INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. Zhanbolatov et al., Vol.12, No.3, September, 2022

# Blockchain-Based Decentralized Peer-to-Peer Negawatt Trading in Demand-Side Flexibility Driven Transactive Energy System

Arshyn Zhanbolatov[1], Svetlana Zhakiyeva [2,*], Nurkhat Zhakiyev [1,3], Korhan Kayisli [3,*]

[1] Department of Science and Innovation, Astana IT University, Nur-Sultan, Kazakhstan

[2] Department of Mathematical and Computer Modeling, L.N. Gumilyov Eurasian National University,

Nur-Sultan, Kazakhstan

[3] Department of Electrical-Electronic Engineering, Engineering Faculty, Gazi University, Ankara, Turkey

Corresponding authors: (zhakiyevas@gmail.com, korhankayisli@gazi.edu.tr )

*Received: 15.06.2022 Accepted: 08.08.2022*

**Abstract-** Growing flexibility from demand-side resources and advancements in distributed ledger technology has opened a wide array of opportunities for peer-to-peer negawatt trading. However, while peer-to-peer energy trading has been extensively studied in the research community, peer-to-peer negawatt trading is only yet being explored. This work presents a conceptual design of a blockchain-based decentralized peer-to-peer negawatt trading platform. It includes an auction mechanism where the winner determination problem is formulated as a fractional knapsack problem, and a greedy algorithm is used to find the optimal solution that minimizes social cost. Furthermore, truthfulness and individual rationality are ensured by applying Vickrey–Clarke–Groves payment scheme. A simulation setup is implemented on the Ethereum blockchain to model the peer-to-peer negawatt trading in a demand-side flexibility-driven transactive energy system. Case studies show that the proposed market mechanism achieves better economic efficiency compared to the existing method.

**Keywords-** Transactive Energy System, Demand-Side Flexibility, Peer-to-Peer Negawatt Trading, Blockchain-Based Decentralized Application, Vickrey–Clarke–Groves Auction.

## 1. Introduction

Most of the challenges in power system operation are driven by the task of matching demand and supply at all times to ensure grid stability and reliability [1]. The GridWise Architecture Council [2] defines transactive energy as “a set of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.” One of the underlying features of transactive energy is the concept of demand response (DR) which refers to the programs targeted at encouraging short-term reductions in energy demand from consumers during on-peak periods. DR draws on demand-side flexibility, which refers to the portion of the demand in the system that can be either curtailed or shifted. The former is offered by low-priority loads (e.g., lighting and HVAC) that can be either partially or entirely turned off, and the latter is offered by shiftable loads (e.g., washing machines) that can be transferred across time slots. In the context of incentive-based DR programs, voluntary rationing is realized by incentive payments where the consumers’ primary motive is to earn a financial reward in exchange for the temporary inconveniences. However, these programs are typically managed by the grid, giving little to no room for the consumers’ contribution to payment decisions resulting in insufficient incentives and ensuing low participation [3].

In the late eighties, Lovins [4] introduced the concept of negawatt trading, where the energy saved, negawatts, are treated as fungible commodities and, similar to that produced by distributed generators, can be subject to competitive bidding and secondary markets. In contrast to conventional DR programs, negawatt markets can give consumers needed freedom in deciding the selling price and in choosing with whom they want to trade, i.e., whether with the grid or with neighbouring consumers via peer-to-peer platforms. At this point, it is essential to note that, unlike peer-to-peer energy trading, negawatt trading does not envisage generation and physical exchange of energy. Therefore, it is cheaper and safer for the electricity network. However, while the former phenomenon has been extensively studied in the research community, the latter is something that is only yet being explored.

To integrate negawatt markets into a power system, there should be means for suitable market mechanisms and fair pricing schemes [5]. Although the market prices for watts have an influence on that of negawatts, the former doesn't completely determine the latter [6-7]. Thus, novel specific market mechanisms and pricing schemes should be designed to include economically efficient negawatt trading. Tomic [8] evaluated a hierarchical market architecture for trading watts and negawatts based on forecasted generation and consumption. Incorporating demand response aggregators to negawatt markets was considered in [9-10]. Distributed incentive design method to minimize power adjustment cost in negawatt trading was presented in [11-12]. Azim and Tushar [13] proposed a peer-to-peer negawatt market framework based on a rule-driven algorithm. In recent years, the game-theoretic approaches have gained interest in the context of peer-to-peer trading as they have a great perspective to be used in energy sharing, including both watts and negawatts [14-15]. A design of a coalition game-based peer-to-peer negawatt trading framework was presented in [16].

Apart from market mechanisms and pricing schemes, secure communication and information systems are needed to integrate the consumers with the market mechanism and provide access to the price and energy statuses. One of the disadvantages of the abovementioned works is that participants blindly trust and rely on central entities, which gives rise to robustness and reliability issues. Given that there is no effective way to control or verify the authenticity of the market operations, there are risks of market manipulation that undermine the integrity of the markets and total system collapse in the scenario of a sudden failure of the central entities. Decentralization is the method of granting peers more opportunities to manage the market operations on their own, and it is gaining popularity as a means of tackling the issue [17-19]. In this work, a conceptual design of a decentralized peer-to-peer negawatt trading platform is presented. The work exploits the use of recent advancements in distributed ledger technology, including the Ethereum blockchain and smart contracts, that have proven capabilities to improve the operation of decentralized systems by providing automation of trading and transparency of transactions and enforcing trust among the participants without any need for intermediary entities [20-28].

