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Blockchain-enabled Peer-to-Peer energy trading

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A R T I C L E   I N F O

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A B S T R A C T

The increasing amount of distributed power generation from rooftop solar panels allows new electricity markets to emerge in which prosumers and consumers can trade locally produced energy. The use of blockchain technology has increasingly emerged in energy markets and shows great potential to facilitate Peer-to-Peer energy trading. However, blockchain technology is still in its infancy meaning it is not yet being used to its' full potential. In this paper, blockchain technology for Peer-to-Peer energy trading and its implications are explored, especially in view of the 'trilemma': scalability, security, and decentralisation. Peer-to-Peer energy trading is the focus of this paper, which ultimately proposes a blockchain scalability solution. This solution is empirically modelled using data collected in a trial case study. The proposed solution increases scalability without compromising security and decentralisation when compared to base layer models.

1. Introduction

Peer-to-Peer (P2P) trading of energy has emerged as a next generation system in energy management that enables prosumers to trade their surplus electricity. This creates opportunities for power system markets and transforms the way consumers use their energy, allowing them to trade energy with their peers. P2P electricity markets may allow consumers to freely choose their source of electric energy by, for instance, investing in locally produced renewable energy.

Blockchain is considered by many as the next digital revolution and it is believed that it will be as impactful as the Internet [1, 2]. It has the potential to enable the spread of power across the system, giving every participant an equal opportunity without a central authority controlling the information (in some cases). The information is open, facilitating transparency. Blockchain has recently gained significant attention from both academics and the electricity industry and been applied in almost all fields, especially in energy trading. The adoption of blockchain technology for P2P electricity trading enables a transition from a highly centralised market controlled by a few key players, to a more democratic decentralised market dominated by microgrids. Although the concept of P2P energy trading is not new [3], it has recently drawn interest from academics and the electricity industry as it provides a solution to the phenomenon known as the 'utility death spiral' [4]. The latter is caused by the increased adoption of rooftop photovoltaic (PV) panels,

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which reduces overall grid electricity demand without affecting peak demand. With fewer paying customers to maintain the necessary infrastructure, utilities are required to increase electricity prices; this in turn encourages greater adoption of PV panels. This is a global phenomenon exacerbated by the decreasing costs of PV technology. Battery adoption by PV users can help to reduce peak demand however excess electricity is still exported to the grid in an inefficient manner, at times when demand is low.

Blockchain-enabled P2P energy trading allows prosumers to sell their surplus electricity directly to local consumers without the need for a retailer, enabling mutually beneficial transactions. The prosumers can benefit from this arrangement by earning more than they would through feed-in-tariffs, while consumers could pay less per kWh and express their preference for renewable energy without the need to own the technology. Since batteries can be used to store untraded electricity, auctions for renewable electricity can create a dynamic market profiting both prosumers and consumers. For example, LO3 energy determined auction prices for the top price per kWh that an energy consumer is willing to pay [5]. Electricity retailers and the network provider also benefit from a more efficient market with lower infrastructure costs. Blockchain-based systems also provide privacy and security to both prosumers and consumers through the elimination of market intermediaries. Energy supply and demand are matched in real-time between agents with complementary energy demand profiles, and the trading is conducted uniquely through smart contracts.

Blockchain has shown great uptake potential in P2P energy trading with a growing number of companies adopting the technology and changing their business model. The revolution of blockchain encourages innovation and signals a smart grid transition [6]. However, it is currently challenging to find the maximal value and to optimise the use of blockchain technology in P2P energy trading because it is still undergoing proof-of-concept and adoption processes. In addition, the current limitations of blockchain technology relating to performance, scalability, and interoperability are still the subject of debate. Large-scale implementation remains a challenge. Moreover, different blockchain networks cannot communicate and inter-connect with each other, leading to interoperability issues, which in turn are likely to have a negative effect on the potential for scalability. This paper aims to achieve the following:

- An investigation into blockchain technology in relation to the trilemma of scalability, security, and decentralisation in P2P energy trading, through a trial occurring in Western Australia;
- The proposal of a scalable, robust, and secure model to support fast and frequent energy trading; and
- An assessment of the viability of the model using a P2P energy trading trial as a case study.

The next section of the paper consists of a literature review wherein the concept of blockchain technology is introduced. The use of blockchain for P2P energy trading and its uptake by different organizations is also reviewed in this section. Even though blockchain technology has gained popularity, its limitations have been discussed only broadly in the literature. The blockchain trilemma, which is the primary focus of this paper, is also discussed in this section. The research questions for this paper are also identified to distinguish the study from existing work. Blockchain-based P2P energy trading models are illustrated in Section 3, including base layer blockchain and blockchain with the proposed solution to tackle base layer scaling limitations. A case study to assess the proposed solution is presented in Section 4. Future work is envisioned for the next phase and is discussed in Section 5. The paper is formally concluded in Section 6.

2. Literature review

2.1. Blockchain for Peer to Peer (P2P) energy trading

2.1.1. P2P energy trading

P2P energy trading has generated increased attention from both industry and academia. For example, Tushar et. al. [7] provides a comprehensive review of P2P energy systems which are used in three different domains, namely: building, storage, and renewable generation. Tushar et. al. [8] present an overview of P2P trading in energy networks including a detailed discussion of the features of P2P networks and P2P energy markets. The survey also proposes a systematic classification of P2P energy trading by indicating challenges in both virtual and physical layers. Hassan et. al. [9] report on the benefits of incorporating blockchain building blocks into smart energy systems and indicate the blockchain technologies that are required to meet the designated systems.

2.1.2. Blockchain use cases

Use cases for blockchain-based energy trading and its implications are reviewed to assess the viability and usefulness of blockchain technology in the energy trading market. Greenspan [10] specifies a set of criteria for using blockchain technology against regular relational databases. In blockchain-based P2P electricity trading markets, intermediaries can be replaced with a distributed network of digital users or validator nodes, known as miners, who work in collaboration to verify transactions and safeguard the integrity of the ledger. Miners dedicate their computational power to maintaining the network (i.e. verifying, storing and updating the replicas of the electricity trading ledger).

