	Total Demand Covered	Eliminated	Eliminated	208.178 kW	205.08 kW
Round #3	Trading Condition	Eliminated	Eliminated	Pass	Pass
Round #3	Offers	Eliminated	Eliminated	Rejected 138.062 kW	Rejected 89.888 kW
Round #3	Withhold offers	Eliminated	Eliminated	Rejected 60 kW	Accepted
Round #3	Rank #1	Eliminated	Eliminated	x	
Offers #3	Available offers from Rank #1			N/A	0.025
Offers #3	MG Eliminated			x	
Round #4	Price	Eliminated	Eliminated	Eliminated	0.088 $/kW
Round #4	SWE	Eliminated	Eliminated	Eliminated	6.577
Round #4	Total Demand covered	Eliminated	Eliminated	Eliminated	205.08 kW
Round #4	Trading Condition	Eliminated	Eliminated	Eliminated	Fail
Round #4	Offers	Eliminated	Eliminated	Eliminated	Rejected
Round #4	Rank 1	Eliminated	Eliminated	Eliminated	x

6.2.1. First round

In round 1, both MG-T2_ID1 and MG-T2_ID2 are found to be group#1 based on their internal prices, as shown in Table 3. These MGs then send trading offers to their neighbours based on the connectivity of the network. It is worth noting that these offers are generated to maximize the export benefit of exporter MGs. Therefore, MG-T2_ID1 has sent offers to MG-T1_ID1 and MG-T1_ID2. Given that those MGs are identical, they received the same offers. On the other hand, MG-T2_ID2 has sent more offers, as it is connected to three MGs. At this stage, group#1 MGs are eliminated from the energy trading.

6.2.2. Second round

In round 2, MG-T1_ID1 and MG-T1_ID2 are found to be the exporters. Therefore, they cleared all withheld offers and generated offers to their neighbours. As a result, utilizing the offers approved by MG-T1_ID2, the internal price dropped to 0.036 $/kW, as shown in Table 3. However, the price in the ID1 did not change, as it was not involved in round 1. MG-T1_ID1 sent offers to MG-T3_ID1. Also, MG-T1_ID2 sent offers to MG-T4_ID1 and MG-T4_ID2, as is illustrated in Table 3.

6.2.3. Third round

Four remaining MGs participated in round 3, as shown in Table 3. As a result of importing low-priced power, the price of MG-T3_ID1 is dropped by 27.4%. Additionally, the price of MG-T4_ID1 is dropped by 17%. This drop allows these two MGs to be selected in group#1. It is worth noting that both of these MGs have accepted some of the offers and rejected the rest, as shown in Table 3. It was not feasible for MG-T3_ID1 to generate any offers, as its neighbours have a lower internal price. Meanwhile, MG-T4_ID1 sent offers to MG-T3_ID2.

6.2.4. Fourth round

The remaining MGs settled their prices, as shown in Table 3. MG-T3_ID2 rejected all the offers because they could not pass the trading

