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Two Novel Blockchain-Based Market Settlement Mechanisms Embedded into Smart Contracts for Securely Trading Renewable Energy

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ABSTRACT The progress of ICT technologies, day-ahead forecast, home energy management systems, implementation of smart meters, and Distributed Energy Sources (DER) enables new business opportunities for prosumers to locally trade the surplus via blockchain platforms leading to considerable advantages at the community level. The current research handles settlement similar to a centralized market that it is not necessarily the best solution for blockchain. Nonetheless, the settlement is essential as sellers and buyers perceive the attractiveness of the local trading through the market results. In this paper, we propose two novel and efficient settlement mechanisms (Global Balancing Settlement GBS and Splitting Settlement SS) for Peer-to-Peer (P2P) electricity exchange enhancing the performance of the classic Pairwise Settlement PS. These will be written as stored procedures embedded into the smart contracts along with auctioning procedures. The simulations are performed using a small residential community with 30% of the electricity that can be locally traded to lower the bills and unstress the public grid. The performance of the two proposed settlement methods is proved by the 14 scenarios that thoroughly indicate that GBS and SS provide better results for both sellers and buyers than PS. In the reference scenario, with GBS, sellers have the highest encashments with almost 4% more, whereas buyers encounter the lowest payments with almost 5% less than in case of the classic settlement. Starting from reference scenario, alternative scenarios are envisioned to extend the analyses and assess the performance of the settlement mechanisms. The highest gain is recorded with GBS mechanism: almost 8.8% for sellers and 6.5% for buyers. Another interesting outcome is that GBS is providing better results than SS. When deviations are small, SS provides almost 6% gain for both sellers and buyers, but when they increase, the gain is exceedingly small or none.

INDEX TERMS market settlement, blockchain, local trading, peer-to-peer, auction, smart contract.

1. INTRODUCTION

Nowadays, most of the consumers do not trade, interact or have smart meters being supplied by a retailer at a standard tariff. However, the new advancement in Renewable Energy Sources (RES), smart meters and other sensors technologies, intelligent systems, including blockchain application on bitcoin, will allow in the near future electricity exchanges at the local communities of residential consumers or prosumers. Already, several projects are emerging [1] offering incentives to continue the investigation and research in this area. The surplus of prosumers could be efficiently traded to the neighbors and not to the grid considering the difference of the tariff rates. Thus, the residential consumers will benefit from direct exchange due to more advantageous rates and elimination of intermediaries. Also, they perceive the transfer of trading control from central authorities to their level and change the paradigm [2] of transmitting and distributing electricity over long distances with considerable losses. Moreover, the prosumers that receive a better revenue due to local trade will encourage RES local integration at larger scale, enhancing investment in new RES facilities.

Ideal trading is performed on market basis, clearing the bids and offers similar to stock exchanges, but there will be always differences between bidding quantities and actual ones, especially when generation is based on RES, requiring rigorous settlement based on the smart meters records. To enhance trading, several intra-day auctions will reduce the imbalance penalties as the auctions take place closer to the delivery time. These auctions enable consumers and prosumers to adjust their bids and offers according to a better forecast that is performed for 24 hours and then is repeated at shorter intervals.

Therefore, P2P transaction settlement reconciles differences between bids and smart-metered generation/ consumption. The smart meters can measure both the energy consumed or generated over a period that is previously configured to serve the settlement purpose. This offers the opportunity to perform the settlement process more precise (compared with the profile approach), timely and better integrate EV and smart appliances [3].

A multi-settlement market consists in electricity surplus or deficit that are bought/sold on forecast basis and initially settled on a forward basis and then resettled considering the actual production and consumption. The blockchain forward market could be organized in a intraday time frame. The bids and offers cleared in the intraday market are contractually binding.

The objective of this paper is to propose two novel settlement mechanisms for a market-based trading system that enhances the local transactions at the blockchain platform level using stored procedures included into the smart contracts that govern the P2P transactions.

The paper is structured into 6 sections. The first section briefly introduces the P2P transaction and settlement concepts. In the second section, some of the most recent and relevant scientific research papers are discussed. The third section depicts blockchain technology, whereas the proposed two methods for settlement are presented in the fourth section. Simulations, results, and comparisons are performed in the fifth section, and conclusion is drawn in the sixth section.

2. LITERATURE REVIEW

The blockchain technology has been investigated recently in correlation with local electricity markets. An electricity market that consists in two producer and one consumer in chemistry industry operates via a blockchain platform [4] focusing on the technical aspects of the blockchain implementation especially the consensus mechanism. Also, a generation transfer from utility companies to consumers from Perth, Australia, becoming citizen utilities using a blockchain platform is described in [2]. The benefits of the city by large deployment of solar and storage facilities encouraged this transformation and inspired other cities.

To our knowledge, there are not many explorations of the designing, improving, and implementing the settlement mechanisms at the blockchain level or most of the approaches handle the settlement as in centralized markets.