The potential impact and benefits of blockchain for P2P energy trading include (i) efficient, flexible, and robust renewable electricity trading market on a virtual P2P basis; (ii) energy security in terms of both cybersecurity and security of energy supply; and (iii) sustainability by facilitating renewable energy generation and low carbon solutions. On the other hand, applying blockchain in P2P energy trading confronts certain technical challenges which are detailed in [8, 9]. Some of these challenges include (i) network management: in terms of protocols and algorithms; (ii) data management: in terms of on-chain and off-chain; (iii) consensus management: in terms of latency and throughput requirements; (iv) power loss: due to P2P energy trading; and (v) pricing: a dynamic pricing model was utilised in the RENeW Nexus pilot project. This model has great potential for further research, for example, to investigate a dynamic pricing model for P2P energy trading.

2.1.3. Uptakes of blockchain technology in energy sector

There is an ever-increasing number of active companies in the energy sector actively employing blockchain technology. Companies worldwide as well as pilot projects are working on blockchain in the energy sector, including P2P energy trading, Business to Business energy trading, wholesale/retail energy markets, energy commodity trading, and not-for-profit support [11, 12]. The most common use is P2P energy trading where companies are utilising blockchain technology. An example of companies utilising blockchain technology for P2P energy trading is shown in Table 1.

Blockchain-based P2P energy trading facilitates the growth of a shared economy and promotes renewable energy. The adoption of blockchain technology for P2P energy trading has been significant. Most of the companies working in this space are recently established, indicating that blockchain technology is currently in a nascent stage of development. However, realistically, the successful adoption of blockchain technology in P2P energy trading has not been widely evident. Hence, there are broad arguments on the challenges and opportunities of the adoption of blockchain technology, particularly concerning the blockchain trilemma.

2.1.4. RENeW Nexus project

The RENeW Nexus project was funded by the Australian Government through the Smart Cities and Suburbs Program [13]. The aim of the project was to explore how cities can use blockchain technology and data analytics to enable P2P trading of energy and water. As part of the first phase of the RENeW Nexus project, electric smart meters were deployed in 50 houses across the city of Fremantle in Western Australia. The energy data was collected in real-time and comprised: (i) energy import from the grid, (ii) energy export to the grid, (iii) energy generation from installed rooftop PV, and (iv) energy consumption in households. During the research and development stage of the trial, the RENeW Nexus project used a private consortium blockchain, at zero transactional cost. However, for this study, the cost of using a public blockchain, modelled as the RENeW Nexus, may transition to a public network after the trial ends. For this paper, energy production and consumption data collected from the houses of 50 participants between 1 August 2018 and 30 September 2018 (2 months) is used.

2.2. Blockchain trilemma

The initial design of the Bitcoin blockchain set a block size limit of 1 megabyte. The purpose of setting this limit was to ensure that the network could not be effectively locked up by a malicious attacker through a denial-of-service attack. Without a block size limit, a denial of service attack could, theoretically, congest the network by sending very large fake data to be mined. With a block size limit, block sizes greater than the limit are immediately rejected by the network.

The challenge of P2P energy trading (and for the energy sector as a whole) lies in the sheer volume of data produced; that is the volume of P2P data transactions running concurrently. This is the case of information of kWh produced, kWh consumed, transactions, and so on being tracked in real-time. Energy generation or consumption at 30-minute time intervals would create numerous ledger entries for households per second. When a very large number of transactions per second are required of the blockchain, the transaction blocks may fill faster than the transactions can be processed. This causes transaction congestion and higher transaction fees.

There is debate concerning the limitation of blockchain technology, its performance and the compromises around the blockchain trilemma (scalability, security and decentralisation). Vitalik believes that current blockchain technology can achieve only two of the three trilemma elements [14], with scalability considered to be the greatest long-term threat to the viability of blockchain technology. However, there are a number of proposed solutions attempting to address the scalability issue. In this paper, Vitalik's definition of trilemma, namely scalability, security, and decentralisation, is used. Decentralisation refers to a system being able to run on a number of nodes in a network and each user having access to the network. Decentralised systems are operated based on consensus in which decisions (e.g. transaction verification) are democratic. Security refers to a system being secure against attackers. On a decentralised network, there is no single point of failure, thereby ensuring a high level of security. Scalability includes node-scalability and performance scalability. Node-scalability refers to the number of nodes scaling without a loss in performance in the blockchain networks. Performance scalability refers to the system being able to process a number of transactions.

Transaction validation latency and transaction throughput are the main issues related to scalability. Transaction validation latency refers to the time it takes for a transaction to be validated and placed in a block (i.e. validation and confirmation time). Transaction throughput refers to the number of transactions validated per second (i.e. processing speed). The scalability issue faced by blockchain technology compromises the high security and the advantage of decentralisation. Even though there are approaches tackling the scalability issue, security and/or decentralisation could be affected and compromised. It is important to explore the implications of blockchain-based energy trading from the trilemma perspective.

Balancing the blockchain trilemma is important in energy trading. The applications of blockchain to P2P energy trading have been discussed widely in many recent studies. P2P energy trading on a decentralised platform reduces the dependency on a central intermediary as energy supply and demand is matched directly. The unbalanced energy consumption in different homes and at different times of the day determines the P2P trading activity. For example, transaction volumes differ greatly between high energy prosumer homes and low energy prosumer homes.

2.3. Research issues

Most literature review papers review blockchain technology at a general level. Yli-Huumo et. al. [15] conducted a systematic

Table 1.
Companies utilising blockchain technology for P2P energy trading (derived from ICObench[11] and adapted from [11, 12]).

