Received: 21 December 2021 | Revised: 19 January 2022 | Accepted: 29 January 2022

IET Smart Grid

DOI: 10.1049/stg2.12058

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Evaluating the added value of blockchains to local energy markets—Comparing the performance of blockchain-based and centralised implementations

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Funding information
Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie, Grant/Award Number: IUK589/001
Open Access funding enabled and organised by Projekt DEAL

Abstract

The continuous decentralisation of the energy system due to the expansion of renewable energies requires new coordination mechanisms such as Local Energy Markets (LEMs) that are capable of integrating millions of prosumers as active participants. Since the end of the 2010s, the blockchain technology has been discussed as a potential infrastructure for LEMs and as a potential game-changer in the energy industry. In this work, the authors introduce LEM specific technology-independent infrastructure requirements, present a Solidity and Python toolbox that allows to compute a comparative performance analysis between a blockchain-based and a central LEM and evaluate the added value of a blockchain-based implementation compared to a conventional reference implementation. Simulations of a LEM with a periodic double auction and settlement showed that a blockchain-based LEM operation requires more than 140 times the computation time compared to a centralised implementation and cannot fulfil data security requirements. Thus, the authors find that blockchain technology in its current state of development does not add significant value to LEMs. All implemented programmes are published in the open-source project *lemlab* as part of the research project *RegHEE*.

1 | INTRODUCTION

Our energy system is continuously transforming from a formerly centralised system with few fossil-fuelled and nuclear power plants to a renewable, distributed, and volatile energy system consisting of millions of participants [1]. Consumers become prosumers and legislation empowers individual households to become an active part of the energy transition [2].

However, the conventional coordination mechanisms used to manage a relatively small number of fossil-fuelled power plants are not-transferable to millions of non-professional prosumer households [3]. Therefore, we need new coordination mechanisms that are capable of integrating millions of prosumers as active participants into our energy system. Recent research has investigated ideas such as aggregating single households and marketing their surplus or deficits on wholesale markets, operating them as Virtual Power Plant (VPP), letting prosumers trade among each other in Peer-to-Peer (P2P) or coordinated Local Energy Markets (LEMs), or centrally optimising their control. As nations realise the necessity for new ways of coordination, they start to incentivise, enable, or fund various variants of the aforementioned ideas [2, 4]. In this work, we focus on auction-based LEMs. LEMs allow prosumers to trade their energy surpluses and deficits locally, to react to external signals such as prices, thereby making them an active part of the energy system [5]. At the same time, LEMs do not necessarily require prosumers to disclose too much personal data and can enable grid operators to maintain grid stability [6].

Towards the end of the 2010s, researchers and the energy industry started to discuss whether the blockchain technology could provide significant benefits to LEMs while at the same time being transparent, automated, and completely decentralised [7]. Immediately following the launch of the Ethereum blockchain in 2015 and the introduction of smart contracts, a study was published by PricewaterhouseCoopers summarising the potential opportunities of lower transaction costs, transparency, and the ability to become electricity or service providers for prosumers and consumers [8]. In the same year, the German energy agency Dena conducted a survey among managers of the energy industry and found that half of the 70 managers interviewed were already experimenting with blockchains or planning to and 21% said that blockchain would become a 'game changer' in the energy industry [9]. In 2018, the Forschungsstelle für Energiewirtschaft characterised blockchain as tamper proof, reliable, transparent, highly automatable, and easily accessible and identified 91 potential use cases in the energy sector [10]. The first scientific papers on blockchains from an energy perspective investigated the potential in microgrid exchanges [11], P2P electricity trading among hybrid electric vehicles [12], and among neighbours [13, 14]. The number of scientific publications has since increased year by year [15–17]. For a detailed description of blockchain technology, see section Blockchain technology of the appendix.

Most papers investigating auction-based LEMs in a blockchain network demonstrated their feasibility on different kinds of blockchains such as Tendermint [18], Ethereum [19, 20], Hyperledger [21], proprietary blockchains [22], or compared different consensus mechanisms [23, 24]. Other papers described off-chain market-clearing algorithms, using the blockchain only to represent monetary values or to store market results [25–28]. Off-chain refers to a centralised system hosted by a single entity that retrieves data from the blockchain (on-chain), processes it on its own system, and then returns the results to the blockchain in order to reduce the computational complexity on-chain. Troncia et al. implemented different variants of LEMs on a blockchain that considered network constraints and compared them to an optimal power flow result [29]. Meeuw et al. compared and evaluated smart grid communication technologies for blockchain applications [30] and Christidis et al. analysed how market positions are efficiently encrypted on a blockchain so that closed-order book LEMs are possible [31].

Narrowing the search to papers that include an auction-based LEM on a blockchain and a performance or scalability analysis, we find papers such as Han et al. that present the throughput, latency, and computational expenses of a single setup [32, 33] or of functionally differing algorithms [34, 35]. Other papers conduct economic analyses of their implementations [27, 36]. However, no publication was found that includes an auction-based LEM on a blockchain, compares its performance to a centralised system, and assesses the actual added value of blockchains to LEMs based on application-specific infrastructure requirements.

Therefore, this paper addresses the above-mentioned research gap by investigating whether a blockchain-based implementation adds significant value to auction-based LEMs in comparison to a centralised implementation. Within this paper, we introduce application-specific infrastructure requirements for LEMs, present an open-source evaluation toolbox for centralised and blockchain-based LEM applications, discuss the results of a comparative performance analysis, and evaluate whether the implementations under investigation can fulfil the introduced requirements.

The paper is structured as follows. Section 2 introduces the application-specific infrastructure requirements for LEMs while section 3 describes the experimental setup of the evaluation toolbox with the blockchain-based and centralised LEM implementations. Section 4 presents the results of the comparative performance analysis, which are discussed in section 5. Finally, section 6 puts the findings of this paper into a broader perspective.

2 | INFRASTRUCTURE REQUIREMENTS FOR LOCAL ENERGY MARKETS

Recent technological advancements such as the blockchain technology, machine learning, Internet of things, or artificial intelligence allow us to design new systems or re-implement existing systems in new ways. Despite these new possibilities, we must define requirements for LEMs that need to be fulfiled by any infrastructure or algorithm that handles personal data and is connected to our energy system (see [35, 37, 38]). We summarise technology-independent infrastructure requirements that are in our opinion essential for LEMs in the following paragraphs.

2.1 | Reliability

A reliable software can be described by the probability of failure-free operation [39]. Applied to a LEM, we can define a 'failure-free' operation as the availability of the LEM for prosumers, grid and market operators, as well as the correct processing of data.