## 2. Novelty and Contribution

Blockchain applications in negawatt trading were previously considered in [29-30]. Sypatayev et al. [29] discussed the possibility of using blockchain in a negawatt trading transactive energy system, where consumers willing to provide more demand reduction than requested can give commands to open the auction market in order to gain higher profits from the trading. However, its scope was limited to a specific case where negawatt transactions occur between the utility operator and the consumers. Furthermore, no attention was given to scenarios when the reduction targets are not met. This work considers a more holistic market model where consumers trade negawatts both to the grid and to other consumers in the network. In this way, consumers having difficulties reducing the agreed amount of demand can buy “the right to use energy” from their peers, which will provide flexibility to the consumers’ decisions and increase the cost savings of both the consumers and the grid. The work closest to this is [30], which presented a conceptual architecture of a blockchain-based peer-to-peer negawatt trading platform. However, the limitation of the work is the simplicity of the auction mechanism and payment scheme. In this work, the auction winner determination problem is formulated as a fractional knapsack problem and a Vickrey–Clarke–Groves payment scheme is applied. To the authors' knowledge, such constrained optimization and game theoretic approach has not been applied previously in the context of blockchain-based peer-to-peer negawatt trading, although it has lent itself to many other blockchain-based trading applications [31-37].

## 3. Problem Statement

Jing et al. [30] consider two trading scenarios. In the first scenario, upon receiving a DR request from the demand response aggregator, consumers can participate in trading by submitting their available negawatt amounts, *A*’s. The sellers are selected starting from the one with the highest *A* until the requested demand reduction, T, is met. Each successful seller receives a financial reward based on a unit price set by the demand response aggregator and the amount of negawatts he or she sold, *S*.

In the second scenario, consumers can buy negawatts from other consumers that are interested in trading. A market clearing price, *MCP*, is calculated as an average of unit bid prices, *b*’s, from all sellers:

$$MCP = \frac{\sum b_i \cdot A_i}{\sum A_i} \tag{1}$$

Unit ask prices of the buyers are compared with the MCP. Only those with the unit ask prices greater than or equal to the MCP can engage in the trading. The sellers are sorted from high to low based on their bid prices, *b*’s. The winners are selected starting from the seller with the highest B until the total requested negawatts from all eligible buyers are met. The selected sellers then receive financial rewards based on the MCP and S.

The above work has several limitations. In the first scenario, the winners are rewarded at the same unit price set by the demand response aggregator. However, as previously implied, a reduction in demand entails a certain level of inconvenience, e.g., a change in work schedule, which may differ from consumer to consumer. Thus, consumers may value the same amount of demand reduction at different prices. Ignoring the influence of consumers’ diversity and preferences may result in higher social costs, insufficient incentives, and ensuing low participation in the DR process.

In the second scenario, the market mechanism does not find the optimal buyer-seller pair. Since the sellers are rewarded based on the average unit bid price, there could be cases when the utility of the winners is negative. Furthermore, bidders may purposefully overstate *b*’s in order to increase their chances of getting selected and receiving higher payments. The work of Jing et al. [30] is considered a starting point and a benchmark for this work. To address the issues, this work proposes a fully decentralized peer-to-peer market model where agents interested in buying negawatts can initiate an auction, and consumers interested in selling negawatts can join the auction by entering their bids. The auction winner determination problem is formulated as a fractional knapsack problem, and a greedy algorithm is used to select the bids that minimize the social cost. The winners are rewarded using Clarke pivot payment rule to ensure truthfulness and individual rationality. Information about multi-agent reinforcement learning-based coordination was published in recent research [38] and resemble research about framework for network traffic [39].

## 4. Model

This work considers a smart grid with a single demand side response aggregator (DSRA), and a set of N consumers registered to a DR program (Fig. 1).