Company	Information	Blockchain platform	Country of operation
Green Power Exchange https://gpx.energy/	The Green Power Exchange Platform, the blockchain-based platform, enables simple P2P energy trading.	Ethereum	USA, China
Greeneum www.greeneum.net	Greeneum is a blockchain-based marketplace. The P2P energy trading platform uses smart contracts, artificial intelligence, and machine learning to create a decentralised, sustainable energy market.	Ethereum	USA, Singapore
Electrify www.electrify.asia	ELECTRIFY develops a decentralised energy marketplace that runs on the blockchain. It supports a P2P trading platform.	Ethereum	USA, China, South Korea
Pylon Network www.pylon-network.org	Pylon Network develops a P2P energy trading platform using blockchain.	Private blockchain	Spain
Alliander www.alliander.com/en	Alliander launched a blockchain-based renewable energy sharing token and has piloted a P2P energy trading platform.	Ethereum	The Netherlands
Dajie www.dajie.eu	Dajie develops P2P energy trading through an Internet of Thing device which functions as a blockchain node.	N/A	UK
WePower www.wepower.network	WePower runs a blockchain-based P2P energy trading platform. It also uses artificial intelligence to estimate supply and demand.	Ethereum	Spain
Conjoule www.conjule.de/en/home	Conjoule's platform, enabled by blockchain technology, supports P2P energy trading amongst rooftop PV owners and interested public-sector or corporate buyers.	N/A	Germany
Power Ledger www.powerledger.io	Power Ledger develops blockchain-based P2P energy trading.	Ethereum	Australia
LO3 Energy (Exergy) www.lo3energy.com	Exergy uses a revolutionary approach to a localised energy marketplaces using blockchain technology.	Private blockchain	USA
Electron www.electron.org.uk	Electron harnesses blockchain technologies to advance the energy market and aims to support P2P energy trading.	Ethereum	UK
Energo Labs www.energolabs.com	Energo Labs creates a blockchain-based P2P platform for a distributed energy system focusing on microgrids.	Qtum	China and Philippines (It is also looking to launch projects in the Netherlands)
SunContract www.suncontract.org	SunContract uses blockchain to create a decentralised P2P electricity market.	Ethereum	Slovenia
Volt Markets www.voltmarkets.com	Volt Markets enables the trading of energy in a P2P market and uses blockchain to streamline the distribution, tracking and trading of energy.	Ethereum	USA
Verv www.verv.energy	VLUX combines deep learning artificial intelligence with blockchain to improve access to affordable, low carbon energy by enabling peers to trade.	Ethereum	USA, China
Toomuch.energy toomuch.energy/	Toomuch.energy develops a P2P energy trading platform for corporate customers.	N/A	Belgium and Austria
Solar Bankers www.solarbankers.com Europe and USA.	Solar Bankers allows energy trading in a P2P manner.	Skyledger	Asia,

literature review of current blockchain technology research. Deshpande et. al. [16] conducted a brief study of distributed ledger technology and blockchain-based on a series of interviews and an internal workshop to determine challenges and opportunities. Zheng et. al. [17] reviewed blockchain architecture and consensus algorithms and identified future trends. Within the energy sector, Chitchyan and Murkin [12] review blockchain technology through overarching business to business energy trading, non-for-profit support and P2P energy trading. Andoni et. al. [18] reviewed the literature and business cases on blockchain solutions for the energy industry and identify technical challenges. Another review paper focused on blockchain-based P2P microgrids challenges. Tushar et. al. [19] provided an overview of incorporating game-theoretic approaches for P2P energy trading. Various aspects of P2P energy trading are also discussed in [20].

However, the blockchain model for P2P trading is not specified in any literature, specifically how it practically solves the trilemma issue. Second-layer solutions appear to provide promising solutions to the blockchain trilemma however, the best way to implement them in P2P energy trading to tackle the blockchain trilemma remains uncertain. Some questions in regard to the blockchain trilemma include:

- Scalability aspect e.g. how to manage scalable off-chain and on-chain transactions on the side-chain and on blockchain ledgers respectively?
- Security aspect e.g. what protocol can be implemented on the side-chain in the event of fraudulent or faulty behaviour? How to handle an overwhelmed network?
- Decentralisation aspect e.g. how to maintain decentralisation with off-chain transactions?

3. Blockchain-based P2P energy trading models

A blockchain model is presented to position P2P energy trading and reflect blockage of the trading (referred to the trilemma of scalability, security, and decentralisation). A scalable, robust, and secure model is then proposed to support fast and frequent trading using the second layer solution that sits on top of a secure and robust blockchain base.

Generally, there are two basic actors in blockchain-based P2P energy trading:

- Energy network participants (i.e. prosumers and consumers) who make use of the blockchain network's functionality for the payment of shared renewable energy. The participants can also be blockchain miners.
- Blockchain miners dedicate their computational power to maintaining the accuracy of the transaction ledger (i.e. storing and updating replicas of the ledger). Miners in a blockchain network need to have computer systems connected to the network's nodes. Block producers, who process all transactions and produce a block of transactions, are also classified as miners as they are the custodians of the blockchain network.

P2P energy trading participants can feed energy into the electrical grid or take energy from the grid depending on their energy use and production balance. Prosumers are incentivised to feed the grid with renewable energy through payment for the energy they provide, in the form of a crypto-currency or a crypto-utility-token.[2] Consumers are also incentivised as they can purchase energy from their peers at a competitive tariff using the crypto-currency. The tariff price is set based on the supply and demand of the available renewable energy. The tariff price can potentially be decided based on a cryptocurrency trading market or via a fixed token supply and variable availability of renewable energy. The cryptocurrency as a crypto asset has its own value which could rise or drop. It is unpredictable depending on the trading market. The fixed token will remain at a stable rate.

Pricing tariffs used in the RENeW Nexus project are shown in Table 2. In the case where energy demand is greater than the P2P network can supply, the energy wholesaler must feed the network above the market price (i.e. 9.9 cents at peak and 5.72 cents at off-peak). This further incentivises peers in the network to create excess renewable energy in order to drive down the price of energy and reward the prosumers. Selling prices during peak and off-peak periods for prosumers would be above 4 cents per kWh and reach 9.9 cents per kWh during peak period and reach 5.72 cents per kWh during off-peak periods. Prosumers can be both consumers and producers of energy; prosumers and consumers can set their own selling and buying prices and when prices are matched, trading then occurs.