Seven components for a microgrid electricity market were identified in [5], stating that C3, C4 and C5 are the main component for local trading: C1 *microgrid setup* that involves the setting of the trading objectives; C2 *connection points* or physical balancing point between the microgrid and public grid; C3 *information system* to manage the local trade using a blockchain protocol as a software application that is assimilated with smart contracts; C4 *market mechanism* (implemented by C3) that includes allocation and payment rules; C5 *pricing mechanism* implemented by C4 setting the auction pricing and limits; C6 *energy management trading system* that forecasts generation and consumption, decides the trading strategy and automatically performs electricity transactions so that the user interaction to be minimized; C7 *regulation* that could further enhance the local trading opportunities.

An architecture of blockchain protocol based on smart contracts and associated with market clearing price, energy allocation and settlement mechanism is proposed in [6]. Smart contracts can be written in Solidity, Pact or Liquidity [7] and are designed to secure the transaction data and specific functions and to calculate the clearing price and energy allocation. The settlement is very briefly presented as a simple mechanism of penalizing sellers and buyers that fail to deliver or consume. The penalty is calculated based on individual transaction as difference between the retailer price and auction price. Also, the local settlement is envisioned via smart contracts in [8] considering the meter readings and trading results, the liability being linked with a crypto wallet or a standard bank account.

A distributed transaction mechanism including settlement into smart contracts is also proposed in [9] that allows P2P trading among prosumers and consumers. Moreover, a two-blockchain-layer is proposed in [10] for Balancing Responsible Parties (BRP) and system operator settlements allowing a higher automation for balancing market and new business models for BRP. Moreover, a review of blockchain technology, a mechanism for distributed power trading considering security constraints and a trading method using Ethereum blockchain and smart contracts are provided in [11] to allow the transparency of the trading.

[12] propose a design and implementation of a blockchain decentralized uniform price market with rules written in smart contracts emphasizing three implementations of electricity market using the Ethereum. Also, a smart contract model is proposed in [13], implementing a Vickrey second price auction for electricity market based allocation using the Ethereum blockchain proving the effectiveness of the auction mechanism.

Auction models for P2P electricity exchanges using Ethereum blockchain in local deregulated and decentralized markets could alleviate the major grid issues such as congestion, losses, etc. [14]. The models are built upon smart contracts as an essential part of the blockchain technology. Also, an auction mechanism is applied [15] to locally trade the electricity using blockchain leading to several advantages, such as: market-based efficient transactions, minimum losses and computational overhead. The gaps between the P2P electricity exchanges and market mechanisms exist, thus a comparative investigation of bidding policies including game theory and discriminatory and non- discriminatory or uniform price auction mechanisms for trading the electricity at the local level is performed in [16]. In addition, a continuous double auction, that can be implemented for a local ancillary service market [17] to solve imbalances with smart contracts, and a settlement process for decentralized electricity transactions using blockchain are proposed in [18], and its feasibility is proven with a microgrid case study. A pricing model and trading solution architecture are investigated [19], offering suggestion to settle the conflicts between the existing market mechanism and blockchain.

However, the topic is emerging and under research in numerous studies and projects. The blockchain itself is not a mature technology and has many facets and implications. A systematic survey regarding the performance of smart contracts application in terms of security and privacy is provided in [20]. Transaction privacy with smart contracts is discussed in [21], [22] using cryptographic protocols. Applications of smart contracts using a systematic mapping are proposed in [23] emphasizing challenges regarding privacy and security of the P2P trading platforms, programmability of smart contracts and scalability of blockchain. A smart contract-based framework with multiple access control, judge and register contracts in an Internet of Things environment are implemented using an Ethereum platform [24]. Fog computing processing and blockchain technologies provide a secure architecture with encryption and authentication for practical applications in the smart cities to diminish the latency and enhance improved security of the blockchain [25]. A comprehensive description and architecture of the blockchain concept are provided in [26], underlining the following aspects among others: types and features of blockchain, consensus algorithms, proof-of-work, proof-of-stake, proof-of-activity, proof-of-burn, and blockchain applications that will transform the society in the near future.

3. BLOCKCHAIN TECHNOLOGY

Blockchain is a storage and transparent data sharing technology at the node level of a network of consumers/prosumers. Transactions are stored in data blocks that have a hash codes generated by a function. Each block is chained with the previous block hash as in Figure 1 preventing transaction misleading and distortion. Yet blockchain has numerous obstacles and challenges [1], [27]. [28] mentions settlement issues, asynchronous bidding, and smart metering system missing data, but it is yet a promising technology for P2P trading that is already implemented at small scale projects.