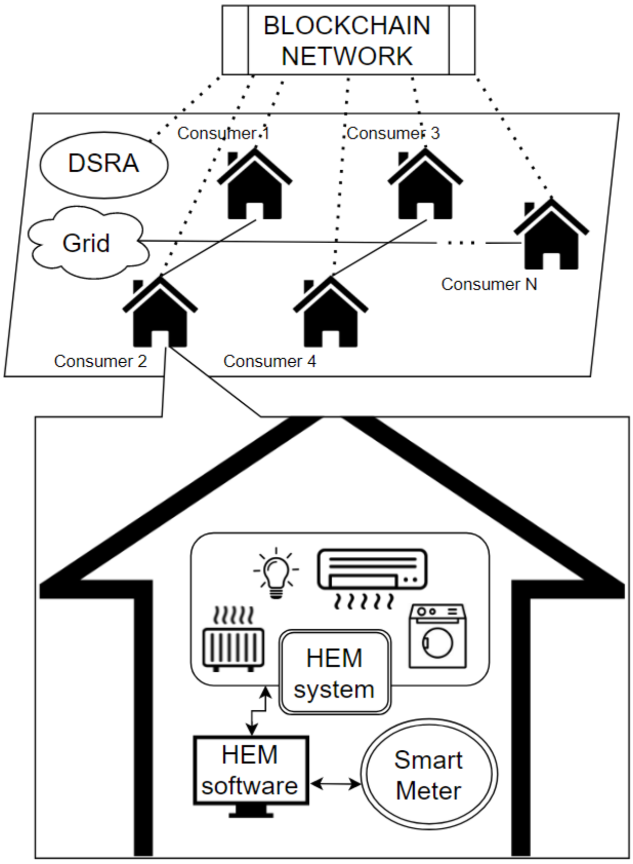


**Fig. 1.** Smart grid model.

The main task of the DSRA is to achieve a desired grid loading by performing peak load shaving during the DR event. To do so, the DSRA broadcasts a request to the blockchain network, which includes the T and the required time period. Consumers willing to have benefit from the DR program, can join the auction by responding to the request with the A’s and B’s. In general, the DSRA may not find enough negawatt sellers to achieve the T and may thus have to rely on fallback options e.g., a standby generator. Reservation price, R, is defined as a cost for the DSRA of using its fallback option to increase power generation by the T during the specified time period. The DSRA may recourse to the fallback option to fill out the gap between the total purchased negawatt amount and the T. It is assumed that the smart grid uses advanced metering infrastructure where each consumer is equipped with a home energy management (HEM) system that controls the use of energy within a household. When the auction ends, the negawatts are traded by scheduling appropriate load controls, which can be realized using HEM software [22].

In this work, the above is defined as a primary negawatt market, in which the negawatt trading is carried out between the DSRA and the consumers. The consumers are paid up front, regardless of whether they deliver the S. The smart meters provide the information about the energy consumption to the grid. The DSRA uses this information to calculate the baseline demand profile of the consumers, so that it can evaluate how much of energy consumption each consumer reduced in practice. In general, the latter can be influenced by unexpected circumstances e.g., urgent service needs. In certain cases, consumers may end up failing to provide the S which leads to reliability issues. In general, the DSRA may apply penalty schemes for violations of the agreed demand reductions. For the scope of this paper, the penalty for each unmet unit of demand is assumed to be priced at the unit reservation price, $r=R/T$. The consumers having difficulties to meet the declared demand reduction, can thus buy “the right to use energy” from their peers by broadcasting a request, in a same manner as the DSRA, in order reduce their costs. The R in this case is calculated based on the penalty price for not delivering the S. In this work, the above is defined as a secondary or a peer-to-peer negawatt market, in which the negawatt trading is carried out between the consumers. The information about improvement of the use of the second order sliding mode control for a performance and simulator software used for smart grids were published in [40-41].

## 5. Blockchain-Based Implementation

In a blockchain network, the DSRA is represented by parameters ‘Address’, which corresponds to the ID of the DSRA operator. The consumers are represented by parameters ‘ID’ and ‘Balance’, which correspond to the ID of the consumer and custom tokens in the consumer’s balance, respectively. The DSRA and the consumers can request negawatts by initiating an auction. The auction is implemented as an Ethereum asset, ‘Auction’, and is characterized by parameters ‘ID’, ‘Buyer’, ‘Timestamp’, ‘Timedelta’, ‘State’, ‘Target’, ‘Reservation’, ‘Offset’ and ‘Payment’. Here, ‘ID’ represents the ID of the auction and ‘Buyer’ represents the address of the agent who initiated the auction. The ‘Buyer’ is acknowledged as an auctioneer of the auction. ‘Timestamp’ and ‘Timedelta’ give information on the date and duration for which the negawatts are needed. ‘State’ represents the current state of the auction which can be either ‘OPEN’, ‘BUSY’, or ‘CLOSED’. ‘Target’ and ‘Reservation’ correspond to the T in kW, and the R in tokens, respectively. ‘Offset’ represents the amount of negawatts still in need after the auction ends, in kW, while ‘Payment’ represents the total payment that the buyer pays for the purchased negawatts, in tokens.

The transaction flow consists of ‘Request’, ‘Bid’ and ‘Close’ transactions. ‘Request’ corresponds to the broadcast request discussed previously and is identified by the parameters ‘Timestamp’, ‘Timedelta’, ‘Target’ and ‘Reservation’. After this transaction is sent, the ‘State’ of the ‘Auction’ changes from ‘CLOSED’ to ‘OPEN’ indicating that a bidding process is active and offers from the consumers are accepted. As a response, interested consumers send a ‘Bid’ comprising ‘ID’, which corresponds to the ID of the ‘Auction’, ‘Amount’ which corresponds to the A in kW, and ‘Price’ which corresponds to the B in tokens. The submitted bids are aggregated as an additional parameter in the ‘Auction’. The auctioneer broadcasts ‘Close’ message to indicate the termination of the bidding process. After the transaction is submitted, the ‘State’ of the ‘Auction’ changes to ‘BUSY’.

In this work, the negawatts are traded in reverse auctions with single buyer and multiple sellers. It is assumed that partial use of the bids i.e., a fraction of the A can be traded based on a corresponding fraction of the B, is allowed. Thus, the auction winner determination problem is formulated as a fractional 0-1 Minimum Cost Maximal Knapsack Packing problem. For an n number of bids, the objective function is defined as:

$$\min_x \left(\sum_i x_i \cdot B_i + x_R \cdot R\right) \tag{2}$$

Subject to the constraints

$$\sum_i x_i \cdot A_i + x_R \cdot T = T \text{ and } x \in [0,1] \tag{3}$$

where $\forall_{i \in \{0,\cdots,n-1\}}$ and $x = \{x_0, \dots, x_{n-1}, x_R\}$ is the selection profile. When all bidders bid truthfully, the term $\sum_i x_i \cdot B_i + x_R \cdot R$ represents the social cost. The reservation is considered as a ‘virtual agent’ that bids $R$ for $T$. The reservation price guarantees that the problem always searches for an optimal solution, whether by trading with the consumers, using external options or both. The problem is solved by the greedy algorithm, that considers the bids in non-decreasing order according to their $b$’s, such that $b_{i+1} \geq b_i \geq 0$ for $i \in \{1, \cdots, n-1\}$. In case, $b_i = b_{i+1}$, bid $i$ corresponds to the one which was submitted later. The greedy algorithm is shown in Algorithm 1.