For P2P energy trading, payment transactions can be executed on a blockchain system, which records the payer, the payee, and the amount of payment as transactions. Payment transactions can be initialised and securely recorded on a decentralised ledger. This is done through the use of smart contracts that enforce predefined rules to calculate the energy payment based on the energy tariff spot price and consumer-prosumer use, which is recorded by energy smart meters. Smart contracts are pieces of a programming code that implement rules for energy payment calculation. The contracts act as agents that have a state and functionality and can be triggered at certain points in time, thereby replacing the intermediaries or central authority.

The following section describes the steps involved in processing transactions. These are illustrated in Fig. 1 above. The steps include:

1 Energy sharing commences between prosumers and consumers in a P2P trading manner.
2 Payment transactions are initiated through smart contracts once energy sharing commences. Tariff and energy import/export will be parsed by smart contracts so that the payment price can be calculated.
3 The transaction record includes the block producers' identification, payer ID, payee ID and the payment amount. The list of many transaction records is encrypted using homomorphic encryption or zero knowledge proof [21], and forms a block.
4 A blockchain miner then validates the block of transactions and produces a candidate book which is broadcast to all participating nodes on the network. All network nodes validate the transactions using a consensus mechanism. In general, miners check the corresponding accounts and whether or not participants have available funds. If they do, the transactions are authenticated and validated by the network.
5 A blockchain is formed by linking blocks together through the hash, common block signatures, effectively keeping a full list of all past records in a linked list.

As the blockchain is in the early stage of innovation, it remains unclear whether or not it alone can support the transaction speed or volume required in existing energy markets. Second-layer solutions could increase transaction speed, and volume can be significantly increased without sacrificing security or decentralisation. Even though second-layer solutions are still in the early stages of development, they appear to be promising solutions to the blockchain trilemma. A generalised use-case for blockchain-based P2P energy trading using a second-layer solution is presented in this paper. This model processes all off-chain transactions and records them in a side-chain. This model makes use of network transaction fees as incentives to keep the network operating autonomously.

The steps described below (and illustrated in Fig. 2 above) are used to process off-chain transactions using a side-chain:

[1] https://icobench.com/

[2] A crypto currency or token is required to cryptographically secure the ledger. The token may be settled with Fiat currency at the end of the billing period if required.

Table 2
Pricing tariffs at peak and off-peak in a case study (RENeW Nexus project).

Grid rates: 3PM – 9PM (peak period)	Grid rates: 9PM – 3PM (off peak period)
Sell to grid: 4 cents per kWh Buy from grid: 9.9 cents per kWh	Sell to grid: 4 cents per kWh Buy from grid: 5.72 cents per kWh

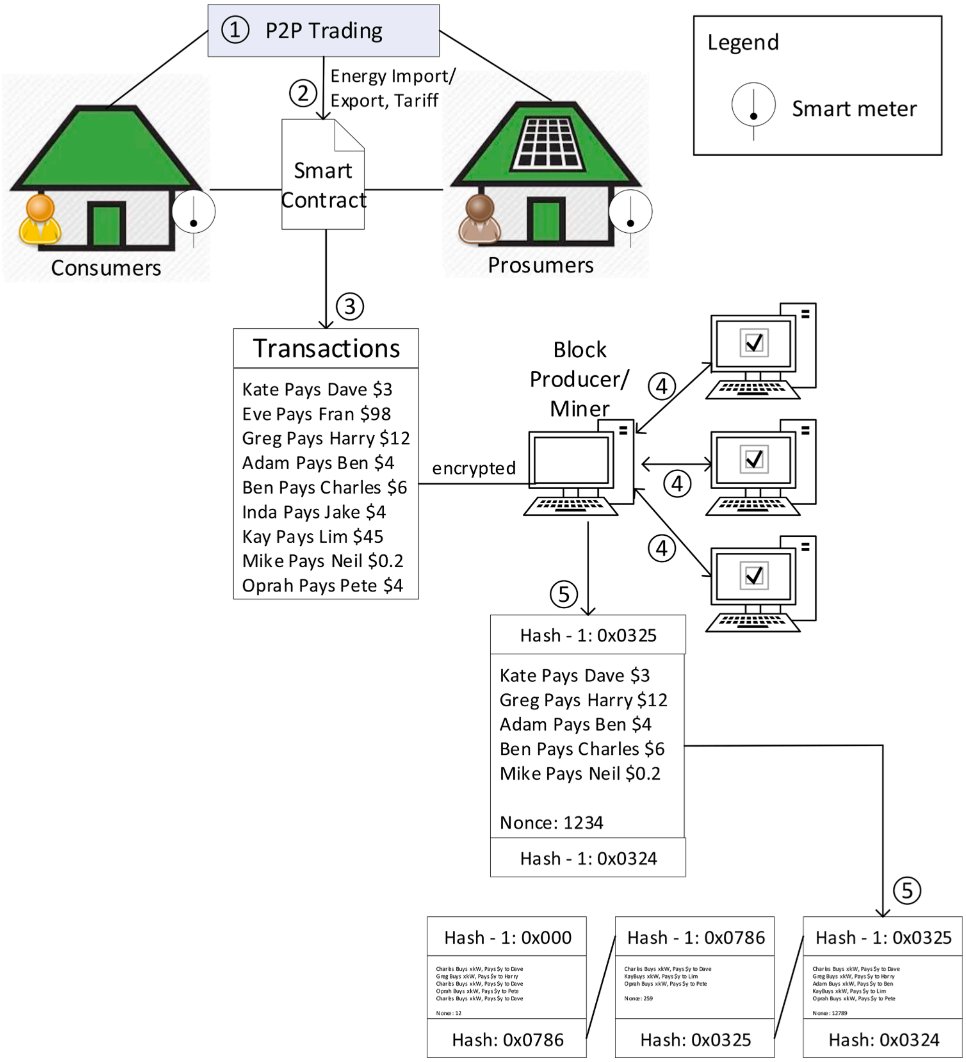

Fig. 1.. Schematic overview of blockchain-based P2P trading.

