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The Costs and Benefits of Blockchain Based Peer-to-peer Energy Trading:

An Evaluation from the Perspective of Carbon Emission and Economic Value.

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The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

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Acronyms

P2P	Peer-to-Peer
PV	Solar photovoltaic
TWh	Terawatt hour
kWh	Kilowatt hour
Mt	Metric ton

Executive Summary

Australia has over 2 million PV installations given a combined capacity of over 11.1 gigawatts as of January 2019 (2019). This area experienced extremely rapid growth between 2010 and 2013 and has continued to grow. As Australia's high capacity of PV installations, distributed energy markets have been established to capitalise on the available energy. Several markets are being trialled around the world including Peer-to-Peer (P2P) energy trading, business-to-business energy trading, wholesale and retail energy, energy commodity trading, and others. The most common market is P2P trading which allows households to trade electricity.

Blockchain is a type of distributed ledger technology that can be used to securely store digital transactions. Blockchain has demonstrated great uptake potential in P2P energy trading with a growing number of start-up companies, pilots, trials, and research projects adopting the technology within their business model. The revolution of blockchain encourages innovation and enables a low-carbon transition and sustainability (Juri, Timo et al. 2016). According to Deloitte (Grewal-Carr V and S. 2016) and PWC (Hasse, Perfall et al. 2016) reports, blockchain has the potential to disrupt the energy sector using energy commodities as digital assets to be traded.

However, concerns over the energy use, the carbon footprint, and the cost of blockchain have recently generated debate. The carbon footprint and cost of blockchain are derived from its validation process which requires specialised hardware with computing power and vast amounts of electricity. Public perceptions on the impact this technology has on the environment and its associate costs have also garnered recent negative publicity. This reduces the perception of the benefits of blockchain technology. To investigate the impact of blockchain, we compare the energy consumed to support blockchain with the total energy saved from the electrical grid from deployment of blockchain-based P2P energy trading.

The aim of this study is to evaluate the cost and benefit of blockchain-based P2P energy trading. The energy consumed and carbons emitted from the blockchain validation process are quantified. The cost of blockchain technology is calculated as well to determine its economic value. This report also provides various insights into the transformation of P2P energy trading using different blockchain scalability solutions. Real data from operating P2P energy trading systems is used in this report.

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 and allows consumers to purchase affordable and locally-produced renewable energy. The increasing amount of distributed power generation from rooftop solar panels provides the opportunity for new electricity markets as well as potentially enabling a transformation to customers sharing electricity. In addition, P2P electricity markets allow consumers to freely choose the source of their electric energy by, for instance, investing in locally produced renewable energy.

To enable a secure and auditable P2P electricity market, innovative technologies are explored. Blockchain enables consumers to take control of the energy system, giving them an equal opportunity without the need for a central regulatory authority. In addition, the adoption of the blockchain technology in P2P electricity trading enables the transition from a highly centralised market controlled by few players, to a more democratic and decentralised market dominated by microgrids. According to Deloitte (Grewal-Carr V and S. 2016) and PWC (Hasse, Perfall et al. 2016) reports, blockchain has potential to disrupt energy sector with energy commodities as digital assets to be traded.

With blockchain-enabled P2P energy trading, prosumers are able to sell their surplus electricity directly to local consumers, thereby facilitating mutually beneficial transactions. Prosumers benefit from this arrangement by earning more than they would through feed-in-tariffs, while consumers pay less for their energy per kWh and are able to take advantage of renewable energy sources without the need to own the technology. Since a battery can be used to store untraded electricity, auctions for renewable electricity can create a dynamic market profiting both prosumers and consumers. Electricity retailers and network providers 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 trading is conducted uniquely through smart contracts.

Blockchain technology and P2P trading have been widely discussed in the context of climate change policy and have been applied in many different climate-related sectors, from climate investment to carbon pricing. With the falling price of solar photovoltaic (PV) modules, the number of households installing PV systems is increasing; P2P energy trading has become one of the most popular applications supported by blockchain technology.

However, there are concerns over the carbon footprint produced by blockchain. Concern also stems from the transactional costs that are needed to maintain the integrity of the decentralised blockchain. Few researches have embraced mathematical proof and projected that blockchain emissions could push global warming (Mora, Rollins et al. 2018) and consumes more energy than mineral mining to produce an equivalent market value (Krause and Tolaymat 2018). Foteinis (Foteinis 2018) investigated blockchain carbon footprint and used the life-cycle impact-assessment methodology to estimate the 2017 global carbon emissions of 43.9 Mt for Bitcoin and Ethereum mining (Hileman and Rauchs 2017). Digiconomist[1] presented Bitcoin and Ethereum energy consumption indexes and estimated that Bitcoin consumes 55.76 TWh and Ethereum consumes 8.38 TWh of electricity annually, equivalent of 0.25% and 0.04% respectively of the world's electricity consumption (2019, 2019).