**Algorithm 1** Greedy Algorithm

```
Input: $n, R, T, \{B_0, \dots, B_{n-1}\}, \{A_0, \dots, A_{n-1}\}$
Output: Optimal selection profile $x^*$
begin
for each $i \in \{1, \dots, n-1\}$ do $x_i^* \leftarrow 0$
end for
$x_R^* \leftarrow 1, i \leftarrow 0$
while $i < n$ and $b_i \leq r$ and $x_R > 0$ do
    if $A_i \leq x_R \cdot T$ then $x_i \leftarrow 1$
    else $x_i^* \leftarrow x_R \cdot T / A_i$
    end if
    $x_R^* \leftarrow x_R^* - x_i^* \cdot A_i / T$, $i \leftarrow i + 1$
end while
end
```

The Knapsack problem is further modelled as a non-cooperative game among the bidders, where bidders try to maximize their payoffs. The individual rewards are computed using the Clarke pivot payment rule:

$$P_i = \min_x \left(\sum_{j \neq i} x_j \cdot B_j + x_R \cdot R\right) - \left(\sum_{j \neq i} x_j^* \cdot B_j + x_R^* \cdot R\right) \tag{4}$$

where the first term is the optimal social cost in the absence of bidder i and the second term is the optimal social cost of other bidders in the presence of bidder $i$. Thus, the payoff each bidder receives is the externality the bidder imposes on the others, and not a direct function of its own bid. The utility of bidder i is:

$$U_i = P_i - x_i^* \cdot B_i$$

$$= \min_x \left(\sum_{j \neq i} x_j \cdot B_j + x_R \cdot R\right) - \left(\sum_j x_j^* \cdot B_j + x_R^* \cdot R\right) \tag{5}$$

Since $\min_x(\sum_{j \neq i} x_j \cdot B_j + x_R \cdot R)$ is independent of the bidder’s bid, the bidder would want to maximize $U_i$ by minimizing $(\sum_j x_j^* \cdot B_j + x_R^* \cdot R)$ which is the exact sum that is minimized by the problem. Thus, the bidders achieve the best outcomes for themselves by bidding truthfully regardless of other bidders’ bids. Furthermore, the mechanism is individually rational since $\sum_{j \neq i} x_j^* \cdot B_j + x_R^* \cdot R \leq \min_x(\sum_{j \neq i} x_j \cdot B_j + x_R \cdot R)$ for all $i$. This can be informally interpreted as ceteris paribus removing a bidder will never decrease the social cost. After each successful trade, the corresponding ‘Bid’ in the ‘Auction’ is appended with parameters ‘Sold’ and ‘Payoff’, where the first corresponds to the $S_i = x_i^* \cdot A_i$ in kW, and the latter corresponds to the $P_i$ in tokens. ‘Offset’ and ‘Payment’ are computed as $x_R^* \cdot T$ and $\sum_i P_i$, respectively. The token balances of the buyer and the sellers are updated accordingly. After all operations are completed, the ‘State’ of the ‘Auction’ is changed to ‘CLOSED’.

## 6. Case Study Details

A simulation setup (Fig. 2) is developed to model the proposed peer-to-peer negawatt trading platform in a demand-side flexibility driven transactive energy system with five consumers. It is broken up into three layers: Data Storage Layer, Market Layer, and Application Layer. At the Data Storage Layer, a private Ethereum blockchain is set up using Ganache to store trading information. The microeconomic calculations are executed at the Market Layer using a smart contract. Deployment of the smart contract to the blockchain enables programming commands written in Solidity language to record and manage all transactions. The interaction of consumers is modeled at the Application Layer using JADE multi-agent environment. To integrate the Application Layer with other layers a smart contract wrapper is generated using web3j libraries. The setup is implemented on the Apache Maven which encloses the JADE and Web3j maven repositories in a Project Object Model (POM).