1 Participants enter a smart contract by first bonding a commitment payment, plus transaction fee, to a multi-signature wallet which is the smart contract that holds the transaction. For example, participants A and B bond $500 each as their commitment to the transaction.
2 The transaction is signed by both parties using digital signatures and sent to the blockchain for confirmation and consensus. A digital signature in this case is used to authorise a transaction. Authorisation of the transaction can be verified using the participant's public key. When both parties countersign a transaction, it can be publicly verified that they both approve the transaction. As long as the private keys are in the sole custody of the individual participants, no other actor can sign the transactions on their behalf. Either or both parties can commit to enforce the contract at some future date. A copy of the block is also recorded using a side chain which will become the root of the side chain.
3 Energy prices are calculated by the smart contract, and transactions can be made between the parties as long as they do not exceed the value of the commitment payment. As shown in Fig. 2, for example, the total transaction cannot exceed $1000.

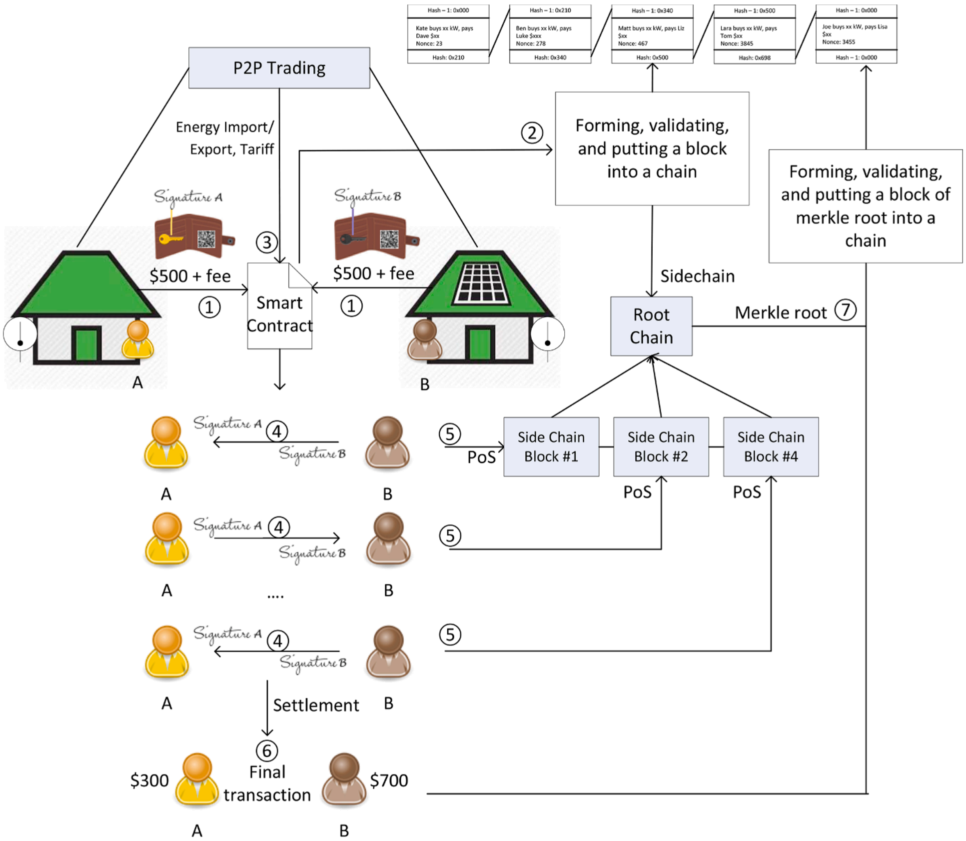

Fig. 2.. Blockchain-based P2P trading with off-chain and side-chain solutions (trading between peers is not limited to two participants).

4. Both parties must cooperate, agree to, and sign the transactions conducted between them. All parties are able to make any number of transactions with their counter-parties as long as they have sufficient funds available within the payment channel.
5. All off-chain transactions are recorded using a side-chain which uses the proof-of-stake consensus i.e. the commitment bond. Side-chain consensus incentives are taken from transaction fees. The blocks are composed into a tree structure in the side-chain. The depth of the tree will grow when more participants start trading amongst each other. A fraud-proof system enforces state transitions of the chain hierarchies [22]. By framing an off-chain transaction entry into a child of a side chain which is enforced by the parent chain, this ensures the side chains can scale with minimised trust.
6. The channel can be closed out or settled cooperatively by the parties and the contract issues a refund to the participants based on the final balance, after the last transaction. The example in Fig. 2 shows that the final transaction is settled by refunding $300 to participant A and $700 to participant B into their respective accounts. This would usually be conducted at the end of a pre-defined billing period, at which time they could continue their participation with the trading network by renewing their commitment in a new contract.
7. In order to record evidence of the side-chain transactions onto a public blockchain ledger, only the Merkle root of the side chain is recorded. This is the only requirement in order to conduct Merkle proofs and ensure the validity of side-chain transaction balances without providing evidence of the individual transactions or price on the public chain. The final transaction balance state is the only balance written to, and broadcast by, the blockchain network when the contract is closed. This provides a private transaction record on a trust-less public blockchain.

For legal and auditing reasons, a full auditable transaction record may be required by the wholesaler or local authority. In this case, in order to provide further participant privacy and security, transactions being validated and recorded on the side chain may be encrypted using homomorphic encryption or zero knowledge proofs [21]. The full side chain ledger may be securely warehoused by the authority of the electrical grid.