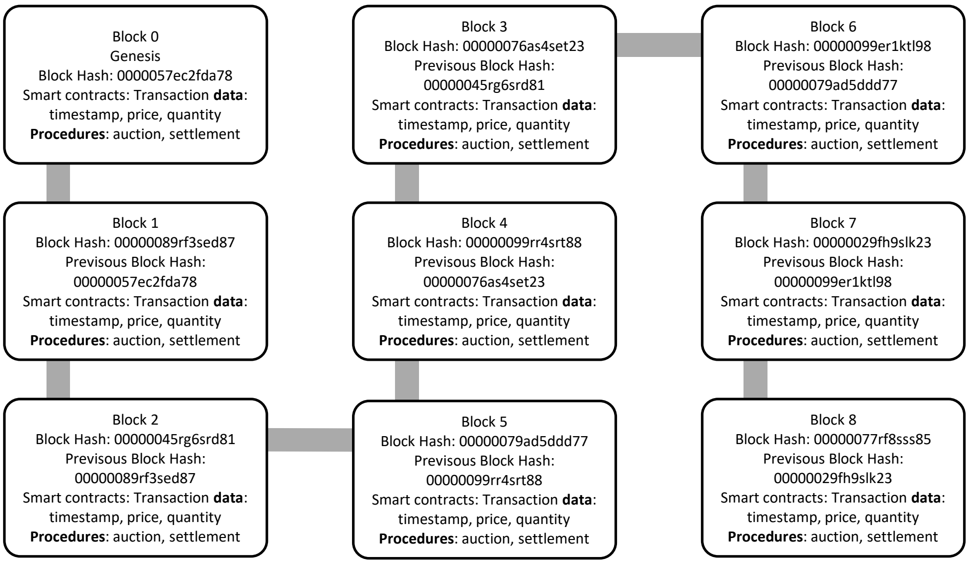

FIGURE 1. Blocks of data and procedural auction and settlement

Through smart contracts, the blockchain establishes the conditions under which a transaction or asset exchange can occur. The business rules, auction mechanism, settlement that govern transactions are agreed upon by members and encapsulated in stored procedures into smart contracts. Proof-of-Work (PoW) is the consensus algorithm in a Blockchain platform [26]. This algorithm is implemented to confirm transactions and append new blocks to the chain [29]. PoW was popularized by Bitcoin and other cryptocurrencies, in which miners compete to generate blocks. Proof-of-Stake (PoS) is also used as consensus algorithm for blockchain.

The security of the trading platform is given by authorized access and encryption of the stored procedures for auctioning and settlement. The data is stored in json files that could be loaded as collections of a NoSQL database (such as: MongoDB, Couchbase) or indexed in searching engines such as ElasticSearch. Data flow and interactions between consumers/producers/retailer and blockchain are presented in Figure 2.

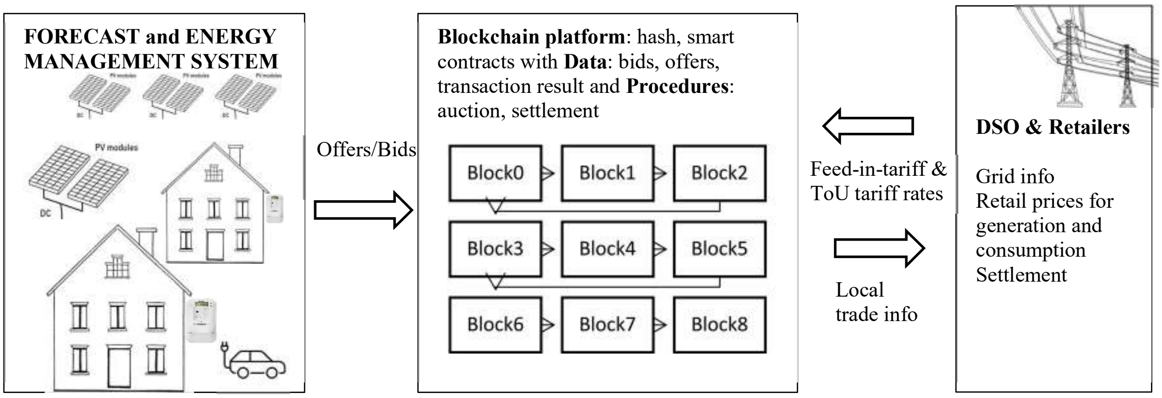

FIGURE 2. Data flow and interactions between consumers/producers/retailer and blockchain

4. PROPOSED SETTLEMENT MECHANISMS

Local trading is performed on market basis clearing the bids and offers, setting the market price (as in uniform auction) or prices, that will be paid/received by the buyers/sellers (as in pay-as-bid auction), and quantities from orders that will be executed. However, the auctioned quantities are calculated with several forecasting algorithms or home intelligent systems such as [30], [31] that are prone to errors. To reduce imbalances, intraday auctions are implemented that are similar to day-ahead auction, the only difference is the time horizon that is shorter implying smaller errors. Basically, in an intraday auction, the forecast is repeated for a shorter interval and if there are differences, these could be auctioned to diminish the mismatch between the consecutive forecasts (Figure 3). Nevertheless, imbalances will exist even if the intraday market will be implemented, but they are smaller and could be settled using a settlement mechanism.