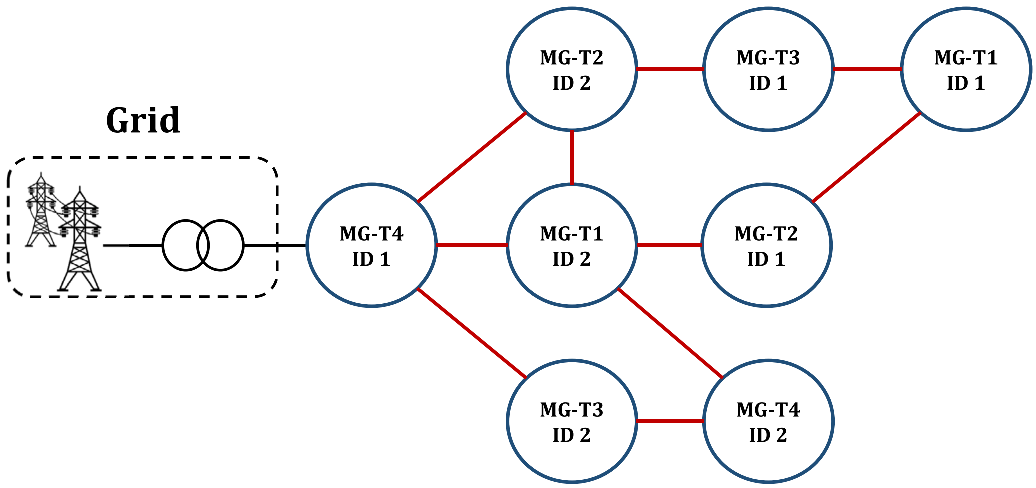
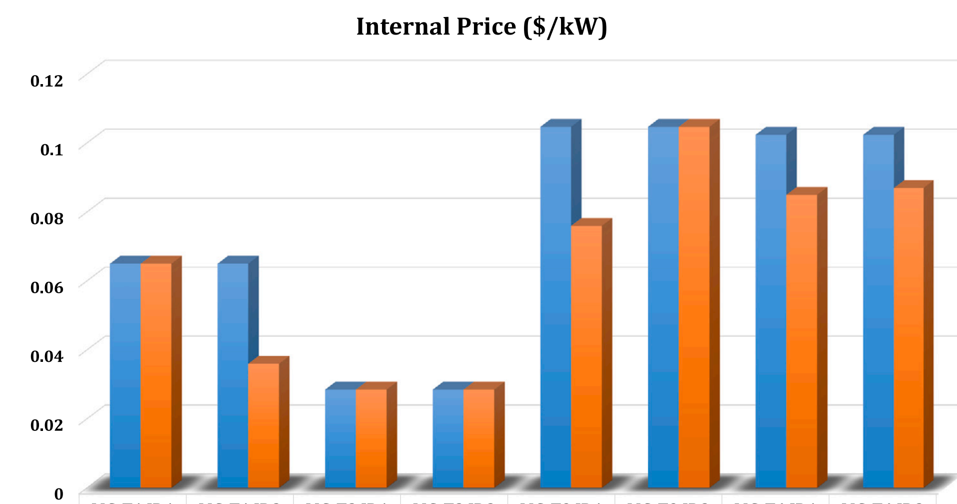


Fig. 7. Microgrid connectivity.



	MG-T1 ID1	MG-T1 ID2	MG-T2 ID1	MG-T2 ID2	MG-T3 ID1	MG-T3 ID2	MG-T4 ID1	MG-T4 ID2
Before	0.065	0.065	0.0285	0.0285	0.1047	0.1047	0.1024	0.1024
After	0.065	0.036	0.0285	0.0285	0.076	0.1047	0.085	0.087

Fig. 8. Internal Prices before and after energy trading.

conditions of the MG. Although the number of MGs in this case study is doubled, the time consumed to settle the market remains the same. For further demonstrations, the internal prices before and after energy trading are illustrated in Fig. 8. The prices have remained constant for the MGs with the lowest prices (i.e. MG-T2_ID1 and MG-T2_ID2). Also, the price was not changed for MG-T1_ID1 as it is consuming power at the same price. As a result of not accepting any offers, the price remained constant for MG-T3_ID2. On the other hand, the prices have changed for importer MGs (i.e., MG-T1_ID2, MG-T3_ID1, MG-T4_ID1, and MG-T4_ID2), which prove the efficiency of the proposed energy trading concept.

The effect of the proposed energy trading algorithm on the total demand covered in each MG is shown in Fig. 9. As expected, the demand is constant for the lowest-priced MGs. Also, the demand is constant for MG-T3_ID2 as it did not import any power. It is worth noting that MG-T3_ID2 is connected to two MGs with high prices, as shown in Fig. 7; thus, it could not import any cheap energy from its neighbours. As a result, MG-T3_ID2 did not benefit from energy trading in this case.

On the contrary, the total demand covered in MG-T1_ID2 is almost doubled at a low price as it is located between two MGs with very low prices and available sources. Although the internal price of MG-T1_ID1 remained the same, the total demand covered increased by almost 20%. The total demand covered is almost tripled for the high-priced MGs, proving the effectiveness of the proposed method.