2.2 | Scalability

A scalable system ensures that a given quality of service is maintained as data input increases [40]. A LEM, for example, must fulfil temporal requirements such as a 15 min market interval. In addition, a scalable infrastructure must provide developers with the ability to implement the necessary functions has an only open-source community that improves and documents functionalities and bottlenecks, and, ideally, provides pre-built libraries for efficient implementations.

2.3 | Data security

An executing infrastructure must comply with existing data protection regulations, depending on the data processed. In the case of a LEM, we process personal data in the form of account balances, market positions, and meter readings, which requires the infrastructure to comply, for example, in Europe with the General Data Protection Regulation (GDPR). Market positions refer to a tuple of quantity and price placed by prosumers on LEMs in order to express their willingness to buy or sell energy. In addition, closed-order book auctions such as a Periodic Double Auction (PDA) require that market positions must be kept concealed in order to prevent gaming. Gaming refers to agent strategies that depend on the expected decisions of other agents [41] and potentially manipulate a market.

2.4 | Tamper resistance

The infrastructure must ensure that stored data cannot be manipulated, is trustworthy and should automatically detect manipulations [37]. Optimally, the validity of the data can be confirmed by anyone.

2.5 | Low operating costs

When considering LEMs for prosumers that trade on an hourly or quarter-hourly basis with traded volumes of a few 100 Wh, it is important that the operating costs of the platform do not significantly influence the incentive to participate in LEMs.

3 | EVALUATION TOOLBOX

In order to objectively compare a blockchain-based and centralised LEM, we built the comparative performance analysis toolbox for *lemlab*. The functional and implemented software components of the toolbox are described in the following subsections. Figure 1 visualises the functional components of the evaluation toolbox. The toolbox consists of a prosumer simulation, a blockchain-based, and a centralised LEM implementation. The performance analysis module is not visualised but accesses the results on the blockchain and the centralised database. The following subsections describe the functional LEM modules, implemented connector classes, used blockchain and central database configuration, and prosumer simulation.

3.1 | Local energy market functions

This section describes the main functions of the LEM from user management to market clearing and settlement. This description is technology independent since it has been mirrored on both systems.

3.1.1 | User and meter management

Before a user can participate in a LEM, a user account needs to be created, labelled, and linked to corresponding meters and their Home Energy Management Systems (HEMSs). HEMSs refer to a smart home device that collects data from the household, retrieves forecasts, has a web interface to the user, optimises operating strategies, acts on a LEM on behalf of the household, and controls the household devices accordingly. During operation it may be necessary to add new users or meters, to edit, or delete existing ones. Additionally, users and market operators must

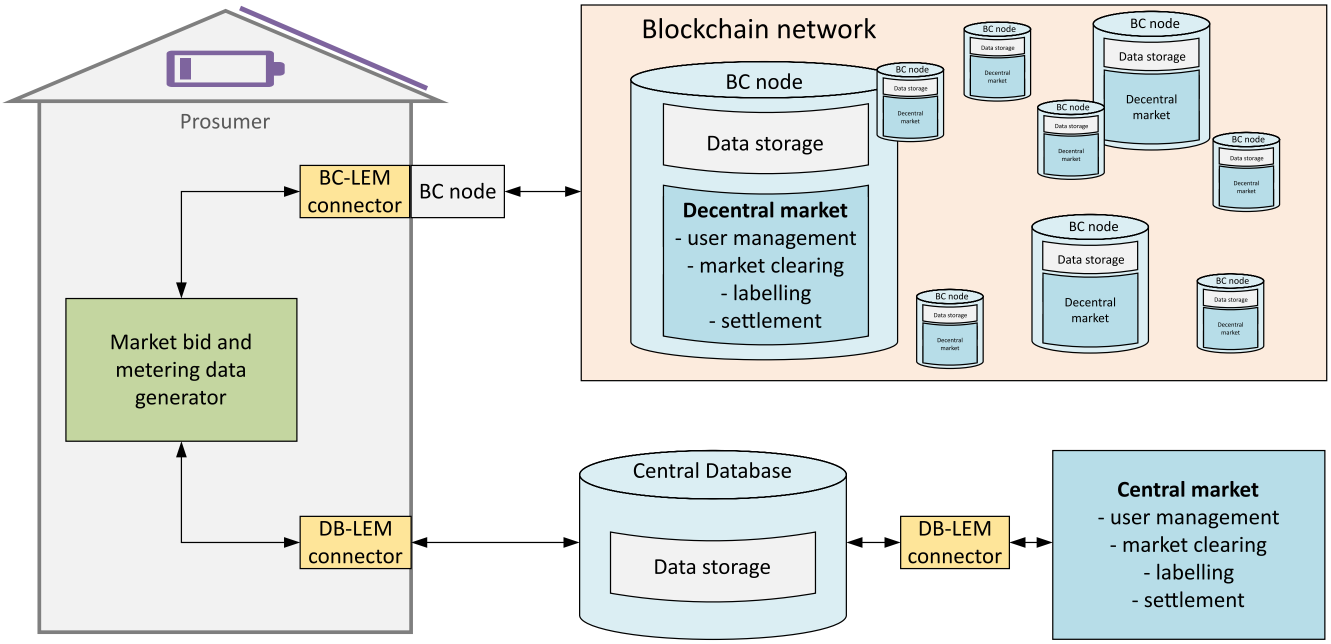

FIGURE 1 Schematic of the evaluation toolbox to analyse the performances of a blockchain-based and central Local Energy Market (LEM). The abbreviations BC refers to a blockchain module and DB to a centralised database module. The performance analysis module is not visualised in the functional overview of the toolbox but accesses the results on the blockchain and the central database

be able to access and alter their data on the LEM. The functions that manage user accounts and meters are normally executed only when a user is added or if unexpected events happen that influence user accounts (e.g. a replaced meter).

3.1.2 | Market clearing

The main goal of a LEM is to match supply and demand energy locally between prosumers. However, different approaches exist which differ greatly and can be distinguished by their market-clearing time. If a LEM is cleared before the energy is exchanged between LEM participants, we talk about an ex-ante clearing. For an ex-ante clearing, we need feed-in and consumption forecasts and a settlement that calculates differences between market results and meter readings. A LEM that clears energy after it has been exchanged is called an ex-post clearing and does not require any forecasts. In this context, we will often talk about the time of delivery that refers to the starting point of the energy exchange period. The toolbox presented in this paper contains an ex-ante clearing but can be easily extended to incorporate ex-post clearings.

Market-clearing algorithms can be further distinguished by the clearing mechanism. In the literature, we often find a Continuous Double Auction (CDA) that clears the market whenever new market positions are placed on the LEM or a PDA that clears the market at pre-defined intervals [42]. Since CDAs discriminate prosumers with slower internet connections and motivate high-frequency trading [43], we implemented a standard PDA in the LEM toolbox that clears in quarter-hourly intervals market positions based on their quantity and price. Market positions are placed by market agents that trade energy on LEMs on behalf of prosumer households.