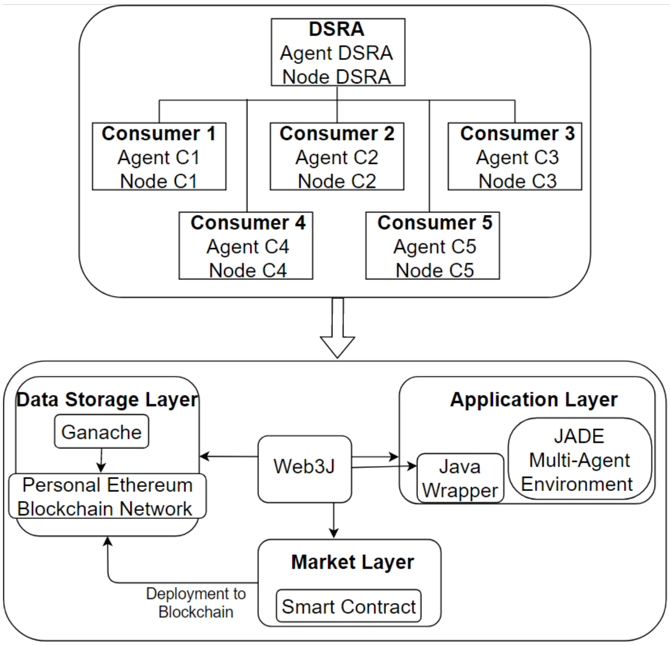


**Fig. 2.** Simulation setup design.

Two trading cases are considered in the simulation. In the first case, the DSRA wants to achieve a demand reduction of 100kW on the specified day between 15:00 and 16:00 and sends a ‘Request’ into the blockchain network. It is considered that the cost for the DSRA to use its fallback option to generate the 100kW during the on-peak hour is 500 tokens. It is considered that each consumer submits a ‘Bid’ with their true values. The details of the bids are tabulated in Table 1.

**Table 1.** Bids in the primary negawatt market

| Bidder | Available (kW) | Price (token) |
|---|---|---|
| **Consumer 1** | 30 | 120 |
| **Consumer 2** | 25 | 100 |
| **Consumer 3** | 45 | 150 |
| **Consumer 4** | 10 | 20 |
| **Consumer 5** | 20 | 60 |

In the second case, consumer with the largest S in the previous auction experiences difficulty in achieving 40% of it due to urgent service needs. To avoid the penalty, which in this case is $0.4 \cdot S \cdot 500/100$ tokens, the consumer decides to buy “the right to use energy” from his peers by submitting a ‘Request’ into the blockchain network.

## 7. Simulation Results and Discussions

Table 2 and Table 3 tabulate the results of the auctions. In the first case, the DSRA was able to buy all of T in the auction and saved 57 tokens by paying 443 tokens to the consumers instead of spending 500 tokens for the fallback option. Consumers 3-5 sold all of their A’s, Consumer 1 sold a 25/30 fraction of his or her A, while consumer 2 did not sell any. The corresponding *U*’s are 22 (=42-20) tokens, 26 (=86-60) tokens, 65 (=205-150) tokens, 100 (=110-25/30·120) tokens and 0 (=0-0·110) tokens. This means that every consumer won or at least did not lose from participating in the auction, making it a win-win game.

In the second case, Consumer 3 who sold the highest amount of negawatts (45 kW) submitted a ‘Request’ with T=18 (=0.4·45) kW and R=90 (=0.4·45·500/100) tokens. The consumer was able to buy all of T in the auction and saved 3 tokens by paying 87 tokens to the other consumers instead of paying penalty charge of 90 tokens. Consumers 1 sold all of his or her negawatts that was available from the previous trading, while Consumer 2 sold a 13/25 fraction of his or her A. The corresponding U’s are 2 (=22-20) tokens and 7.8 (=65-13/25·110) tokens. Thus, every consumer won from the trading.

The Fig. 3 illustrates how the U’s of consumer 1 in the first case and consumer 2 in the second changes with B. It shows that they achieved the highest possible utilities when bidding truthfully which correlates with the statement made

**Table 2.** Results of the auction in the primary negawatt market

| **ID** | **Buyer** | **Timestamp** (dd/mm/yyyy hh:mm) | **Timedelta** (hours) | **Target** (kW) | **Reservation** (token) | **Offset** (kW) | **Payment** (token) |
|---|---|---|---|---|---|---|---|
| 0 | The DSRA | 08/05/2021 15:00 | 1 | 100 | 500 | 0 | 443 |

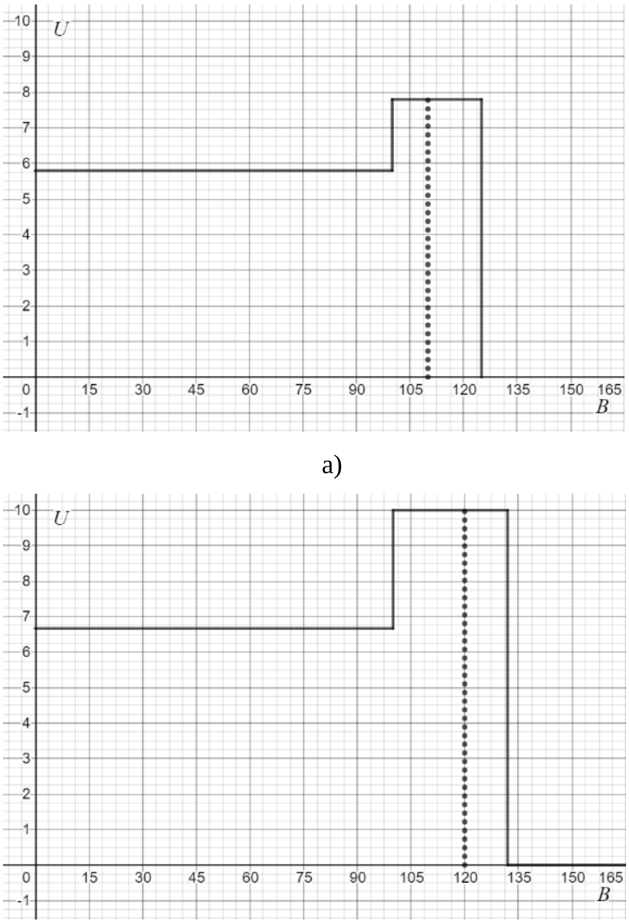
| **Bid** | **Bidder** | **Available** (kW) | **Price** (token) | **Sold** (kW) | **Payoff** (token) |
|---|---|---|---|---|---|
| 0 | Consumer 4 | 10 | 20 | 10 | 42 |
| 1 | Consumer 5 | 20 | 60 | 20 | 86 |
| 2 | Consumer 3 | 45 | 150 | 45 | 205 |
| 3 | Consumer 1 | 30 | 120 | 25 | 110 |
| 4 | Consumer 2 | 25 | 110 | 0 | 0 |