The blockchain and second-layer solution allow instantaneous, low-cost transactions of just a few cents across a network of participants. P2P electricity trading can be recorded and billed on the blockchain for any pre-defined time period, such as every five seconds or 15 minutes. With trading transactions recorded using a second layer, it can be instantly operated at very low cost. Unlike common two-monthly payments, this solution allows micro-payments to be available promptly and hence can be used to cover transaction fees. The off-chain transactions are not recorded on the blockchain and are enforced with bonded fraud proofs. The bonded fraud proofs ensure that the network works faithfully and autonomously with minimal, to no, downtime. The bond payment does not necessarily have to come from the households; it can come from an organisation that operates a blockchain network. In the event of fraudulent or faulty behaviour, the blockchain will penalise the faulty actor. A threshold can be imposed to settle transactions which could be for a set time period (e.g. daily, fortnightly, weekly, or monthly), on a number of trading transactions, or participants may cooperatively determine a time, or a combination of these strategies can be put in place. Once a certain threshold is met, final settlement transactions will be sent to the blockchain for confirmation and consensus. On confirmation and authentication, the transactions are written to the ledger and broadcast by the network. The energy trading network may also be the blockchain network, where participants could all be a blockchain node and agree to have no fees. However, there are challenges with this approach, as it does not leverage the full security value of a large, well-established blockchain of participants, which spans a multitude of different use cases and motivations. It is instead a rather basic distributed database, which is more prone to a coordinated attack and is at a greater risk of being hacked.

The second-layer solution reduces transaction fees and facilitates the fast execution of smart contracts. However, there is a risk that if a very large number of participants try to exit the contract at the same time, the network may become overwhelmed and may not be able to process all of the contracts. In this case, the participants are refunded their initial commitment payment and none of the trading transactions is written into the ledger. This poses a significant challenge for energy trading. There is currently no known way of withholding the electricity entering or leaving the energy grid based on the execution of a smart-contract for payment. In this case, policy would need to be written to incur a fee and/or a high tariff charged by the wholesale producer. In the case of participants being unable to service the smart contract with sufficient funds, a penalty fee policy can be applied.

4. P2P energy trading case study

The aim of the analysis is to model the number of transactions and the transactional costs of the participant energy trading using the two blockchain models presented in this paper, and the cost saving by using the second-layer solution. The transaction cost was modelled using the data collected from the RENeW Nexus project.

The number of transactions reflects the energy balance between prosumers and consumers which is determined by the energy supply and demand. If energy import is greater than energy export, this indicates energy demand. On the contrary, if energy import is lower than energy export, this indicates energy supply. Demand and supply will be matched and the number of transactions is calculated as shown in Fig. 3.

Where energy demand is greater than energy supply, energy demand will be ranked and matched with energy supply. Ranking energy demand in ascending order results in the maximum number of transactions whilst matching it in descending order results in the minimum number of transactions. On the other hand, where demand is lower than supply, energy supply will be ranked and matched with energy demand. Ranking energy supply in descending order results in the maximum number of transactions while ranking it in ascending order results in the minimum number of transactions. Fig. 4 shows the pseudo-code for the calculation of the minimum and maximum numbers of transactions.

The number of transactions during the two months (No. TX) is calculated using Eq. 1 for the minimum number of transactions and

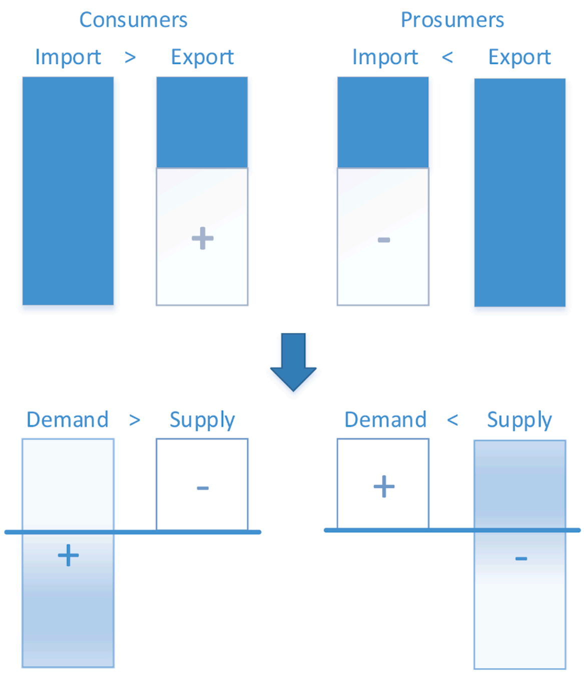

Fig. 3.. Matching energy demand and energy supply.

```
Begin
For each file of settlement period (i.e. 5 mins and 30 mins)
        Read energy import and energy export for all 50 households in that settlement period
        For each time slot
                Determine the energy demand and supply by comparing energy import and export
                If total energy demand is greater than total energy supply
                        Initial MaxTransOrder by ranking energy demand from smallest to largest
                        Initial MinTransOrder by ranking energy demand from largest to smallest
                        Initial kt to 1
                        For all energy demand at each time slot
                                if cumulated MinTransOrder[1:k] is greater than or equal total energy supply
                                        minK = k; kt = t; break
                                end if

                        end For
                        For all energy demand at each time slot starting from kt
                                if cumulated MaxTransOrder[1:k] is greater than or equal total energy supply
                                        maxK = k; break
                                end if

                        end For
                Else
                        Initial MaxTransOrder by ranking energy supply from largest to smallest
                        Initial MinTransOrder by ranking energy supply from smallest to largest
                        Initial kt to 0
                        For all energy supply at each time slot
                                if cumulated MinTransOrder[1:k] is greater than or equal total energy demand
                                        minK = k; kt = t; break
                                end if
                        end For
                        For all energy supply at each time slot starting from kt
                                if cumulated MaxTransOrder[1:k] is greater than or equal total energy demand
                                        maxK = k; break
                                end if
                        end For
                end if

        end for
end for
Sum total transactions (minK and maxK, respectively) in a day
End
```

Fig. 4. Average number of transactions made on the Ethereum public blockchain during two settlement periods: 5-minute and 30-minute settlements.