The effect of the energy trading platform on the internal generation units is shown in Fig. 10. As expected, the internal generation units in the high-priced MGs are not dispatched after market settlement. Nevertheless, due to applying the trading condition discussed before, that is not guaranteed as in MG-T3_ID2.

The total exported power from each MG participating in energy trading is shown in Fig. 11. MG-T1_ID2 has the most considerable export power among all MGs because it is connected to low-priced MGs and high priced ones. Therefore, it is imported low-priced power for internal use and exported its surplus to the high-priced MGs. It can be seen that MG-T2_ID1 has slightly higher export power than MG-T2_ID2; this happened because MG-T2_ID1 is connected to more MGs; thus, its ability to export becomes higher. It goes without saying that export's ability is much less in case of high prices, as shown in Fig. 11.

Furthermore, the export benefits gained for all MGs are illustrated in Fig. 12. It can be concluded that the export benefits follow the same pattern of export power; however, this might not always be the case.

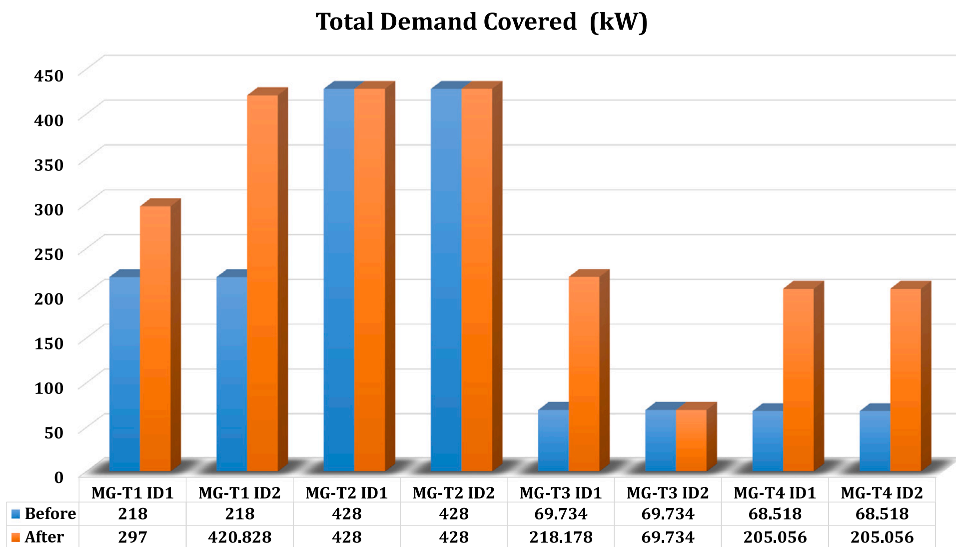


Fig. 9. Total Demand covered before and after energy trading.

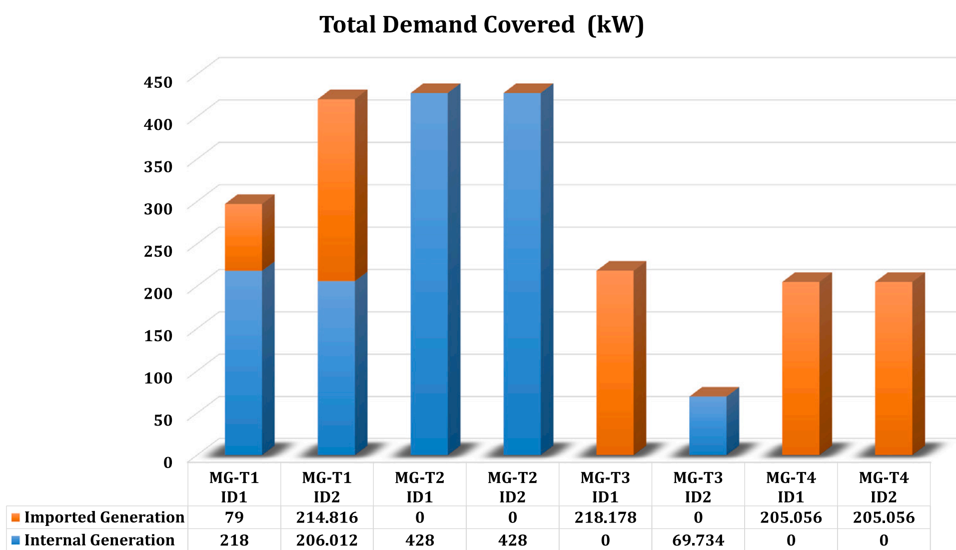


Fig. 10. Internal and imported generation after energy trading.