**Table 3.** Results of the auction in the peer-to-peer negawatt market

| **ID** | **Buyer** | **Timestamp** (dd/mm/yyyy hh:mm) | **Timedelta** (hours) | **Target** (kW) | **Reservation** (token) | **Offset** (kW) | **Payment** (token) |
|---|---|---|---|---|---|---|---|
| 1 | Consumer 3 | 08/05/2021 15:00 | 1 | 18 | 90 | 0 | 87 |

| **Bid** | **Bidder** | **Available** (kW) | **Price** (token) | **Sold** (kW) | **Payoff** (token) |
|---|---|---|---|---|---|
| 0 | Consumer 1 | 5 | 20 | 5 | 22 |
| 1 | Consumer 2 | 25 | 110 | 13 | 65 |

in Section 5. The social costs in both cases were compared with those resulting from using the method described in Section 3 for the same inputs. The Fig. 4 shows 13.2% decrease in social cost in the first case and 2.52% decrease in the second.



a)

b)

**Fig. 3.** Change utility with bid price a) for consumer 1 in the primary negawatt market and b) consumer 2 in the peer-to-peer negawatt market

Overall, the results prove that the proposed method achieves relatively better economic efficiency by maximizing revenue and minimizing the social cost of the auction participants while ensuring truthfulness and individual rationality. However, this comes at the expense of higher computational complexity due to the increased number of iterations in the auction algorithm. LP relaxation of the problem can be considered in the future to reduce the computational burden while preserving truthfulness [42]. The scalability issue also stems from the compute-intensive proof-of-work consensus mechanism adopted by Ethereum. Simulations with a higher number of bidders were not possible as the gas required to perform the 'Close' transactions exceeded the gas limit of the Ganache. This also implies higher average transaction fees for the auction participants. Nevertheless, the introduction of a proof-of-stake approach during the later phases of the transition to Ethereum 2.0, which is expected to tack place in 2022-2023, and improvements to the Ethereum fee market proposed in EIP 1559 [43] will significantly help in improving the performance characteristics of the blockchain-implementation.

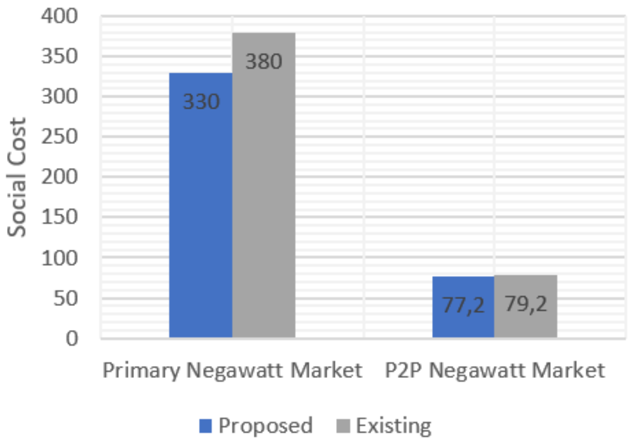


**Fig. 4.** Social cost in the proposed and the existing methods

## 8. Conclusion

This work presented the conceptual design of the decentralized platform for peer-to-peer negawatt trading between the DSRA and the consumers registered to the DR program through the Vickey-Clarkes-Groves auction. Unlike conventional negawatt markets with limited consumers' flexibility and contribution to payment decisions that result in high social costs, insufficient incentives, and low participation in the DR process, the proposed platform was designed to allow any consumer interested in buying negawatts to initiate an auction where consumers interested in selling negawatts can join by entering their bids. Thus, it takes into account consumers' diversity and preferences and gives them the freedom to choose with whom they want to trade, i.e., whether with the DSRA in the primary market or with neighbouring consumers in the peer-to-peer. Furthermore, automation and transparency of trading provided by blockchain smart contracts eliminate the risks of market manipulation and single points of failure seen in centralized systems.

In order to minimize the social cost, the auction winner determination problem was formulated as the fractional 0-1 Minimum Cost Maximal Knapsack Packing problem, and the Greedy Algorithm was used to obtain the optimal selection profile. The problem was further modeled as the non-cooperative game among the bidders where they try to maximize their payoffs computed using the Clarke pivot payment rule. The platform was implemented in the Ethereum blockchain, and two trading cases were considered in the demand-side flexibility-driven transactive energy system with five consumers. In both cases, the results showed that each participant ended up with positive and the highest possible utility by bidding truthfully, which confirms individual rationality and truthfulness. It was also shown that the adopted market mechanism achieves higher economic efficiency in terms of social cost relative to the existing one in the literature. However, this came at the expense of higher computational complexity and scalability issues due to the increased number of iterations in the auction algorithm and compute-intensive proof-of-work consensus mechanism adopted by Ethereum. Nevertheless, LP relaxation of the problem, the introduction of the proof-of-stake approach as part of Ethereum 2.0, which is expected to tack place in 2022-2023, and improvements to the Ethereum fee market proposed in EIP 1559 [41] will greatly help in improving the performance characteristics of the blockchain-implementation and will be topics of future research.