In summary, the market-clearing functions read stored market positions, compute a sorted ascending supply and a descending demand curve, find the intersection of the two, calculate a uniform clearing price, label cleared positions, and store them.

3.1.3 | Settlement

After the ex-ante market clearing and the exchange of energy took place for a specific time of delivery, the LEM needs to be settled. Settling a market refers to functions that are executed after meter readings are transferred to the LEM. After the arrival of meter readings, balancing energies can be calculated for each user. Balancing energy refers to the differences between market results and measured energy consumption and feed-in. Based on balancing energies user accounts are credited or debited by the appropriate amounts. Finally, price components such as grid fees and taxes are applied.

3.1.4 | Labelling

Labels in a LEM offer prosumers information about the origin of their consumed electricity and ideally motivate consumers to consume more climate-neutral and less fossil-fuelled energy (see [44]). In the evaluation toolbox presented in this paper, the labelling of energy quantities is implemented in all of the aforementioned LEM functions as pre-defined energy qualities. Energy qualities refer to labels such as green, local, or local-green electricity but can be easily replaced by any other label type.

During a user registration, each meter that measures energy feed-in is labelled with a specific energy quality. Whenever prosumers wish to sell energy from or to the LEM, market agents on behalf of their prosumer households place ask positions with the quality labels of their meters on the LEM. After the PDA, cleared energy qualities can then be labelled based on the shares of the cleared ask positions. Finally, settlement functions label balancing energies based on the actual shares exchanged in the LEM or as an unknown energy quality.

3.2 | Local energy market connectors

In order to interact with the central database and the blockchain infrastructure, we implemented two Python classes that abstract all interactions with the two database infrastructures for the LEM user. These connectors retrieve data from the databases, trigger functions in smart contracts, and wait for transaction receipts in order to ensure a completed execution.

3.3 | Ethereum blockchain

This subsection describes all components that are necessary to implement a LEM on a private or consortium Ethereum blockchain. The words private and consortium indicate the accessibility and operation type of the blockchain network. Private blockchains are operated and useable only by a homogeneous group such as a company, whereas consortium blockchains are operated and managed by a variety of groups or institutions [45].

As this paper focusses on the implementation of a LEM application, we used a private blockchain with a Proof-of-Authority (PoA) consensus mechanism. This setup allows us to have an insignificant energy demand, to minimise external influences, and to modify the blockchain's parameters according to our will (see [24]). We set up two Linux machines as block validators, signing blocks every 5 s. To allow LEM executions with more than a hundred market positions, we set the block gas limit to 1.5 billion gas. All connected nodes use OpenEthereum clients that establish the connection to the network.

In Ethereum, all functions are implemented in smart contracts. The following paragraphs summarise their functional scope.

ClearingExAnte: the contract contains all functions for the market clearing and stores static and dynamic user data. Static user data refer to users' identifiers on the platform and their related meters. Dynamic user data refer to their placed market positions. As for the clearing functionality, we implemented functions that sort all placed market positions, filter them by their time of delivery, calculate a market-clearing price, calculate the cleared energy qualities, and update user balances. In addition, the contract contains functions to add, edit, or remove users and meters, and to place market positions.

Settlement: functions that are executed after energy has been exchanged between LEM users and meter readings are available. In this contract, we store all meter readings, balancing energies, and settlement prices in a 'rolling horizon array' for a configurable number of timesteps. The rolling horizon approach allows us to keep the storage consumption to a minimum. Past data can be accessed via past blocks. Furthermore, this contract is linked to the *ClearingExAnte* contract at deployment in order to access market results and user data.

Sorting, *Param*, and *LEMLib*: in addition to the core modules *ClearingExAnte* and *Settlement,* we implemented a variety of reusable subcontracts that contain static LEM parameters, data structures for exchanged and stored information, sorting algorithms, and a variety of array functions, for example, finding the minimal and maximal value of an array. Especially, the sorting library with implementations of *quick_sort*, *counting_sort*, and *insertion_sort* offers a variety of different sorting algorithms in Solidity. These functions are implemented in the contracts *Sorting*, *Param*, and *LEMLib*.

3.4 | Central database

Our central reference database setup is a relational database implemented as a PostgreSQL server. On this server, we set up roles for market operators and users who have different reading and writing privileges on the different tables. Features such as composite keys and upsert statements are used in order to prevent data collisions. Multiple tables store LEM data ranging from static user and meter information to dynamic market positions and results, meter readings, balancing energies, and settlement prices. The number of tables increases if additional market-clearing variants are executed in parallel.

3.5 | Prosumer

In a real-world setting, a prosumer would need to be equipped with a HEMS that acts on the LEM on behalf of the prosumer, and a smart meter to reliably transmit verified meter readings to the platform. Such a prosumer configuration is set up in a German field trial with 17 households as part of the research project RegHEE—Local Trade of Renewable Energies and Labelling on a Blockchain Platform [46]. As the focus of this paper is not to precisely model prosumer behaviour but to analyse whether the LEM requirements can be fulfiled by a blockchain-based LEM and a centralised approach, we simulated prosumer inputs in a data generator arbitrarily (see Figure 1).

During market initialisation, we generate a pre-defined number of user accounts and associated smart meters and register them on the two LEM platforms. Afterwards, the bid generator creates a random set of market positions based on parameter ranges given in Table 1 and pushes them into the two LEMs. After the ex-ante market clearing is completed, the data generator retrieves the market-clearing results from the LEM platforms, adds or subtracts an arbitrary value from the market results and reinserts these values as meter readings to the platform. The arbitrary values simulate deviations from the market results. In order to generate independent and identically distributed (i.i.d.) random data samples, we used the numpy package *random*.

4 | COMPARATIVE PERFORMANCE ANALYSIS

This section presents a quantitative performance evaluation of the decentral blockchain-based LEM and the central database LEM. After briefly describing the setup of the analysis, we will present the results of the analysis in three parts: an equality check, a time complexity analysis, and a computational effort analysis of the blockchain-based LEM. The script to conduct this or similar analyses is publicly available in the open-source project *lemlab* [47].