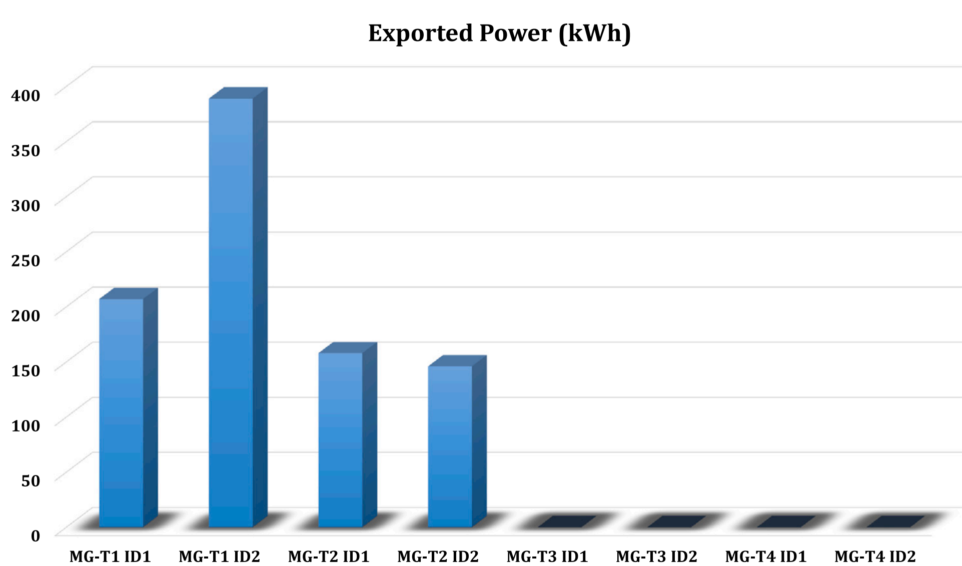


Fig. 11. Total exported power.

Table 3
Sequential Market Clearing Results Using PR-Focused (L = 0.25).