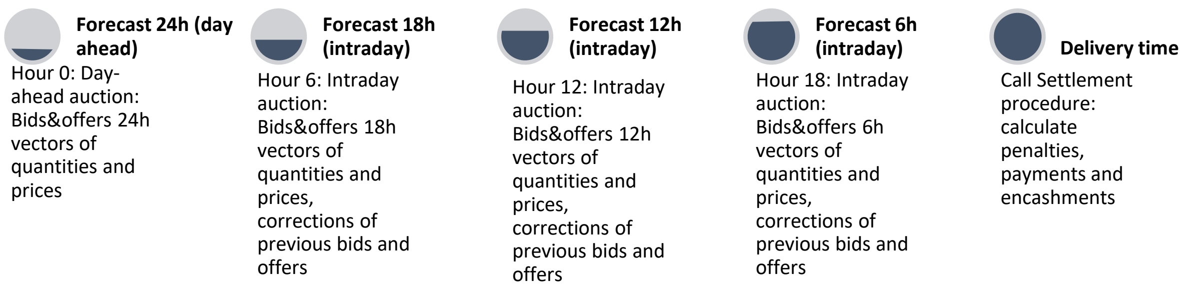

FIGURE 3. Intraday markets for blockchain

However, settlement is important as it reflects the differences between forecast and actual generation or consumption, making the bidding process financially binding. As sellers' and buyers' offers and bids directly influence the auctioning results, after the delivery time, they are responsible for the undelivered or unconsumed quantities. Therefore, the way the differences between actual values and forecasted values are settled is also significant as it ends with the trading payment or encashment that incentive the local sellers and buyers to continue to trade.

Thus, we propose two novel settlement mechanisms that will be described in the following paragraphs, and compare them with the classic Pairwise Settlement (PS) that is implemented in electricity markets and presented in [6]. It consists in a settlement performed in pairs: buyer-seller. The settlement mechanism is the following: if a seller i fails to deliver the auctioned quantity or a buyer j fails to consume the auctioned quantity, they will pay a penalty that is related to the price difference between the auction price and retailer price for sellers (feed-in-tariff) or buyers (Time-of-Use (ToU) tariff). This settlement mechanism could be written as a procedure embedded into smart contracts implemented at the blockchain level as well. The pseudocode of the PS mechanism is provided in Table 1.

TABLE 1
PS MECHANISM PSEUDOCODE

Seller imbalance	*Buyer imbalance*
rP_s retailer price for sellers	rP_b retailer price for buyers
aP auction price	aP auction price
asQ_i auctioned selling quantity of seller *i*	abQ_j auctioned buying quantity of buyer *j*
dQ_i delivered quantity of seller *i*	cQ_j consumed quantity of buyer *j*
ndQ_i non-delivered quantity of seller *i*	ncQ_j non-consumed quantity of buyer *j*
n number of sellers	m number of buyers
S_i^{pen} penalty of seller *i*	B_j^{pen} penalty of buyer *j*
S_i^{en} encashment of seller *i*	B_j^{pay} payment of buyer *j*
Pairwise settlement mechanism algorithm	
$FOR\ i\ IN\ RANGE(1,n)$:	$FOR\ j\ IN\ RANGE(1,m)$:
IF $dQ_i < asQ_i$:	IF $cQ_j < abQ_j$:
$ndQ_i = \|asQ_i - dQ_i\|$	$ncQ_j = \|abQ_j - cQ_j\|$
$S_i^{pen} = ndQ_i \times (rP_b - aP)$	$B_j^{pen} = ncQ_j \times (aP - rP_s)$
$S_i^{en} = dQ_i \times aP - S_i^{pen}$	$B_j^{pay} = cQ_j \times aP + B_j^{pen}$
ELIF $dQ_i > asQ_i$:	ELIF $cQ_j > abQ_j$:
$S_i^{en} = (asQ_i \times aP) + (dQ - asQ_i) \times rP_s$	$B_j^{pay} = (abQ_j \times aP) + (cQ_j - abQ_j) \times rP_b$
ELSE: $S_i^{en} = asQ_i \times aP$	ELSE: $B_j^{pay} = abQ_j \times aP$

However, other mechanisms could be envisioned considering the fact that participants can compensate and alleviate their deviations in a global settlement. This approach enhances the results of the settlement procedure that is profitable for blockchain participants that form a microsystem and incentive them to trade locally. The microsystem is internally balanced by participants and externally by the retailer that indicates a price for sellers and buyers. In this sense, we propose two settlement mechanisms that better reward the participants. Compared with classic settlement, the proposed settlement mechanisms have a global approach considering all participants and the microsystem status (deficit or surplus) as in Figure 4.

FIGURE 4. Classic vs. global settlement mechanism

The first proposed settlement mechanism is inspired from the activity of the balancing responsible parties. The participants k are balanced taking into account their individual deviations that can be locally compensated. This approach leads to the improvement of the retailer price for sellers and buyers improving the results of the settlement process. The Global Balancing Settlement (GBS) pseudocode is presented in Table 2.