4.1 | Configuration

For this performance analysis, we implemented automated test cases that insert a random set of market bids, clear the centralised and blockchain-based LEM using the same market positions, simulate meter readings with arbitrary deviations from the market results, and settle the central and blockchain-based LEMs according to the meter readings. These test cases were executed for 50 to 550 market positions with an increment of 50. The maximum number of 550 inserted market positions is a direct consequence of the set block gas limit of 1.5 billion gas. The block gas limit refers to the maximum number of operations, measured in Ethereum's own computational currency gas, that can be inserted into a block to ensure a decentralised consensus mechanism. In each test, we measure the execution time for position placement, market clearing, logging of meter readings, and market settlement. Additionally, we measure the gas consumption and compare

TABLE 1 Parameters used in the comparative performance analysis to simulate prosumer buy and ask bids on the LEM

Parameter	Value range	Unit
type	{buy, sell}	-
qty	U(1, 1000)	Wh
price	U(0.2, 0.1)	€/kWh

whether the results of the two markets are equivalent. All test cases and market position placements are executed from a single computer that is connected to the institute's Local Area Network (LAN). The two blockchain authorities and the central database server are connected to the same network. In order to reduce the impact of blockchain node instabilities and network loads, we executed all test cases 10 times and restart a test in case of connection problems. Hence, a total of 110 simulations in approximately 22 h were executed for this analysis.

4.2 | Equivalence analysis

Before we compare the computation time of the blockchain-based and central LEM, we need to ensure that both implementations computed equivalent results. However, equivalent results must be defined first. Since the PDA only sorts market positions by price, it is possible that positions from different users but of the same type and price lead to different results on two different systems because the sorting might place one position before the other. Even though, the results are not equal they can be considered equivalent and valid as long as they maximise social welfare and ensure individual rationality. Therefore, we considered market results equivalent if they cleared an equal social welfare. Social welfare is defined as the area enclosed by the supply and demand curve and the y-axis [48]. All 110 simulated test cases resulted in equivalent market-clearing results. Thus, we have demonstrated that a blockchain-based LEM is capable of computing equivalent results to a centralised implementation.

4.3 | Time complexity analysis

In this subsection, we present the results of the time complexity analysis. In a time complexity analysis, we insert an increasing amount of data into our function under investigation and measure the times basic operations are executed or the wall clock time the algorithm under investigation requires to process inserted data. In a blockchain setup, we need to consider a significant amount of time to wait for transaction receipts that ensure the correct processing of the data. Therefore, a pure consideration of the basic operations would be insufficient. Hence, we assume wall clock measurements of a time complexity analysis with 10 simulations of the same experimental setup and visualising the distribution of those measurements as a reasonably accurate approach to evaluate and compare the performance of the centralised and blockchain-based LEM. We acknowledge that wall clock measurements are dependent on the network load and the executing machine. Therefore, we limited the blockchain network load as much as possible by only executing LEM-related transactions during the experiment. These measurements are then used to evaluate the performance and scalability of the two LEM implementations.

Figure 2 shows the computation time of the centralised and blockchain-based LEM. The measurements include the time to post the market positions on the LEM, calculate a market-clearing price, log meter readings, and settle the LEM. Additionally, we calculated the ratio of the means of the computation times for each number of inserted positions. All shown data points were fitted with polynomials from the numpy *polyfit* library. Coefficients and residuals for the fitting curves are summarised in Table A1.

Since both versions of LEM are triggered and run on the same computer, the results depend on the computer's performance. As the simulations ran for approximately 22 h inside the institute's internal network, we were not able to exclude all peripheral network load effects. However, the spreads of results across the 10 samples in Figure 2 show that most peripheral network load effects were within insignificant ranges and allow us to use our timing results as reasonable comparative parameters. The centralised LEM takes 0.65 s to process 50 and 2.3 s for 550 market bids. The green dotted curve represents a second-order polynomial.

The blockchain-based LEM processes 50 bids in 94 s and 550 bids in 1343 s on average. The blue dotted curve is a second-order polynomial. Diamond markers in Figure 2 visualise the ratio between the mean blockchain-based and centralised LEM computation times and allow us to quantify the performance of the two algorithms independent of the executing machine's performance. We see that the computation time for 50 bids is 144 times and, for 550 bids, it is 583 times larger than on the blockchain-based LEM.

Since the calculation time for 450 entered market positions already exceeds a 15 min market interval, we consider the entered number of market positions to be sufficient to evaluate the usability of a blockchain-based LEM in a realistic environment.

Furthermore, we analysed which functions require the most computation time and visualised the percentage of computation time for the centralised and blockchain-based LEM in Figure 3. In the case of the central LEM, the computation shares stay almost constant from 50 to 550 inserted bids. Posting bids consumes from 2.6% to 5.5%, logging meter readings less than 1%, clearing the market 41%–44%, and settling the market 52%–56% of the computation time on the central LEM. On the blockchain-based LEM, the shares shift from the lowest to the highest amount of inserted bids significantly. The share for market clearing increases from 38% for 50 inserted bids to 58% for 550 bids. At the same time, the share for the market settlement decreases from 53% for 50 bids inserted to 37% for 550 bids. Posting bids and logging meter readings stay in the ranges from 5% to 1% of the computation time.

Based on these results, the blockchain-based market-clearing algorithm should be the first to be investigated in terms of its optimisation potential. The appendix contains the results of the Ethereum-specific gas consumption (see Figure A1).

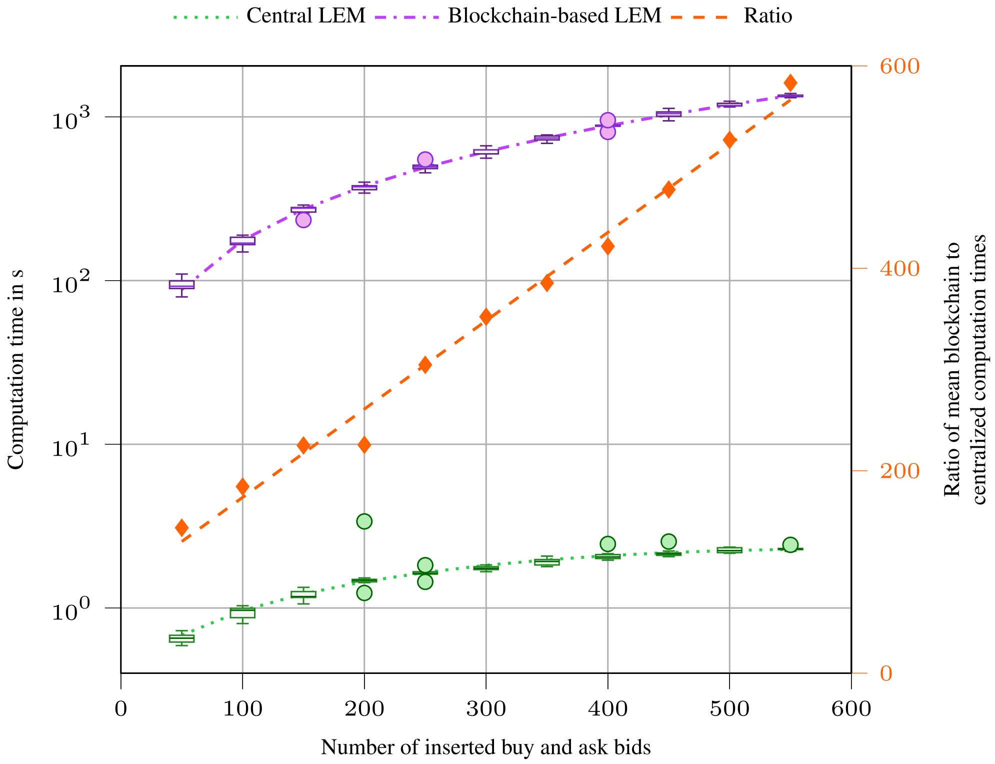

FIGURE 2 Purple and green box plots show the computation time in seconds on the left *y* axis. Outliers are marked as circles. Boxes indicate the first and third quartile, and whiskers 1.5 of the inter-quartile range (between first and third quartile). Orange markers indicate the ratios of mean blockchain to centralised Local Energy Market (LEM) computation times as a scatter plot on the right *y* axis. Coefficients for the polynomial fitting curves are summarised in Table A1