		MG-T1_ID1	MG-T1_ID 2	MG-T2_ID 1	MG-T2_ID 2	MG-T3_ID 1	MG-T3_ID 2	MG-T4_ID 1	MG-T4_ID 2
Round #1	Price	0.065 $/kW	0.065 $/kW	0.0285 $/kW	0.0285 $/kW	0.1047 $/kW	0.1047 $/kW	0.1024 $/kW	0.1024 $/kW
	Social welfare	19.3084	19.3084	26.90522	26.90522	1.903386	1.903386	2.02628	2.02628
	Total Demand covered	218 kW	218 kW	428.032 kW	428.032 kW	69.734 kW	69.734 kW	68.518 kW	68.518 kW
	Sellers			x	x				
Offers #1	Available offers from Sellers	79 kW from MG-T2_ID1	79 kW from MG-T2_ID1	N/A	N/A	61.077 kW from MG-T2_ID2	N/A	21.107 kW from MG-T2_ID2	N/A
			135.816 kW from MG-T2_ID2						
	MG Eliminated			x	x				
Round #2	Price	0.065 $/kW	0.036 $/kW	Eliminated	Eliminated	0.1047 $/kW	0.1047 $/kW	0.1024 $/kW	0.1024 $/kW
	Social welfare	21.614	25.205			1.903386	1.903386	2.02628	2.02628
	Trading Conditions	Pass	Pass			Fail	N/A	Fail	N/A
	Rejected offers	N/A	Rejected 11.988 from MG-T2_ID2			N/A	N/A	N/A	N/A
	Withhold Offers	N/A	N/A			61.077 kW from MG-T2_ID2	N/A	21.107 kW from MG-T2_ID2	N/A
	Total Demand covered	297 KW				69.734 kW	69.734 kW	68.518 kW	68.518 kW
	Sellers	x	x						
Offers #2	Available offers from Sellers	N/A	N/A	Eliminated	Eliminated	428.716 kW from MG-T1_ID1	N/A	213.89 kW from MG-T1_ID2	213.89 kW from MG-T1_ID2
	MG Eliminated	x	x						
		MG-T1_ID1	**MG-T1_ID 2**	**MG-T2_ID 1**	**MG-T2_ID 2**	**MG-T3_ID 1**	**MG-T3_ID 2**	**MG-T4_ID 1**	**MG-T4_ID 2**
Round #3	Price	Eliminated	Eliminated	Eliminated	Eliminated	0.076 $/kW	0.1047 $/kW	0.085 $/kW	0.087 $/kW
	Social welfare					7.474	1.903386	7.36	6.322
	Trading Conditions					Pass	N/A	Pass	Pass
	Rejected offers					Rejected 221.615 kW from MG-T1 ID 1	N/A	Rejected 29.941 kW from MG-T1 ID 2	Rejected 8.834 kW from MG-T1 ID 2
	Withhold Offers					Rejected 60 kW from MG-T2 ID 2	N/A	Accepted 21.107 kW from MG-T2_ID2	N/A
	Total Demand covered					218.178 kW	69.734 kW	205.056 kW	205.056 kW
	Sellers					x		x	
Offers #3	Available offers from Sellers	Eliminated	Eliminated	Eliminated	Eliminated	N/A	74 kW from MG-T4_ID1	N/A	0
	MG Eliminated					x		x	
Round #4	Price	Eliminated	Eliminated	Eliminated	Eliminated	Eliminated	0.1047 $/kW	Eliminated	0.087 $/kW
	Social welfare						1.903386		6.322
	Trading Conditions						Fail		N/A
	Rejected offers						74 kW from MG-T4_ID1		N/A
	Withhold Offers						N/A		N/A
	Total Demand covered						69.734 kW		205.056 kW
	Sellers								x
Offers #4	Available offers from Sellers	Eliminated	Eliminated	Eliminated	Eliminated	Eliminated	0	Eliminated	N/A
	MG Eliminated								x

The export benefits in this platform depend on the market settlement in the importer MG.

6.2.5. Ranking execution

The PR-focused ranking algorithm was run through out the market clearing. The numbers Qi was swapped smoothly and efficiently between MGs which proves the effectiveness of the proposed ranking algorithm. Table 4 illustrate the swapping of the numbers.

6.3. Computational time

The proposed framework was tested on a PC with the following specifications: Intel® Core™ i5-8250U/8 / 1.60 GHz - Hash rate = 584 h/s. A breakdown of the computational time for rank#1, and PR-Focused algorithms is detailed in Table 5.

6.4. Sequential market solution versus Nash solution

The output from the proposed sequential clearing algorithm using #1-focused is compared with the Nash solution provided in [31]. As illustrated in Table 6, the total demand in each case is almost the same using both frameworks. Also, MG-T2 has a lower export value in the decentralized, because of the greedy decision from MG-T1, which rejected offers from MG-T2, however, that is not possible using the Nash framework. On the other hand, the exported power increased in the decentralized technique for MG-T1, because it imported from cheap