### Conflicts of Interest

The authors declare no conflict of interest.

### Acknowledgements

This work was supported by the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP09261258). Co-autors N.Z and K.K. acknowledges the Scholarship Programme from the Islamic Development Bank (ID 2021-588606). We acknowledge the Frontiers Champions programme of Royal Academy of Engineering for developing an academic network and would like to thank Prof. Ilhami Colak and Dr. Thomas Morstyn for providing insightful feedback.

## References

[1] I. Chupryna, R. Tormosov, K. Chupryna, M. Oleksandr, and P. Natali, “Systematization of international and domestic experience in project management aimed at adapting public-private partnerships to the implementation of sustainable energy development programs,” Scientific Journal of Astana IT University, no. 7, pp. 42–54, 2021.

[2] The GridWise Architecture Council, "Gridwise transactive energy framework version 1.0", January 2015.

[3] T. Muhammad, H. Chen, I. Idris, L. Nauman and A. Saif, “Demand Response Programs Significance, Challenges and Worldwide Scope in Maintaining Power System Stability”, International Journal of Advanced Computer Science and Applications (ijacsa), 9(6), 2018.

[4] A. B. Lovins, “The Negawatt Revolution”, Across Board (NY)., vol. XXVII, no. 9, pp. 18–23, 1990

[5] W. Tushar, T. Saha, and C. Yuen, “Challenges and prospects for negawatt trading in light of recent technological developments”, Nat Energy 5, pp. 834–841, 2020.

[6] F. P. Sioshansi, “Negawatt pricing,” Electricity Pricing in Transition, pp. 191–206, 2002.

[7] R. L. Borlick, “Pricing negawatts,” Fortnightly. [Online]. Available: https://www.fortnightly.com/fortnightly/2010/08/pricing-negawatts. [Accessed: 07-Aug-2022].

[8] S. Tomic, “Economic effects of trading watts and Negawatts by agile customers in hierarchic energy markets,” 2012 9th International Conference on the European Energy Market, 2012.

[9] A. Algarni and T. Namerikawa, “Integrating demand response aggregators with negawatt trading mechanisms in electricity markets,” 2019 North American Power Symposium (NAPS), 2019.

[10] A. Safari, M. Tahmasebi, and J. Pasupuleti, “Smart buildings aggregator bidding strategy as a negawatt demand response resource in the Spinning Reserve Electricity Market,” 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2019.

[11] Y. Okawa and T. Namerikawa, “Distributed Power Supply-demand management based on negawatt trading with Energy Storage System,” 2016 European Control Conference (ECC), 2016.

[12] Y. Okawa and T. Namerikawa, “Distributed Optimal Power management via NEGAWATT

trading in real-time electricity market," IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 3009–3019, 2017.

[13] M. I. Azim and W. Tushar, "P2P negawatt trading: A potential alternative to demand-side management," 2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), 2021.

[14] I. Reis, I. Gonçalves, A. Lopes, and H. Antunes. "Business models for energy communities: A review of key issues and trends", Renewable and Sustainable Energy Reviews. 2021, 144, 111013.

[15] J. Bürer, M. Capezzali, M. Carpita, D. Lapparent, and V. Pallotta, "BlockChainTechnology for energy transition", In Blockchain Technology and Innovations in Business Processes. 2021 (pp. 153-188). Springer, Singapore.

[16] M. I. Azim, W. Tushar, and T. K. Saha, "Cooperative negawatt P2P energy trading for low-voltage distribution networks," Applied Energy, vol. 299, p. 117300, 2021.

[17] A. Esmat, M. de Vos, Y. Ghiassi-Farrokhfal, P. Palensky, and D. Epema, "A novel decentralized platform for peer-to-peer energy trading market with Blockchain technology," Applied Energy, vol. 282, p. 116123, 2021.

[18] M. Mehdinejad, H. Shayanfar, and B. Mohammadi-Ivatloo, "Peer-to-peer decentralized energy trading framework for retailers and prosumers," Applied Energy, vol. 308, p. 118310, 2022.

[19] A. Aminlou, B. Mohammadi-Ivatloo, K. Zare, R. Razzaghi, and A. Anvari-Moghaddam, "Peer-to-peer decentralized energy trading in industrial town considering central shared energy storage using alternating direction method of multipliers algorithm," IET Renewable Power Generation, 2022.

[20] S. Seven, G. Yao, A. Soran, A. Onen and S. M. Muyeen, "Peer-to-Peer Energy Trading in Virtual Power Plant Based on Blockchain Smart Contracts", in IEEE Access, vol. 8, pp. 175713-175726, 2020.

[21] I. Tonev, "Energy Trading Web Platform Based on the Ethereum Smart Contracts and Blockchain", 2020 12th Electrical Engineering Faculty Conference (BulEF), 2020, pp. 1-4, doi: 10.1109/BulEF51036.2020.9326010.

[22] Y. Amanbek, A. Kalakova, S. Zhakiyeva, K. Kayisli, N. Zhakiyev, and D. Friedrich, "Distribution Locational Marginal Price Based Transactive Energy Management in Distribution Systems with Smart Prosumers – A Multi-Agent Approach", Energies, 2022 15(7), 2404.