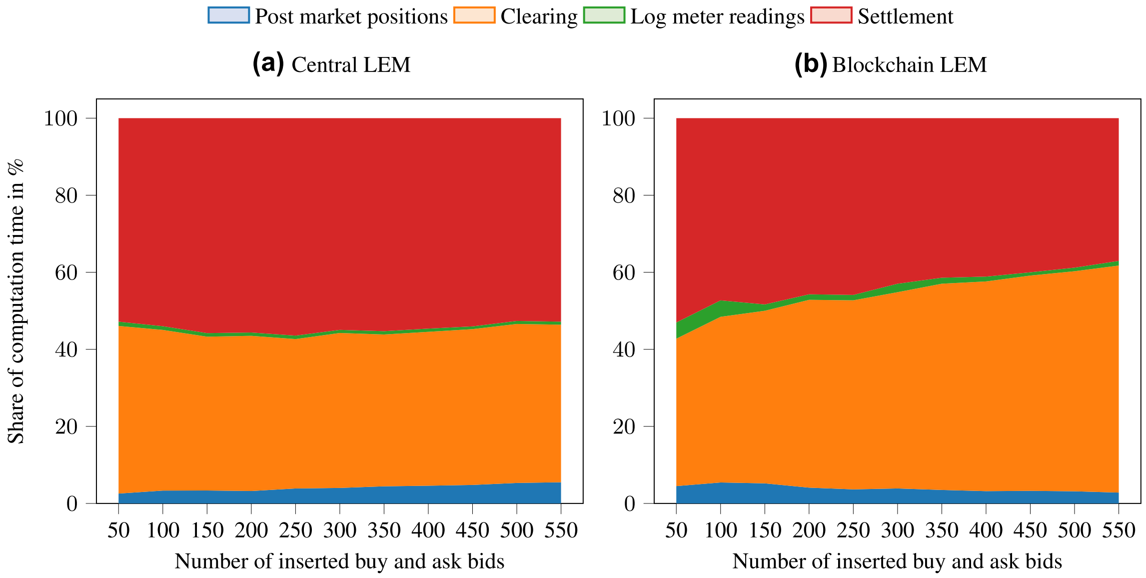

FIGURE 3 Share of computation time used for the main Local Energy Market (LEM) functions: posting bids, market clearing, meter reading logging, and market settlement in the blockchain-based and central LEM

5 | DISCUSSION

We will first discuss whether both implementations meet the LEM specific infrastructure requirements introduced in section 2 before putting the results in a broader perspective.

As mentioned in section 4.2, we were able to compute equivalent results on the blockchain-based and central LEM. Hence, we conclude that both implementations are reliable in terms of correct data processing. It is worth mentioning that this correct data processing was only possible with the help of waiting periods for transaction receipts that increased the overall computation time extensively and made the wall time measurements necessary for the time complexity analysis. In addition, the blockchain-based LEM did not prove to be continuously available during the analysis because the blockchain node lost frequently the connection to the network and needed to be restarted due to unidentifiable synchronisation problems. On the other hand, the central LEM did not cause any connection problems during our analysis. Hence, we conclude that the blockchain-based LEM is less reliable for a continuous operation compared to a centralised implementation.

As the open-source project *lemlab* shows, a LEM is programmable and deployable on an Ethereum blockchain network. The results of the performance analysis indicate that the implemented blockchain-based LEM is scalable up to 400 bids in a time of less than 900 s, which would correspond to a 15-min market interval. Further improvements in the code can potentially increase the number of processable market positions in both implementations but we do not expect the relative difference of computation times to be significantly affected. Therefore, we conclude that the blockchain-based LEM is limited in its scalability and would likely not allow the use of advanced market-clearing algorithms such as optimisation functions. The central LEM processed 550 market positions in less than 3 s and single experiments showed that 10,000 market positions can be processed in less than 5 min. Noteworthy are the necessary modifications of the blockchain parameters such as gas floor target, transaction gas limit, and gas capacity to 1.5 billion gas in order to insert transactions for the market clearing with more than 1 billion gas. If we would have kept them at their default with an average of 15 million gas, we would not have been able to process 50 bids on the LEM and would have needed to split the functionality further apart.

In addition, we want to point out major challenges that hindered an efficient implementation: basic libraries for sorting and filtering data on blockchains are not available, variable size arrays could not be initialised, debugging Solidity code is still a major obstacle and slows down development due to missing integrated development environments for larger code projects, and the stability of blockchain nodes on Windows machines was insufficient for development but could potentially be fixed with additional blockchain authorities running on Windows machines.

Whether our implementation is GDPR compliant and a pseudonym for users is sufficient to anonymise personal data is a matter of legal assessment and is likely to vary from country to country. What we can say with certainty is that all market positions and meter readings are transmitted to the blockchain network as unencrypted transactions. However, the blockchain-based LEM can be gamed as long as the positions are written unencrypted to the blockchain. Christidis et al. presented three variants of encrypting positions in a first phase and sending a key for their decryption in a second phase that potentially can avoid LEM gaming [31]. Nevertheless, position encryption and decryption would increase computation time and would not be useful for privacy applications such as logging of meter readings. Overall, we conclude that the blockchain-based LEM implementation cannot fulfil the data security requirement. The central LEM can fulfil the requirement as long as the position and meter reading transfer can be encrypted and the access rights to the central database are carefully designed.

By nature, data that is stored in the state of the blockchain is tamper proof as long as hash functions cannot be reversed. In this context, the blockchain has a significant advantage over a centralised system that stores data on a proprietary server and can manipulate it at will. Nevertheless, we would like to emphasise that trusted entities that insert data into the blockchain are potential vulnerabilities in terms of tamper proof. If they are not completely trustworthy, the advantage of a tamper-proof blockchain is gone. In contrast, the possibilities to manipulate a central LEM are for a market operator manifold. Therefore, a tamper-resistant central LEM requires all LEM participants' trust.