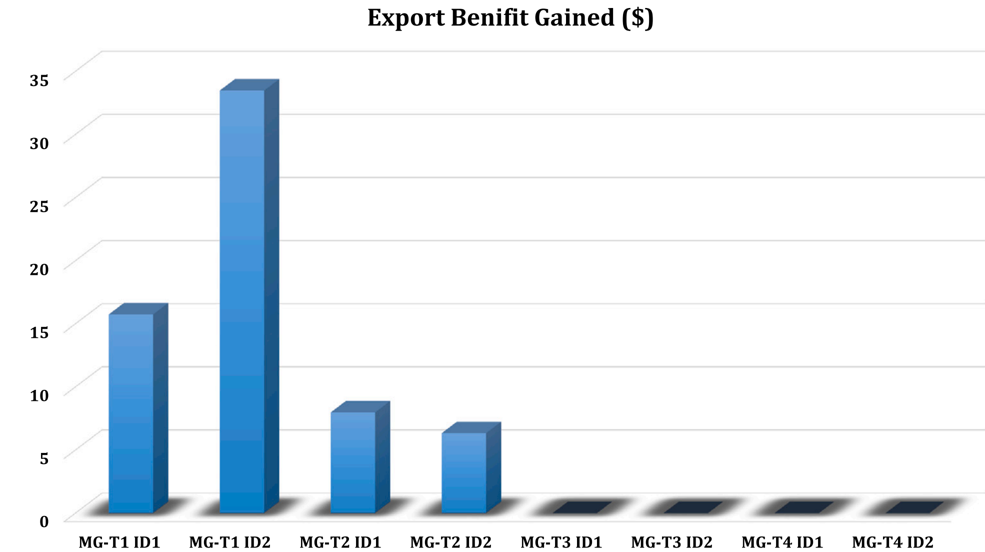


Fig. 12. Export benefits gained.

Table 4
PR-focused Q swapping.

Time →

Microgrid Name	Node code	Qi-Initiation	Qi-gain swab (e-h)	Qi-gain swab (d-f)	Qi-gain swab (b-e)		Qi-gain swab (d-f)	Qi-gain swab (b-a)	Qi-gain swab (a-e)		Qi-gain swab (c-d)	Qi-gain swab (a-e)	Qi-gain swab (h-e)		Qi-Guaranteed swap (c-d)	Qi-Guaranteed swap (d-f)	Qi-Guaranteed swap (f-e)	Qi-gain swab (e-h)	Qi-gain swab (a-g)	
T4 ID1	a	4	4	4	4	Offers #1 starts	4	1	3	Offers #2 starts	3	1	1	Offers #3 starts	1	1	1	1	6	Offers #4starts
T2 ID2	b	3	3	3	1		1	4	4		4	4	4		4	4	4	4	4	
T3 ID1	c	8	8	8	8		8	8	8		2	2	2		8	8	8	8	8	
T1 ID1	d	2	2	7	7		2	2	2		8	8	8		2	7	7	7	7	
T1 ID2	e	5	1	1	3		3	3	1		1	3	5		5	5	2	3	3	
T2 ID1	f	7	7	2	2		7	7	7		7	7	7		7	2	5	5	5	
T3 ID2	g	6	6	6	6		6	6	6		6	6	6		6	6	6	6	1	
T4 ID2	h	1	5	5	5		5	5	5		5	5	3		3	3	3	2	2	

Table 5
Execution Time for different case studies.

	Four MGs using Rank#1 algorithm	Eight MGs using Rank#1 algorithm	Eight MGs using PR-focused algorithm
Ranking time	20.1 seconds	40.3 seconds	22.5 seconds
Generating offers	2 seconds	2 seconds	2 seconds
Total time for ranking and generating offers	22.1 seconds	42.3 seconds	24.5 seconds

energy and exported its internally generated power on the next round, as demonstrated earlier. It is worth mentioning that the internal price for MG-T3 and MG-T4 is less in the decentralized case as it imported more power from MG-T1 with better prices. Nevertheless, it can be concluded that the decentralized technique solution is very close to the centralized Nash one.

7. Monetary fund verification

In order to verify the proposed blockchain modifications, Python was used to code the blockchain. The coded blockchain succeeded in creating both the offered transactions and the unconfirmed transactions. A sample of the transactions recorded in the blockchain is

Table 6
Comparison between #1-focused and Nash solution.