TABLE 2
GBS MECHANISM PSEUDOCODE

aQ_k – auctioned quantity Q_k – delivered or consumed quantity nQ_k – non-delivered or non-consumed quantity nQV_k – value of non-delivered or non-consumed quantity nQV_t – total value of non-delivered or non-consumed quantity k – participant (seller or buyer) l – number of participants $rnQV_k$ – rectified value of non-delivered or non-consumed quantity	rP_s – retailer price for sellers rP_b – retailer price for buyers rrP_s – rectified retailer price for sellers rrP_b – rectified retailer price for buyers EP_k – encashment or payment (+ encashment, - payment) $inQV_k$– value of non-delivered or non-consumed quantity as individual G gain uG unit gain

Global balancing settlement mechanism algorithm

Read: aQ_k, Q_k

$FOR\ k\ IN\ RANGE(1, l)$:

$nQ_k = Q_k - aQ_k$

$IF\ nQ_k > 0:\ nQV_k = nQ_k \times rP_s\ ELSE: nQV_k = nQ_k \times rP_b$

$$nQV_t = \sum_{k=1}^{l} nQV_k, \forall\ k = \overline{1, l}$$

$IF\ nQV_t > 0:\ inQV_t = nQV_t \times rP_s\ ELSE: inQV_t = nQV_t \times rP_b$

$IF\ nQV_t \times inQV_t > 0: G = \left||nQV_t| - |inQV_t|\right|\ ELSE: G = |nQV_t| + |inQV_t|$

$$uG = \frac{G}{\sum_{k=1}^{l}|nQ_k|}$$

$rrP_s = rP_s + uG$

$rrP_b = rP_b - uG$

$IF\ nQ_k < 0: rnQV_k = nQ_k \times rrP_b\ ELSE: rnQV_k = nQ_k \times rrP_s$

$EP_k = aQ_k \times aP + rdQV_k$

The second proposed settlement mechanism consists in splitting the seller and buyers into two groups of participants and defining a coefficient for each group that reflects the contribution of participants to the imbalance. The Splitting Settlement (SS) mechanism handles the deviations for the two parties internally balancing the surplus and deficit. The calculation of encashment or payment first considers the surplus or deficit of the total sellers or buyers and then verifies the deviation of each participant.

TABLE 3
SS MECHANISM PSEUDOCODE

Sellers settlement	*Buyers settlement*
E_i – encashment of seller i asQ_i – auctioned selling quantity of seller i dQ_i – delivered quantity of seller i ndQ_i – non-delivered quantity of seller i ndQ_t – total non-delivered quantity of seller i $indQ_t$ – total non-delivered quantity of seller i as individual α_i – imbalance coefficient of seller i i – seller n – number of sellers	P_j – payment of buyer j abQ_j – auctioned buying quantity of buyer j cQ_j – consumed quantity of buyer j ncQ_j – non-consumed quantity of buyer j ncQ_t – total non-consumed quantity of buyer j $incQ_t$ – total non-consumed quantity of buyer j as individual β_j – imbalance coefficient of buyer j j – buyer m – number of buyers
Splitting settlement mechanism algorithm	
Read: asQ_i, dQ_i $FOR\ i\ IN\ RANGE(1, n)$: $ndQ_i = \|dQ_i - asQ_i\|$ $\alpha_i = \frac{ndQ_i}{indQ_t}$ $dQ_t = \sum_{i=1}^{n} dQ_i$	Read: abQ_j, cQ_j $FOR\ j\ IN\ RANGE(1, m)$: $ncQ_j = \|cQ_j - abQ_j\|$ $\beta_j = \frac{ncQ_j}{incQ_t}$ $cQ_t = \sum_{j=1}^{m} cQ_j$

$$asQ_t = \sum_{i=1}^{n} asQ_i$$
$$ndQ_t = dQ_t - asQ_t$$
$IF\ ndQ_t > 0$:
  $IF\ asQ_i < dQ_i: E_i = dQ_i \times aP$
  $ELSE: E_i = dQ_i \times aP - (|ndQ_t| \times \alpha_i) \times (rP_b - aP)$
$ELSE$:
  $IF\ asQ_i < dQ_i: E_i = asQ_i \times aP + (dQ_i - asQ_i) \times rP_s$
  $ELSE: E_i = dQ_i \times aP$

$$abQ_t = \sum_{j=1}^{m} abQ_j$$
$$ncQ_t = cQ_t - abQ_t$$
$IF\ ncQ_t > 0$:
  $IF\ abQ_j < cQ_j: P_j = cQ_j \times aP$
  $ELSE: P_j = cQ_j \times aP - (|ncQ_t| \times \beta_j) \times (aP - rP_s)$
$ELSE$:
  $IF\ abQ_j < cQ_j: P_j = abQ_j \times aP + (cQ_j - abQ_j) \times rP_b$
  $ELSE: P_j = cQ_j \times aP$

5. SIMULATIONS AND RESULTS

For simulations, the input data represents the results of a uniform auction. The executed orders belong to three sellers (S1, S2, S3) and four buyers (B1, B2, B3, B4) and the aP can vary between 9.01 and 13.99 c€/kWh, and we suppose it is 11.4 c€/kWh. The retailer price for sellers is 9 c€/kWh, whereas for buyers is 14 c€/kWh. The results for the classic PS are provided in Table 4.

TABLE 4
PS RESULTS

	asQ/abQ (kWh)	dQ/cQ (kWh)	Penalty (c€)	Encashment(+)/ Payment(-) (c€)
S1	100	110	0	1230
S2	100	80	52	860
S3	100	90	26	1000
B1	100	110	0	-1280
B2	100	80	48	-960
B3	75	90	0	-1065
B4	25	15	24	-195

The proposed mechanisms, GBS and SS, require more input data and additional calculation that are provided in Table 5, but the output brings more gain for both sellers and buyers.