In order to ensure a continuous prosumer household participation, operating costs need to be low, especially, when we consider the significantly smaller energy quantities, compared to a wholesale electricity market. Since we used an energy-efficient PoA consensus mechanism in our setup, the energy demand is insignificantly low and can be compared to a centralised setup that has redundant servers running (see section Blockchain technology). Therefore, we conclude that low operating costs are achievable with a central and a blockchain-based LEM implementation. Table 2 summarises the LEM requirement analysis.

Finally, the question remains as to how decentralised our blockchain-based LEM actually is. In our LEM, we need a market operator who adds users, maps them to their meter readings, keeps them accountable for their actions on the LEM, and triggers the market clearings periodically. Some of those functionalities could be implemented in smart contracts but would further inflate the computation time and were out of the scope of this project. Additionally, we would need to select trustworthy authorities that validate new blocks and ensure that they do not illegally collude. In summary, a decentralised blockchain-based LEM would need to be designed extremely carefully, is not readily feasible, and may need to be regulated.

TABLE 2 Qualitative comparison of Local Energy Market requirement fulfilment

LEM requirement	Central LEM	Blockchain-based LEM
Reliability	+ +	+[b]
Scalability	+ +	–[c]
Data security	+ +	– –
Tamper resistance	+[a]	+ +
Low operating costs	+ +	+ +[d]

[a] If market operator trustworthy.

[b] If we wait for transaction receipts.

[c] Up to 400 market positions for a 15 min market interval.

[d] If we use energy-efficient and not completely decentralised consensus mechanisms.

6 | CONCLUSION

This paper presents LEM specific infrastructure requirements, a modular open-source Solidity toolbox for LEMs that allows to develop applications for a blockchain-based and a central reference setup in parallel and to quantify and evaluate their performances against each other. Furthermore, we show the results of a comparative performance analysis and discuss whether the technology-independent LEM specific infrastructure requirements are met by the blockchain-based and central LEM implementations. Our results indicate that the blockchain promises of a decentrally and transparently managed infrastructure can only be realised to a limited extent in the context of LEMs, that a blockchain-based LEM implementation is reliable but requires more than 140 times the computation time compared to a centralised implementation, and cannot fulfil data security requirements. Only the tamper resistance represents a significant added value that comparable centralised implementations cannot provide to a similar degree. Thus, we conclude that blockchain technology in its current state of development is not a 'game changer' for LEMs. Nevertheless, we invite researchers to collaborate and work on the open-source LEM toolbox [47], adapt it to their needs, and send us their suggestions for improvements. The solidity toolbox for LEMs is another part in the scientific toolset to model prosumer-centric applications more precisely and evaluate the potential of blockchain implementations in the energy context. Future research should focus on the identification of optimisation potential, verifiable tamper resistance in proprietary systems, data security on blockchains and their legal assessment, and a deeper analysis of the timing complexity.

ACKNOWLEDGEMENTS

This work was funded by the Bavarian Ministry of Economic Affairs, Regional Development and Energy, Germany and supported by the Zentrum Digitalisierung.Bayern, Germany (grant number IUK589/001).

Open access funding enabled and organised by Projekt DEAL.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in lemlab repository at https://github.com/tum-ewk/lemlab.

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REFERENCES

1. Renewable capacity statistics 2021 (19.04.2021) https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021
2. European Parliament, Council of the European Union. Directive (eu) 2019/944 of the european parliament and of the council of 5 june 2019 on common rules for the internal market for electricity and amending directive 2012/27/eu (recast): directive (eu) 2019/944 (06/2019) (2019). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2019.158.01.0125.01.ENG&toc=OJ:L:2019:158:TOC
3. Khorasany, M., Mishra, Y., Ledwich, G.: Market framework for local energy trading: a review of potential designs and market clearing approaches, IET Generation. Transm. Distrib. 12(22), 5899–5908 (2018). https://doi.org/10.1049/iet-gtd.2018.5309
4. Post-2025 market design: directions paper (2021). https://esb-post2025-market-design.aemc.gov.au/32572/1609802925-p2025-january-directions-paper.pdf
5. Mengelkamp, E.M.: Engineering local electricity markets for residential communities (2019). https://doi.org/10.5445/IR/1000095229
6. Tushar, W., et al.: Peer-to-peer energy systems for connected communities: a review of recent advances and emerging challenges. Appl. Energy. 282, 116131 (2021). https://doi.org/10.1016/j.apenergy.2020.116131
7. Andoni, M., et al.: Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew. Sustain. Energy Rev. 100, 143–174 (2019). https://doi.org/10.1016/j.rser.2018.10.014
8. von Perfall, A., et al.: Blockchain - chance für energieverbraucher? kurzstudie für die verbraucherzentrale nrw. düsseldorf (2016)
9. Burger, C., et al.: Blockchain in der energiewende (2016). https://www.esmt.org/system/files_force/dena_esmt_studie_blockchain_deutsch_0.pdf?download=1&download=1
10. Bogensperger, A., et al.: Die blockchain-technologie - chance zur transformation der energiewirtschaft? berichtsteil anwendungsfälle (2018). https://www.ffe.de/attachments/article/846/Blockchain_Teilbericht_UseCases.pdf
11. Wang, J., et al.: A novel electricity transaction mode of microgrids based on blockchain and continuous double auction. Energies. 10(12), 1971 (2017). https://doi.org/10.3390/en10121971
12. Kang, J., et al.: Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains. IEEE Trans. Ind. Inf. 13(6), 3154–3164 (2017). https://doi.org/10.1109/TII.2017.2709784
13. Peck, M.E., Wagman, D.: Energy trading for fun and profit buy your neighbor's rooftop solar power or sell your own-it'll all be on a blockchain. IEEE Spectrum. 54(10), 56–61 (2017). https://doi.org/10.1109/MSPEC.2017.8048842
14. Sabounchi, M., Wei, J.: Towards resilient networked microgrids: blockchain-enabled peer-to-peer electricity trading mechanism. In: IEEE conference on energy internet and energy system integration, pp. 1–5. EI2 (2017). https://doi.org/10.1109/EI2.2017.8245449
15. Ante, L., Steinmetz, F., Fiedler, I.: Blockchain and energy: a bibliometric analysis and review. Renew. Sustain. Energy Rev. 137, 110597 (2021). https://doi.org/10.1016/j.rser.2020.110597
16. Wang, Q., Li, R., Zhan, L.: Blockchain technology in the energy sector: from basic research to real world applications. Comput. Sci. Rev. 39, 100362 (2021). https://doi.org/10.1016/j.cosrev.2021.100362
17. Hasankhani, A., et al.: Blockchain technology in the future smart grids: a comprehensive review and frameworks. Int. J. Electr. Power Energy Syst. 129, 106811 (2021). https://doi.org/10.1016/j.ijepes.2021.106811
18. Brousmichc, K.-L., et al.: Blockchain energy market place evaluation: an agent-based approach. In: IEEE 9th annual information technology, electronics and mobile communication conference (IEMCON), pp. 321–327. IEEE (2018). https://doi.org/10.1109/IEMCON.2018.8614924. 01.11.2018 - 03.11.2018
19. Okwuibe, G.C., et al.: A blockchain-based double-sided auction peer-to-peer electricity market framework. In: IEEE electric power and energy conference (EPEC), pp. 1–8. IEEE (2020). https://doi.org/10.1109/EPEC48502.2020.9320030. 09.11.2020 - 10.11.2020
20. Zhang, C., Yang, T., Wang, Y.: Peer-to-peer energy trading in a microgrid based on iterative double auction and blockchain. Sustainable Energy,