	MG-T1		MG-T2		MG-T3		MG-T4	
	D-#1-focused[1]	C-Nash[2]	D-#1-focused	C-Nash	D-#1-focused	C-Nash	D-#1-focused	C-Nash
Exported Energy	391.05 kW	299.388 kW	157.995 kW	218.962 kW	0	0	0	0
Imported Energy	135.816 kW	105.116 kW	0	0	208.178 kW	208.178 kW	205.056 kW	205.056 kW
Effective Social Welfare	$23.257	$23.239	$26.905	$26.950	$7.059	$7	$6.577	$7.127
Export revenue	$32.96	$30.539	$10.772	$18.445	0	0	0	0
Demand Covered	353.816 kW	323.116 kW	428.032 kW	428.032 kW	208.178 kW	208.178 kW	205.056 kW	205.056 kW
Import/Export	**E & I**	**E & I**	**E**	**E**	**I**	**I**	**I**	**I**
Internal Price	0.065 $/kW	0.065 $/kW	0.0285 $/kW	0.0285 $/kW	0.081 $/kW	0.102 $/kW	0.088 $/kW	0.102 $/kW

[1] Decentralized based on #1-focused model
[2] Centralized based on Nash model

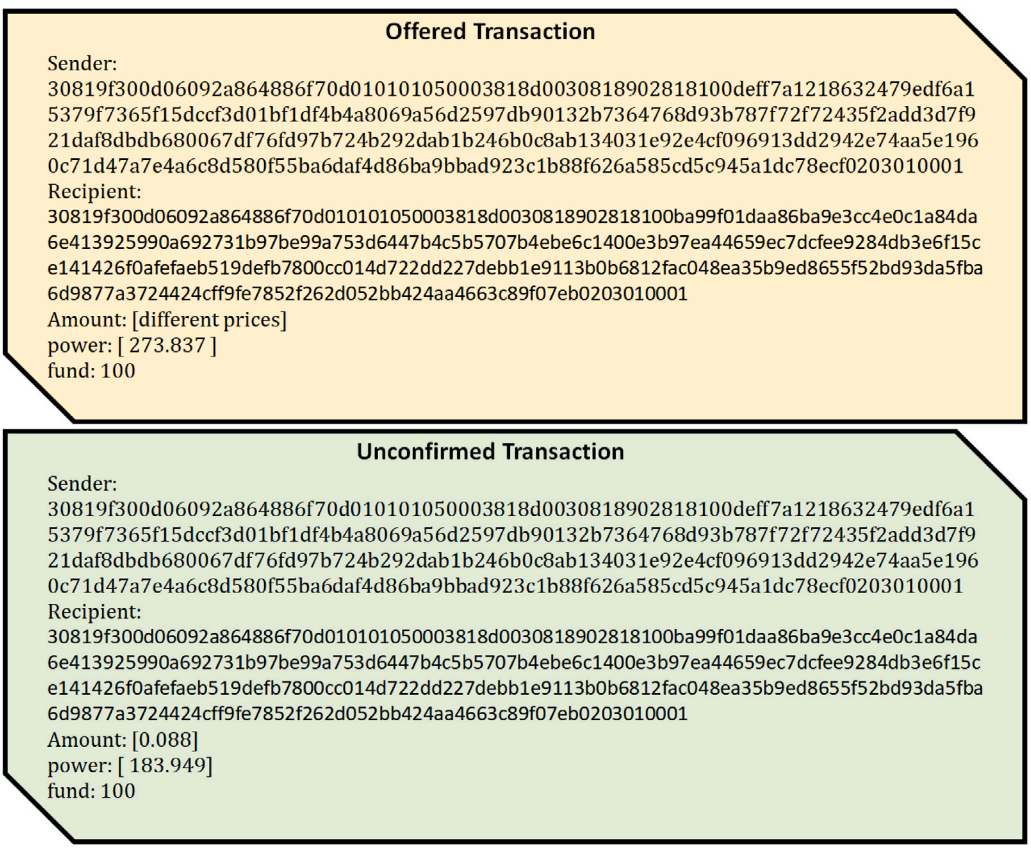


Fig. 13. Offered and unconfirmed transaction sample.

shown in Fig. 13. As can be seen, the total transaction was 273.837 kW between MG-T1 and MG-T4, and the coded blockchain succeeded in allowing the recipient MG (i.e., MG-T4) to reject 89.888 kW, as requested (please refer to Table 2).