Eq. 2 for the maximum number of transactions.

$$\mathrm{minNo.TX} = \sum_{\mathrm{i}=1}^{61} \min_{\mathrm{D}==\mathrm{S}} \mathrm{k_t} \tag{1}$$

$$\max No.TX = \sum_{i=1}^{61} \max_{D==S} k_t \tag{2}$$

Where	D	represents total energy demand
	S	represents total energy supply
	k_t	represents the possible number of transactions t represents time slots in a day (i.e. if 5-min settlement, $t = 288$ slots; if 30-min settlement, $t = 48$ slots)
	i	represents number of days (i.e. 61 days)

The settlement period for the current wholesale Australian electricity market is every 30 minutes. However, by 2021, the settlement period will change to every five minutes [23]. Hence, the energy data for 5-minute and 30-minute settlements are considered, and the minimum and the maximum number of transactions are calculated accordingly.

The daily average number of transactions for every 5 minutes and 30 minutes is shown in Fig. 4 below. The light red and light blue envelopes represent the range of the minimum and the maximum number of transactions over the respective 5-minute and 30-minute periods of the RENeW Nexus trial. The results show the number of transactions range between 380 and 2600 transactions for 5-minute settlements, while for 30-minute settlements the range is between 50 and 410 transactions.

To estimate the cost of blockchain transactions on a public blockchain, the Ethereum blockchain and its associated costs were used. The Ethereum blockchain is a public network using Ether or ETH as its cryptocurrency which is used to pay the transaction costs of using the network. The Ethereum blockchain network uses 'gas' as a unit to measure the computational work of running transactions or smart contracts. The computational work is a measure of time spent, and the cost of electricity and computing hardware used to execute the codes and finalise the transactions. Gas price, which refers to the cost of each unit of gas, is a crucial element to executing transactions in the Ethereum. The historical gas price data was collected from Etherscan.[3] The gas price in Wei unit was converted into ETH units (1 ETH = 10^18 wei) and then into USD based on the exchange rate. The amount of gas used for this paper was 21,000 units of gas for a single transaction according to [24]. Eq. (3) below shows the calculation of the Ethereum blockchain costs for executing a transaction in Ethereum:

$$Cost = Ether\ price \times \left[Gas\ amount \times Gas\ price \times 10^{-18}\right] \tag{3}$$

The daily average cost per transaction in USD during a 2 month period is shown in Fig. 5.

The total blockchain costs are shown in Eq. (4):

$$Total\ blockchain\ cost = \sum_{i=1}^{61} No.TX_i \times Cost_i \tag{4}$$

The minimum and the maximum number of transactions and the minimum and the maximum cost for 50 houses during the 2 month period are shown in Table 3.

Given the second layer approach, the block finality time (i.e. the time taken to put transactions on the chain) can be set to bypass computation costs for every single transaction being recorded in the blockchain. This results in greater cost saving. In relation to the 2-month transaction costs, the highest transaction cost was 43 cents on 8 August 2018, hence the maximum cost is calculated based on the highest transaction cost. The lowest transaction cost was 5 cents on 8 September 2018, hence the minimum cost is calculated based on the lowest transaction cost. The calculation of the second-layer solution is shown in Eq. 5 for the minimum cost and Eq. 6 for the maximum cost.

$$L2\mathrm{min}cost = No.TX(t_{\min}) \times Cost(t_{min}) \tag{5}$$

$$L2\mathrm{max}cost = No.TX(t_{\max}) \times Cost(t_{max}) \tag{6}$$

Where $t_{\min}$ is on 8 September and $t_{\max}$ is on 8 August 2018.

Table 4 shows a cost comparison of blockchain with and without second-layer solutions along with cost-saving and the percentage of the savings. The second-layer solution yields a very significant cost saving of approximately 95 to 98 per cent. The second-layer solution costs are minimal compared to the cost of every single transaction being put on the blockchain.

5. Future work

The third generation of blockchain or the future of blockchain-based energy trading is still undergoing development. The vision of Blockchain 3.0 is to be an improved version of Blockchain 2.0. The expansion of blockchain technology with the exploitation of emerging technologies such as Big Data, Data Analytics, Machine Learning, Artificial Intelligence, and the Internet of Things, may also lead to the 3.0 generation of blockchain.

In P2P energy trading, several companies have adopted a combination of emerging technologies with blockchain; for example, Verv (www.verv.energy) is combining machine learning with artificial intelligence and blockchain, as are Greeneum (www.greeneum.net) and Drift (www.joindrift.com). These emerging technologies are studied to improve security and capability. For example, big data technologies may improve the accuracy and security of data and machine learning may be exploited as a means of detecting irregular and illegal activities in the blockchain [25], whilst sensor data recorded on a blockchain ledger may be exploited by artificial intelligence for analytics.

Currently, smart contracts have very simple utility. They are rule-based programs that can execute a small number of actions based on pre-defined logic. However, with the integration of machine learning and artificial intelligence, smart contracts may self-learn/self-adapt and may be able to function in a semi-autonomous way, greatly increasing the breadth of the utility of these smart contracts. Hence, smart contracts incorporated with machine learning and artificial intelligence could, for example, enable negotiations between nodes on the tokenised value of a unit of electricity, and cooperation between nodes to optimise household energy consumption. There is an innovative synergy between the emerging technologies and blockchain in P2P energy trading which warrants future exploration.

The paper is not intended to cover the detailed technical and implementation aspects of blockchain thereby making it more accessible to a wider readership. However, future research may investigate in-depth the technical issues of blockchain technology. In