TABLE 5
INPUT AND ADDITIONAL CALCULATION FOR GBS

rPs (c€)	rrPs (c€)	aP (c€)	rPb (c€)	rrPb (c€)	G (c€)	uG (c€)
9	11.10526	11.4	14	11.89474	200	2.105263

According to the proposed mechanisms described in section 4, encashments and payments are calculated. The results of the GBS and SS are provided in Table 6 and Table 7.

TABLE 6
GBS RESULTS

	asQ/abQ (kWh)	dQ/cQ (kWh)	ndQ/ncQ (kWh)	ndQV/ ncQV (c€)	rndQV/ rncQV (c€)	Encashment(+)/ Payment(-) (c€)
S1	100	110	10	90	118.9473	1258.9473
S2	100	80	-20	-280	-222.1052	917.8947
S3	100	90	-10	-140	-111.0526	1028.9473
B1	-100	-110	-10	-140	-111.0526	-1251.0526
B2	-100	-80	20	180	237.8947	-902.1052
B3	-75	-90	-15	-210	-166.5789	-1021.5789
B4	-25	-15	10	90	118.9473	-166.0526

TABLE 7
SS RESULTS

	asQ/abQ (kWh)	dQ/cQ (kWh)	ndQ/ncQ (kWh)	alpha/beta	Encashment(+)/ Payment(-) (c€)
S1	100	110	10	0.250000	1254.000
S2	100	80	20	0.500000	886.000
S3	100	90	10	0.250000	1013.000
B1	100	110	10	0.181818	-1254.000
B2	100	80	20	0.363636	-916.363

B3	75	90	15	0.272727	-1026.000
B4	25	15	10	0.181818	-173.181

For comparison, the encashments and payments for the three settlement mechanisms that can be implemented in blockchain as encrypted procedures embedded in smart contracts are graphically represented in Figure 5.

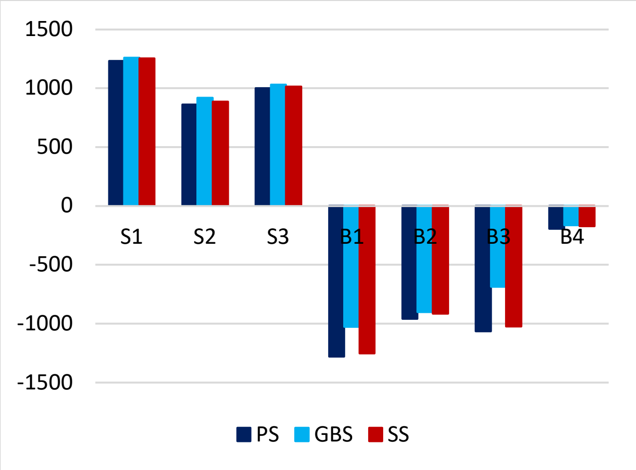

FIGURE 5. Comparing the results of three settlement mechanisms

It is obvious that the GBS and SS outperform the classic settlement mechanism (PS), leading to better results in terms of encashment and payment.

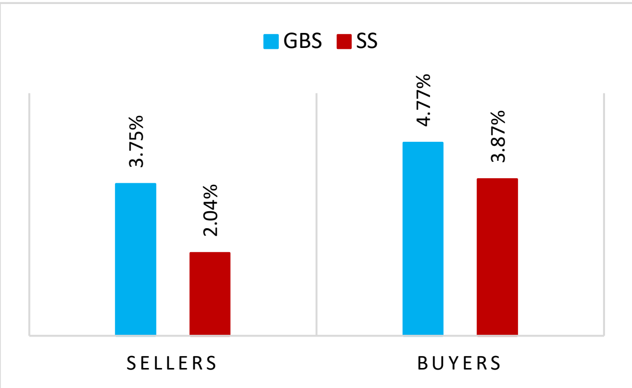

FIGURE 6. Improvement of the results compared with classic settlement in percentage

With GBS, sellers have the highest encashments with almost 4% more, whereas buyers encounter the lowest payments with almost 5% less than in case of the classic settlement (as in Figure 6).

Starting from this reference scenario, thirteen alternative scenarios are envisioned to extend the analyses and assess the performance of the two settlement mechanisms in comparison with the classic approach. The thirteen and reference scenarios are depicted in Table 8.

For building the alternative scenarios, we started from the assumptions that other deviations from the day-ahead or hour-ahead schedules are also possible. Therefore, we build these deviations by modifying the generation and consumption in both directions (surplus or deficit) to assess the outcome of the proposed methods. The gains for sellers (S) and buyers (B) are summed up for the two settlement mechanisms in each scenario. The highest gain is recorded with GBS mechanism when both sellers and buyers deviate with -20% from the reference scenario, that means sellers and buyers deliver and consume 20% less than in the reference scenario. It can be noticed that GBS and SS mechanisms always provide better results for sellers (S) and buyers (B) in terms of encashment and payment compared with classic settlement. Another interesting outcome is that GBS is providing better results than SS as in Figure 7. When deviations are small, SS provides up to 5% gain for both sellers and buyers, but when they increase, the gain is very small or none.