Grids and Networks. 27, 100524 (2021). https://doi.org/10.1016/j.segan.2021.100524

21. Doan, H.T., Cho, J., Kim, D.: Peer-to-peer energy trading in smart grid through blockchain: a double auction-based game theoretic approach. IEEE ACCESS. 9, 49206–49218 (2021). https://doi.org/10.1109/ACCESS.2021.3068730
22. Chen, S., et al.: A trusted energy trading framework by marrying blockchain and optimization. Adv. Appl. Energy. 2, 100029 (2021). https://doi.org/10.1016/j.adapen.2021.100029
23. Heck, K., Mengelkamp, E., Weinhardt, C.: Blockchain-based local energy markets: decentralized trading on single-board computers. Energy Systems. 12(3), 603–618 (2021). https://doi.org/10.1007/s12667-020-00399-4
24. Machacek, T., Biswal, M., Misra, S.: Proof of x: experimental insights on blockchain consensus algorithms in energy markets. In: IEEE power & energy society innovative smart grid technologies conference (ISGT), pp. 1–5. IEEE (2021). https://doi.org/10.1109/ISGT49243.2021.9372194. 16.02.2021–18.02.2021
25. Blom, F., Farahmand, H.: On the scalability of blockchain-supported local energy markets. In: International conference on smart energy systems and technologies (SEST), pp. 1–6. IEEE (2018). https://doi.org/10.1109/SEST.2018.8495882. 10.09.2018–12.09.2018
26. Liu, S., et al.: A high-performance local energy trading cyber-physical system based on blockchain technology. IOP Conf. Ser. Earth Environ. Sci. 227, 032009 (2019). https://doi.org/10.1088/1755-1315/227/3/032009
27. Foti, M., Vavalis, M.: Blockchain based uniform price double auctions for energy markets. Appl. Energy. 254, 113604 (2019). https://doi.org/10.1016/j.apenergy.2019.113604
28. Esmat, A., et al.: A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. Appl. Energy. 282, 116123 (2021). https://doi.org/10.1016/j.apenergy.2020.116123
29. Troncia, M., et al.: Distributed ledger technologies for peer-to-peer local markets in distribution networks. Energies. 12(17) (2019). https://doi.org/10.3390/en12173249
30. Meeuw, A., Schopfer, S., Wortmann, F.: Experimental bandwidth benchmarking for p2p markets in blockchain managed microgrids. Energy Proc. 159, 370–375 (2019). https://doi.org/10.1016/j.egypro.2018.12.074
31. Christidis, K., et al.: A framework for designing and evaluating realistic blockchain-based local energy markets. Appl. Energy. 281, 115963 (2021). https://doi.org/10.1016/j.apenergy.2020.115963
32. Han, D., et al.: Smart contract architecture for decentralized energy trading and management based on blockchains. Energy. 199, 117417 (2020). https://doi.org/10.1016/j.energy.2020.117417
33. Son, D., Al Zahr, S., Memmi, G.: Performance analysis of an energy trading platform using the ethereum blockchain. In: 2021 IEEE international conference on blockchain and cryptocurrency (ICBC), pp. 1–3. IEEE (2021). https://doi.org/10.1109/ICBC51069.2021.9461115. 03.05.2021 - 06.05.2021
34. Vieira, G., Zhang, J.: Peer-to-peer energy trading in a microgrid leveraged by smart contracts. Renew. Sustain. Energy Rev. 143, 110900 (2021). https://doi.org/10.1016/j.rser.2021.110900
35. Tsaousoglou, G., et al.: Truthful, practical and privacy-aware demand response in the smart grid via a distributed and optimal mechanism. IEEE Trans. Smart Grid. 11(4), 3119–3130 (2020). https://doi.org/10.1109/TSG.2020.2965221
36. Oprea, S.V., Bara, A., Andreescu, A.I.: Two novel blockchain-based market settlement mechanisms embedded into smart contracts for securely trading renewable energy. IEEE ACCESS. 8, 212548–212556 (2020). https://doi.org/10.1109/ACCESS.2020.3040764
37. Muzumdar, A., et al.: A trustworthy and incentivized smart grid energy trading framework using distributed ledger and smart contracts. J. Netw. Comput. Appl. 183-184, 103074 (2021). https://doi.org/10.1016/j.jnca.2021.103074
38. Tushar, W., et al.: Peer-to-peer trading in electricity networks: an overview. IEEE Trans. Smart Grid. 11(4), 3185–3200 (2020). https://doi.org/10.1109/TSG.2020.2969657
39. Iannino, A., Musa, J.D.: Software reliability Advances in Computers Volume 30, pp. 85–170. Elsevier (1990). https://doi.org/10.1016/S0065-2458(08)60299-5
40. Steed, A., Oliveira, M.F.: Scalability. In: Networked graphics, pp. 393–458. Elsevier (2010). https://doi.org/10.1016/B978-0-12-374423-4.00012-4
41. Fudenberg, D., Tirole, J.: Game theory, 6th ed. MIT Press, Cambridge (1998)
42. Shoham, Y., Leyton-Brown, K.: Multiagent systems: algorithmic, game-theoretic, and logical foundations. Cambridge University Press, Cambridge (2009). https://doi.org/10.1017/CBO9780511811654
43. Wah, E., Hurd, D., Wellman, M.: Strategic market choice: frequent call markets vs. continuous double auctions for fast and slow traders. In: Proceedings of the the third conference on auctions, market mechanisms and their applications. ACM (2015). https://doi.org/10.4108/eai.8-8-2015.2260356
44. Harrington, L., Waide, P.: Labels and standards for energy. In: Encyclopedia of energy, pp. 599–611. Elsevier (2004). https://doi.org/10.1016/B0-12-176480-X/00471-X
45. Song, Z., Zhang, X., Liang, M.: Reliable reputation review and secure energy transaction of microgrid community based on hybrid blockchain. Wireless Commun. Mobile Comput. 2021, 1–17 (2021). https://doi.org/10.1155/2021/9916735
46. Zade, M., Lumpp, S.D., Sperling, U.: Reghee - regionaler handel und stromkennzeichnung von erneuerbaren energien über eine blockchain-plattform (2021). https://reghee.de/
47. Lumpp, S.D., et al.: An open-source tool for the agent-based development and testing of local energy market applications (2021). https://github.com/tum-ewk/lemlab
48. Zade, M., et al.: Satisfying user preferences in community-based local energy markets — auction-based clearing approaches. Appl. Energy. 306, 118004 (2022). https://doi.org/10.1016/j.apenergy.2021.118004
49. Edgar, T.W., Manz, D.O.: Science and cyber security. In: Research methods for cyber security, pp. 33–62. Elsevier (2017). https://doi.org/10.1016/B978-0-12-805349-2.00002-9
50. Wood, G.: Ethereum: a secure decentralized generlised transaction ledger berlin version (2021). https://ethereum.github.io/yellowpaper/paper.pdf
51. N. Alzahrani, N. Bulusu, Towards true decentralization: a blockchain consensus protocol based on game theory and randomness, In: L. Bushnell, R. Poovendran, T. Başar (Eds.), Decision and Game Theory for Security, Volume. 11199 of Lecture Notes in Computer Science, Springer International Publishing, Cham, 2018, pp. 465–485. https://doi.org/10.1007/978-3-030-01554-1_27
52. Rauchs, M., Dek, A., Blandin, A.: Cambridge bitcoin electricity consumption index (2021). https://ccaf.io/cbeci/index
53. Zade, M., et al.: Is bitcoin the only problem? a scenario model for the power demand of blockchains. Front. Energy Res. 7 (2019). https://doi.org/10.3389/fenrg.2019.00021
54. Oyinloye, D.P., et al.: Blockchain consensus: an overview of alternative protocols. Symmetry. 13(8), 1363 (2021). https://doi.org/10.3390/sym13081363