[3] https://etherscan.io

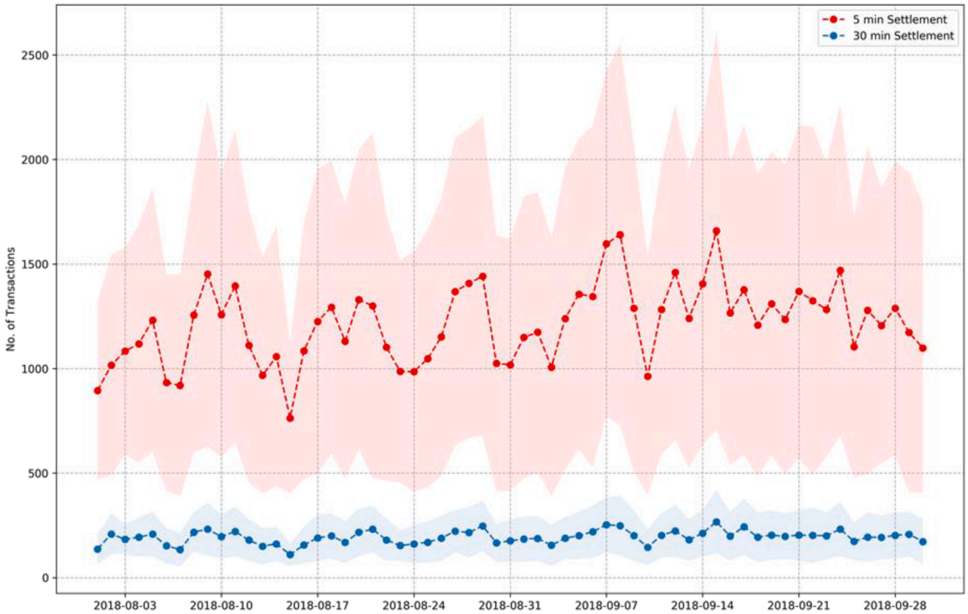

Fig. 5. Daily average cost per transaction in USD.

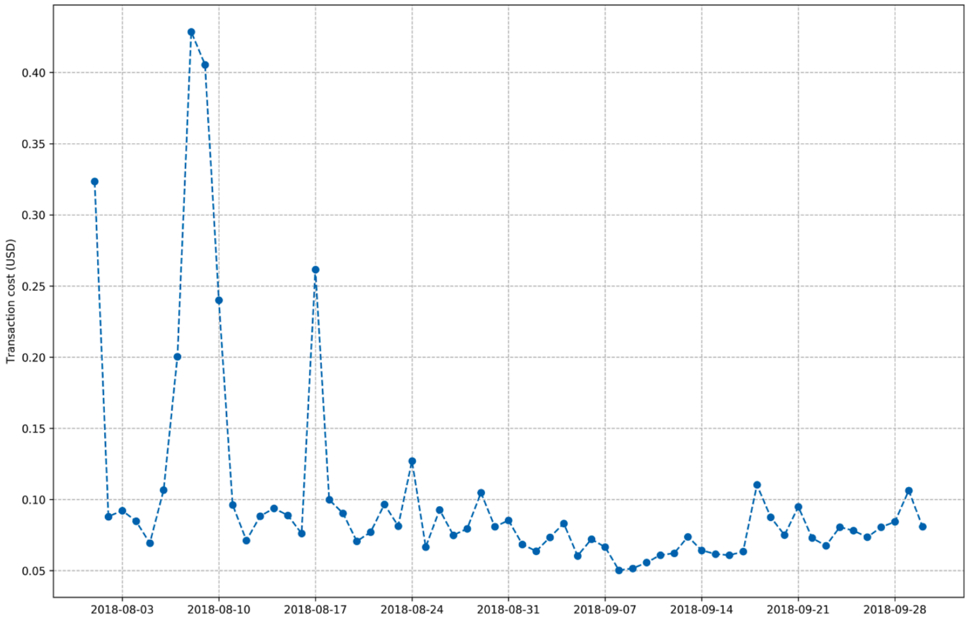

Fig. 6. Daily average cost per transaction in USD.

Table 3
The number of transactions and the cost in USD.

	Min No. TX	Max No. TX	Min total cost (USD)	Max total cost (USD)	Min cost per day per household (USD)	Max cost per day per household (USD)
5 minute settlement	32,282	115,975	$3296.11	$11,694.97	$1.08	$3.83
30 minute settlement	5333	18,259	$549.56	$1844.06	$0.18	$0.60

Table 4
Minimum and maximum costs and cost savings.

	No. TX on the 8th Aug (L2 min No. TX)	No. TX on the 8th Sep (L2 max No. TX)	L2 min cost	L2 max cost	Without L2 min cost	Without L2 max cost	min cost saving	max cost saving
5 minute settlement	1256	1640	$82.45	$538.32	$3296.11	$11,694.97	$3213.66 (≈98% saving)	$11,156.65 (≈95% saving)
30 minute settlement	217	249	$12.52	$93.01	$549.56	$1844.06	$537.04 (≈98% saving)	$1751.05 (≈95% saving)

terms of pricing, a dynamic pricing model was utilised in the RENeW Nexus pilot project. This model has great potential for further research, for example, to investigate the use of a dynamic pricing model for P2P energy trading.

6. Conclusion

This study endeavours to present a complete picture of the current state of scalability solutions having regard to the factors of the blockchain trilemma for energy trading. P2P energy trading is in the nascent stage of development however, blockchain is fundamentally a promising technology for energy trading and the distribution of energy which has received increased attention in recent times. Moreover, there are many newly established start-up companies within this sector. Important parameters, apart from the technology, would make energy trading successful include economic, legal, and regulatory considerations. For example, the costs of processing trading transactions are lower than today's coordination costs; energy can be traded more frequently than today's regulations allow to reap the full benefits of renewable energy; competitive prices for energy producers and prosumers would stimulate the renewable energy market; P2P trading is assured of security (e.g. against fraud, criminal violence, participant misconduct, etc.). In relation to the examples provided in this paper, blockchain is seen as a promising technology for P2P energy trading.

This paper investigates the efficient implementation of blockchain technology for P2P energy trading having regard to the factors of the blockchain trilemma. A blockchain scalability solution is proposed by utilising second layer solutions, which are empirically modelled in a P2P energy trading case study. The proposed solution utilises the second layer solution in which a number of off-chain transactions are processed and recorded on a side-chain. Only the final transaction balance is written in the blockchain greatly reducing the costs involved with the transactions.

CRediT authorship contribution statement

Pornpit Wongthongtham: Conceptualization, Methodology, Visualization, Writing – original draft. **Daniel Marrable:** Conceptualization, Software, Writing – review & editing. **Bilal Abu-Salih:** Validation, Writing – review & editing. **Xin Liu:** Methodology. **Greg Morrison:** Supervision.

Declaration of Competing Interest

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

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