TABLE 7
COMPARISION OF SCENARIOS

Scenarios	Gain GBS [%]	Gain SS [%]
Both -20%	15.2612	0.0000
S=-5%, B=5%	11.4219	2.7598
S=10%, B= 20%	10.3193	1.6142
Both -10%	9.4094	1.3129
Both 20%	8.8424	0.9072
Both -5%	8.7659	3.8530
Reference scenario	8.5129	5.9104
Both 5%	8.2880	4.2520
Both 10%	8.0869	2.2755
S=30%, B=20%	8.0694	0.6279
S=20%, B=10%	6.5843	1.5685
S=30%, B=10%	5.8161	1.2892
S=5%, B=-5%	5.6466	5.3451
S=5%, B=-10%	4.3698	3.8918

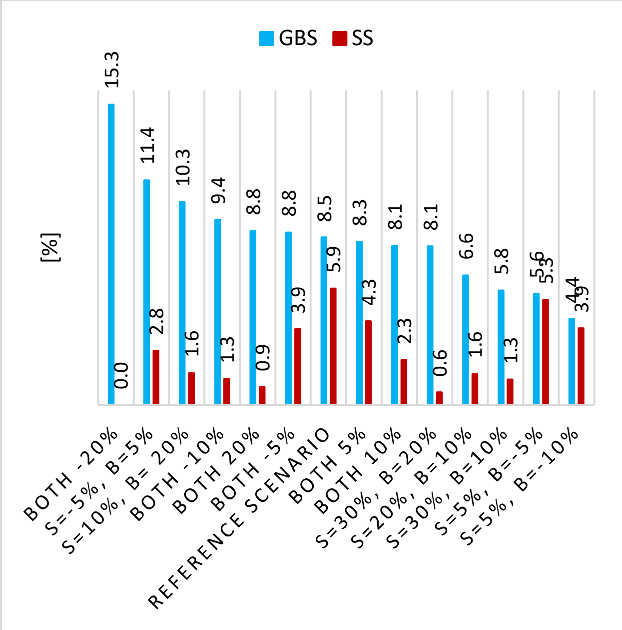

FIGURE 7. **Results of reference and alternative scenarios**

Similar gains or closer gains are obtained for the two proposed settlement mechanisms in S=5%, B=-5% or B=-10% scenarios meaning that sellers deliver 5% more and buyers consume 5% or 10% less than the reference scenario. Also, more iterative scenarios were built in Python to proof the gain limits that can be provided by GBS and SS. Therefore, we can state that GBS and SS outperforms the classic settlement approach.

6. CONCLUSION

New business opportunities for prosumers and consumers arise to locally trade the electricity surplus at better prices using blockchain platforms. In this paper, we propose a market-based trading mechanism that includes intraday auctions and settlement embedded as stored procedures into smart contracts that govern the electricity exchanges. The researchers treat the settlement similar as in centralized markets, but it is not the best solution for blockchain. Thus, we propose two novel settlement mechanisms (GBS, SS) that improves the results of the classic settlement. The simulations showed that GBS and SS mechanisms always outperform the classic approach. The encashments are increased by almost 4% and payments and reduced by 5% in the reference scenario. However, the gain of sellers and buyers can be up to 15% with GBS mechanism or almost 6% with SS mechanism as resulted from the alternative scenarios. As future scope, we will continue to adapt and enhance the two settlement mechanisms with the real-time implementation of smart contracts. For this purpose, we intend to extend the performance of trading and settlement mechanisms using a programming language for writing smart contracts, such as: Solidity, Pact, Liquidity, etc. that can be handled to implement smart contracts.

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REFERENCES

[1] M. Andoni *et al.*, "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renewable and Sustainable Energy Reviews*. 2019.

[2] J. Green and P. Newman, "Citizen utilities: The emerging power paradigm," *Energy Policy*, 2017.

[3] Ofgem, "Electricity Settlement Reform." [Online]. Available: https://www.ofgem.gov.uk/electricity/retail-market/market-review-and-reform/smarter-markets-programme/electricity-settlement-reform.

[4] J. J. Sikorski, J. Haughton, and M. Kraft, "Blockchain technology in the chemical industry: Machine-to-machine electricity market," *Appl. Energy*, 2017.

[5] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets," *Appl. Energy*, vol. 210, pp. 870–880, Jan. 2018.

[6] K. Nakayama, R. Moslemi, and R. Sharma, "Transactive Energy Management with Blockchain Smart Contracts for P2P Multi-Settlement Markets," in *2019 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2019*, 2019.

[7] R. M. Parizi, Amritraj, and A. Dehghantanha, "Smart contract programming languages on blockchains: An empirical evaluation of usability and security," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2018.

[8] M. Utz, S. Albrecht, T. Zoerner, and J. Strüker, "Blockchain-based management of shared energy assets using a smart contract ecosystem," in *Lecture Notes in Business Information Processing*, 2019.