How to cite this article: Zade, M., et al.: Evaluating the added value of blockchains to local energy markets—Comparing the performance of blockchain-based and centralised implementations. IET Smart Grid. 5(4), 234–245 (2022). https://doi.org/10.1049/stg2.12058

APPENDICES

Acronyms

BC	Blockchain
CDA	Continuous Double Auction
DB	Database
GDPR	General Data Protection Regulation
HEMS	Home Energy Management System
LAN	Local Area Network
LEM	Local Energy Market
P2P	Peer-to-Peer
PDA	Periodic Double Auction
PoA	Proof-of-Authority
PoW	Proof-of-Work
VPP	Virtual Power Plant

Blockchain technology

Blockchains are virtual state machines that store data on distributed nodes. The data inserted into a blockchain becomes part of the blockchain's state and is stored as a hashed value in discrete blocks. Hash values refer to outputs of one-way mathematical functions that compute a unique value of a pre-defined length for any kind of input data but make it very difficult to reproduce the input data based on a hash value [49]. Blocks contain the current state and all requested state changes in the form of transactions [50]. When we talk about a chain of blocks, we are referring to each new block that contains a hash value of the previously added block. Advanced blockchains such as Ethereum allow us to deploy code on a blockchain and process data in a programmable manner. These scripts are informally known as smart contracts [50].

In order to decide what state changes are valid, so-called consensus mechanisms were developed for blockchains. Consensus mechanisms refer to network protocols that define how a network of equal and independent nodes can agree on the validity of current and historical states of the shared data [51]. The most prominent consensus mechanism is Proof-of-Work (PoW). PoW allows all nodes in a network to add new blocks to the chain as long as they provide a proof of their 'work' in the form of a hash value that contains all inserted transactions and fulfils a certain condition. This condition could be a certain number of leading zeros. Nodes are motivated to prove their work to the network because they are rewarded with coins in the blockchain's own currency if they are the first ones that compute a hash value that fulfils the aforementioned conditions. The outcome of a hashing function cannot be foreseen with today's computers and therefore must be computed by trial and error. This process is energy intensive and therefore widely criticised [52, 53]. To avoid the high energy demand in blockchains, the PoA consensus mechanism was introduced [54]. As the name indicates, selected authorities are allowed to validate blocks and append them to the blockchain. This reduces the energy demand of the blockchain significantly but at the same time does not provide a similarly decentralised structure as the PoW consensus mechanism. Over the past years, a variety of other consensus mechanisms were proposed to tackle these challenges [54].

Polynomial fitting functions and residuals

Table A1 lists all polynomial coefficients used to fit the data in Figure 2 and residuals.

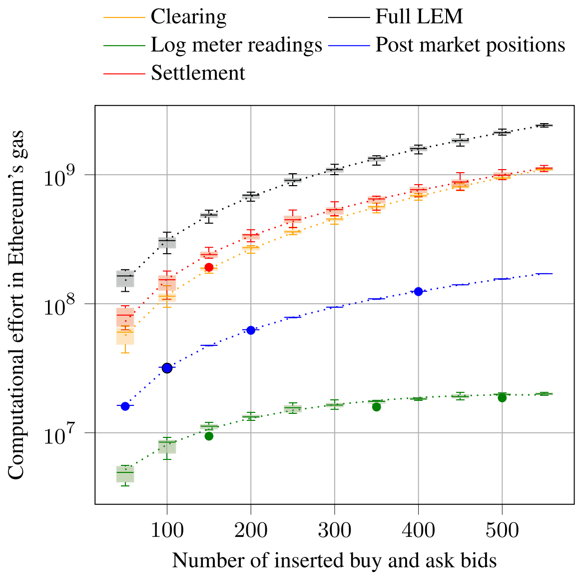

FIGURE A1 Computation effort in Ethereum's gas as box plots. Outliers are shown as circles

TABLE A1 Coefficients and residuals of polynomial fitting curves

	Computation time Central LEM	Blockchain-based LEM	Ratio of mean Computation times
a	$-5.5*10^{-6}$	$1.7*10^{-3}$	$8.7*10^{-1}$
b	$6.5*10^{-3}$	1.5	86.4
c	$3.7*10^{-1}$	8.2	
Residuals	$4.8*10^{-2}$	313	2156.3

Gas analysis

Figure A1 shows the computational effort for the different main functions of the blockchain-based LEM in Ethereum's own computation currency ‘gas’. The clearing and settlement of the LEM consume most of the gas. Settling the market consumes slightly more gas than clearing the market up until 500 inserted bids and seems to reach a tipping point at 550 bids. Noteworthy is that the settlement is split up into four separate transactions while the clearing of the market is initiated with a single transaction. Hence, we assume the additional gas consumption from 50 to 500 bids is due to transaction overheads.