[23] M. Sidra, D. Volkan, S. Kanhere, and R. Jurdak, "TrustChain: Trust Management in Blockchain and IoT Supported Supply Chains", IEEE International Conference on Blockchain (Blockchain). pp. 14-17, 2019.

[24] M. Banja, and M. Jégard, " An Analysis of Capacity Market Mechanism for Solar Photovoltaics in France," International Journal of Smart Grid (IJSmartGrid), 3(1), pp. 10-18.

[25] J. Moradi, H. Shahinzadeh, H. Nafisi, G. B. Gharehpetian, and M. Shaneh, "Blockchain, a sustainable solution for cybersecurity using cryptocurrency for financial transactions in Smart Grids," 2019 24th Electrical Power Distribution Conference (EPDC), 2019.

[26] H. Hosseinian, H. Shahinzadeh, G. B. Gharehpetian, Z. Azani, and M. Shaneh, "Blockchain outlook for deployment of IOT in distribution networks and Smart Homes," International Journal of Electrical and Computer Engineering (IJECE), vol. 10, no. 3, p. 2787, 2020.

[27] P. Frauenthaler, M. Sigwart, C. Spanring, M. Sober, and S. Schulte, " ETH Relay: A Cost-efficient Relay for Ethereum-based Blockchains", 2020 IEEE International Conference on Blockchain.

[28] M. Pipattanasomporn, S. Rahman, and M. Kuzlu, "Blockchain-based Solar Electricity Exchange: Conceptual architecture and laboratory setup," 2019 IEEE Power &amp; Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2019.

[29] D. Sypatayev, H. S. V. S. Kumar Nunna, and A. Shintemirov, "A Novel Peer-to-Peer Negawatt Trading Transactive Energy System for Prosumers", 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), 2020, pp. 181-186, doi: 10.1109/CPE-POWERENG48600.2020.9161457.

[30] Z. Jing, M. Pipattanasomporn, and S. Rahman, "Blockchain-based Negawatt Trading Platform: Conceptual Architecture and Case Studies", 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), 2019, pp. 68-73, doi: 10.1109/GTDAsia.2019.8715890.

[31] Y. Gu, D. Hou, X. Wu, J. Tao, and Y. Zhang, "Decentralized transaction mechanism based on smart contract in Distributed Data Storage", Information, vol. 9, no. 11, p. 286, 2018.

[32] L.M. Sguerra, P. Jouvelot, E. J. G. Arias, G. Memmi, F. Coelho, "Blockchain Performance Benchmarking: a VCG Auction Smart Contract Use Case for Ethereum and Tezos", Fourth International Symposium on Foundations and Applications of Blockchain, United States, May 2021.

[33] M. U. Hassan, M. H. Rehmani, and J. Chen, "Optimizing blockchain based Smart Grid Auctions: A green revolution," IEEE Transactions on Green Communications and Networking, vol. 6, no. 1, pp. 462–471, 2022.

[34] M. K. AlAshery, Z. Yi, D. Shi, X. Lu, C. Xu, Z. Wang, and W. Qiao, "A blockchain-enabled multi-settlement quasi-ideal peer-to-peer trading framework," IEEE Transactions on Smart Grid, vol. 12, no. 1, pp. 885–896, 2021.

[35] L. Liu, M. Han, Y. Zhou, R. M. Parizi, and M. Korayem, "Blockchain-based certification for education, employment, and skill with Incentive Mechanism," Advances in Information Security, pp. 269–290, 2020.

[36] L. Liyuan, H. Meng, Z. Yiyun, and P. Reza, "E^2 C-Chain: A two-stage incentive education employment and Skill Certification Blockchain," 2019 IEEE International Conference on Blockchain (Blockchain), 2019.

[37] S.-V. Oprea, "Local Market Mechanisms survey for peer-to-peer electricity trading on Blockchain Platform," Scientific Bulletin of Naval Academy, vol. XXIII, no. 1, pp. 186–191, 2020.

[38] F. Charbonnier, T Morstyn, and MD. McCulloch, "Scalable multi-agent reinforcement learning for distributed control of residential energy flexibility". Applied Energy, May 15 2022.

[39] I. Savellia, and T. Morstyn, "Electricity prices and tariffs to keep everyone happy: A framework for fixed and nodal prices coexistence in distribution grids with optimal tariffs for investment cost recovery", Omega, 102450, Volume 103, 2021.

[40] F. Mazouz, S. Belkacem, I. Colak "DPC-SVM of DFIG Using Fuzzy Second Order Sliding Mode Approach", International Journal of Smart Grid-ijSmartGrid. 2021 Dec 28;5(4):174-82.

[41] A. Allaoua, M. Layadi, I. Colak, and K. Rouabah, "Design and Simulation of Smart-Grids using OMNeT++/Matlab-Simulink Co-simulator", in 2021 10th International Conference on Renewable Energy Research and Application (ICRERA) 2021 (pp. 141-145). IEEE.

[42] R. Lavi and C. Swamy, "Truthful and near-optimal mechanism design via Linear Programming," 46th Annual IEEE Symposium on Foundations of Computer Science (FOCS'05).

[43] Ethereum Improvement Proposals. [Online]. Available: https://eips.ethereum.org/. [Accessed: 07-Aug-2022].