8. Conclusion

This paper proposed a novel decentralized energy trading platform for IMGs. The proposed platform is based on a sequential market clearing approach to give the MG with the cheapest energy price the advantage of maximizing its benefit by exporting its cheap surplus power to directly connected MGs. The selection of this MG is done in a decentralized fashion using two ranking algorithms. The first one is called rank#1 and is suitable for a low number of MGs. The other algorithm is called multi-round and has been developed for a high number of MGs.

Table A.7
Generator Offers in MGs.

Generator	MG T1					
	Block 1		Block 2		Block 3	
	Quantity $\overline{PG_{s,1}^{1}}$	Price $\gamma G_{s,1}^{1}$	Quantity $\overline{PG_{s,2}^{1}}$	Price $\gamma G_{s,2}^{1}$	Quantity $\overline{PG_{s,3}^{1}}$	Price $\gamma G_{s,3}^{1}$
G1	70	0.071	67	0.077	66	0.087
G2	70	0.035	78	0.081	69	0.088
G3	70	0.010	62	0.076	53	0.085
G4	78	0.004	76	0.067	68	0.092
	MG T2					
	Block 1		Block 2		Block 3	
	Quantity $\overline{PG_{s,1}^{2}}$	Price $\gamma G_{s,1}^{2}$	Quantity $\overline{PG_{s,2}^{2}}$	Price $\gamma G_{s,2}^{2}$	Quantity $\overline{PG_{s,3}^{2}}$	Price $\gamma G_{s,3}^{2}$
G1	75	0.020	78	0.036	57	0.108
G2	60	0.023	66	0.028	62	0.105
G3	78	0.026	80	0.036	60	0.102
G4	74	0.012	76	0.024	60	0.107
	MG T3					
	Block 1		Block 2		Block 3	
	Quantity $\overline{PG_{s,1}^{3}}$	Price $\gamma G_{s,1}^{3}$	Quantity $\overline{PG_{s,2}^{3}}$	Price $\gamma G_{s,2}^{3}$	Quantity $\overline{PG_{s,3}^{3}}$	Price $\gamma G_{s,3}^{3}$
G1	61	0.114	64	0.138	59	0.142
G2	77	0.105	75	0.124	62	0.152
G3	76	0.107	74	0.123	52	0.151
G4	69	0.110	63	0.136	58	0.155
	MG T4					
	Block 1		Block 2		Block 3	
	Quantity $\overline{PG_{s,1}^{4}}$	Price $\gamma G_{s,1}^{4}$	Quantity $\overline{PG_{s,2}^{4}}$	Price $\gamma G_{s,2}^{4}$	Quantity $\overline{PG_{s,3}^{4}}$	Price $\gamma G_{s,3}^{4}$
G1	60	0.107	79	0.134	61	0.144
G2	73	0.113	77	0.134	68	0.148
G3	74	0.102	70	0.122	68	0.145
G4	66	0.119	62	0.138	55	0.150

Note: All quantities data are in kWh, and energy prices are in $/kWh

This platform was tested through the implementation of the proposed algorithms and mounted on different software packages, including MATLAB, GAMS, and Python. The results show that the proposed algorithm can achieve valid results. Furthermore, the proposed algorithm promotes the independent operation of the MGS and ensures that each one can participate in the market following its own SBD actions. Additionally, two different ranking algorithms to handle a small number of MGs with high accuracy as well as a high number of MGs with lower accuracy are proposed. Therefore, there is no limit on the number of MGs. However, the limitation of this work is its need for a secure communication network, smart meters infrastructure for all customers, and a bidding smart agent that can generate the bidding curve for each participant. Ultimately, all the MGs gained benefits from the trading, and the global welfare was improved.

CRediT authorship contribution statement

Mohamed R. Hamouda: Conceptualization, Methodology/Study design, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Mohamed E. Nassar:** Conceptualization, Methodology/Study design, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision. **M.M.A. Salama:** Conceptualization, Methodology/Study design, Validation, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Generator bidding data

The parameters that have been utilized in the case studies for The generators biddings' limits are shown in Table A.7.

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