[9] S. Yu, S. Yang, Y. Li, and J. Geng, "Distributed energy transaction mechanism design based on smart contract," in *China International Conference on Electricity Distribution, CICED*, 2018.

[10] P. Danzi, S. Hambridge, C. Stefanovic, and P. Popovski, "Blockchain-Based and Multi-Layered Electricity Imbalance Settlement Architecture," in *2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids, SmartGridComm 2018*, 2018.

[11] X. Jin *et al.*, "Blockchain-enabled Transactive Method in Distributed Systems Considering Security Constraints," in *2019 IEEE Congress on Evolutionary Computation, CEC 2019 - Proceedings*, 2019.

[12] M. Foti and M. Vavalis, "Blockchain based uniform price double auctions for energy markets," *Appl. Energy*, 2019.

[13] A. Hahn, R. Singh, C. C. Liu, and S. Chen, "Smart contract-based campus demonstration of decentralized transactive energy auctions," in *2017 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2017*, 2017.

[14] M. Sabounchi and J. Wei, "Towards resilient networked microgrids: Blockchain-enabled peer-to-peer electricity trading mechanism," in *2017 IEEE Conference on Energy Internet and Energy System Integration, EI2 2017 - Proceedings*, 2017.

[15] S. Thakur, B. P. Hayes, and J. G. Breslin, "Distributed double auction for peer to peer energy trade using blockchains," in *Proceedings of the 2018 5th International Symposium on Environment-Friendly Energies and Applications, EFEA 2018*, 2019.

[16] J. Lin, M. Pipattanasomporn, and S. Rahman, "Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets," *Appl. Energy*, 2019.

[17] M. Galici, E. Ghiani, F. Pilo, S. Ruggeri, and M. Troncia, "Blockchain local markets for the distributed control of microgrids," in *25th International Conference on Electricity Distribution*, 2019.

[18] J. Wang, Q. Wang, and N. Zhou, "A Decentralized Electricity Transaction Mode of Microgrid Based on Blockchain and Continuous Double Auction," in *IEEE Power and Energy Society General Meeting*, 2018.

[19] B. Li *et al.*, "Design of Distributed Energy Trading Scheme Based on Blockchain," *Dianwang Jishu/Power System Technology*. 2019.

[20] S. Rouhani and R. Deters, "Security, performance, and applications of smart contracts: A systematic survey," *IEEE Access*. 2019.

[21] A. Kosba, A. Miller, E. Shi, Z. Wen, and C. Papamanthou, "Hawk: The Blockchain Model of Cryptography and Privacy-Preserving Smart Contracts," in *Proceedings - 2016 IEEE Symposium on Security and Privacy, SP 2016*, 2016.

[22] Y. Yuan and F. Y. Wang, "Blockchain and Cryptocurrencies: Model, Techniques, and Applications," *IEEE Trans. Syst. Man, Cybern. Syst.*, 2018.

[23] D. Macrinici, C. Cartofeanu, and S. Gao, "Smart contract applications within blockchain technology: A systematic mapping study," *Telematics and Informatics*. 2018.

[24] Y. Zhang, S. Kasahara, Y. Shen, X. Jiang, and J. Wan, "Smart contract-based access control for the internet of things," *IEEE Internet Things J.*, 2019.

[25] P. Singh, A. Nayyar, A. Kaur, and U. Ghosh, "Blockchain and fog based architecture for internet of everything in smart cities," *Futur. Internet*, 2020.

[26] A. Kaur, A. Nayyar, and P. Singh, "Blockchain: A Path to the Future," in *Cryptocurrencies and Blockchain Technology Applications*, G. Shrivastava, D.-N. Le, and K. Sharma, Eds. Wiley, 2020, pp. 25–42.

[27] E. Mengelkamp, B. Notheisen, C. Beer, D. Dauer, and C. Weinhardt, "A blockchain-based smart grid: towards sustainable local energy markets," in *Computer Science - Research and Development*, 2018.

[28] J. Forbes, "Real-time Energy Trading with Your Neighbors via Blockchain is Way Harder Than it Sounds," 2018. [Online]. Available: https://medium.com/@causamexchange/real-time-energy-trading-with-your-neighbors-via-blockchain-is-way-harder-than-it-sounds-ee8c24dfe214.

[29] A. Gervais, G. O. Karame, K. Wüst, V. Glykantzis, H. Ritzdorf, and S. Čapkun, "On the security and performance of Proof of Work blockchains," in *Proceedings of the ACM Conference on Computer and Communications Security*, 2016.

[30] S. V. Oprea and A. Bara, "Machine Learning Algorithms for Short-Term Load Forecast in Residential Buildings Using Smart Meters, Sensors and Big Data Solutions," *IEEE Access*, 2019.

[31] S. V. Oprea, A. Bâra, Ş. Preda, and O. B. Tor, "A smart adaptive switching module architecture using fuzzy logic for an efficient integration of renewable energy sources. A case study of a RES System located in Hulubeşti, Romania," *Sustain.*, 2020.