In this report, we evaluate the environmental impact of blockchain technology in terms of its energy use, its carbon emission production and its economic value. In addition, different blockchain scalability solutions are studied to explore different options for the transformation of P2P energy trading systems. We consider both blockchain base layer model and second layer solution, unlike many current literatures that only report on base layer model. We calculate energy consumption from mining blockchain and then compare with household energy consumption and with energy saving from deployment of P2P energy trading. Carbon emitted from blockchain usage is calculated and compared with the amount of carbon emitted from household usage and with the emission saving from P2P energy trading.

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[1] https://digiconomist.net/

Glossary and Key Terms

In order to make this report more understandable to the wide readership, we provide a glossary of key terms that are relevant to this report.

Blockchain refers to a type of distributed ledger technology that has been defined as a trust-less, distributed, decentralised, transparent, encrypted, and immutable database (Kuo, Kim et al. 2017, Zheng, Xie et al. 2017).

Digital cryptographic signature is a mathematical mechanism that allows one to authorise a transaction (Katz, Menezes et al. 1996).

Hashrate is the measurement unit of the processing power dictated by the number of computations being performed across the network (Rosenfeld 2014).

Smart contract is a piece of programming code that implements rules to digitally facilitate, verify, and/or enforce the negotiation (Mik 2017).

Digital keys (public key and private key). Public keys are widely disclosed and private keys remain undisclosed (Rivest, Shamir et al. 1978). For ease of reference, the public key is likened to an individual's bank account whereby the private key is the secret PIN to the bank account (Asolo 2019).

Wallets (single-signature wallet and multi-signature wallet). The wallet contains digital keys allowing one to make transactions. A single-signature wallet requires only one signature from the owner of the private key while a multi-signature wallet requires signatures from multiple people before funds will be transferred (Aitzhan and Svetinovic 2018). A multi-signature wallet increases the security of the transaction. This is useful when executing transactions where trust hasn't yet been established or when creating community funds.

A crypto currency or token is required to cryptographically secure the ledger (Wood 2014). The token may be settled using Fiat currency at the end of the billing period if required.

Potential Benefits and Impacts of Blockchain

Blockchain enabled P2P energy trading allows prosumers and consumers to interchangeably trade energy surplus and demand on a virtual P2P basis. Energy is still delivered through a physical grid given that demand and supply are managed and controlled to comply with power system stability. Prosumers and consumers are directly connected through a trading platform in a trust-less network using a distributed ledger. They do not entirely trust each other with degree of mistrust in the sense that a prosumer or a consumer is not willing to let others modify the trading transactions or let fraudulent transactions occur. Prosumers are incentivised to feed their surplus energy into the electrical grid while consumers can purchase energy from their peers via the grid at competitive prices. Specific rules or conditions can be set in blockchain based P2P trading to allow for transactions which can be independently and automatically verified. For instance, the funds available in the ledger must be the same before and after every transaction to prevent fraudulent activities and double spending. A set of rules can be established demonstrating the flexibility of the electricity market model.

In typical trading markets, payment in the trading process involves a trusted party such as a central bank to settle payment transactions. The trusted intermediary is responsible for storing, safeguarding, updating, and consolidating the ledger. This incurs transactional, contractual, and compliance costs and requires users to trust the third party to handle those responsibilities. However, there are some substantial disadvantages of centralised systems. For example, centralised systems present a single point of failure which is susceptible to technical failure and cyber-attacks.

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. The partnership of distributed users is incentivised using game-theoretic equilibria and rewards (Adam Back, Matt Corallo et al. 2014). Blockchain has mechanisms to ensure that the participants' accounts are not overdrawn or double-spent through the consensus process. The verifiable process for energy transactions in blockchain makes intermediaries redundant. Blockchain enables prosumers and consumers to provably agree on energy trading transactions that are entered by whom and when, without the need for an intermediary. With blockchain and IoT support using smart meters, energy billing between prosumers and consumers can be processed automatically through smart contracts in real time. Payment transactions can be made directly to consumers and prosumers without a central billing authority. Payments can therefore be made more frequently such as, for example, every five seconds in contrast to the common two-month invoice period. Energy micro-payments and pay-as-you-go solutions are not only beneficial to consumers but also to utility companies (Andoni, Robu et al. 2019). The creation of a time-stamped trading transaction is verifiable and transparent. Energy trading transactions are recorded in multi-location data structures, thereby providing resilience and robustness to the blockchain system. On the other hand, security of energy supply can be achieved by increasing the volumes of renewable energy and implementing efficient and flexible electricity trading markets (M. and SNG. 2017).

Generally, renewable electricity is not retrieved once it has been exported to the grid at which point it is amalgamated with the electricity produced from fossil-fuel power plants. Among the total energy mix, a market share of energy from renewable sources can be established in terms of energy mix procurement. The provenance of the energy consumed or supplied can be tracked using the blockchain technology. The transparency and provenance attributes offered by blockchain technology could affect consumer behaviour, resulting in a shift in energy consumption between peak and off-peak hours where possible. For example, consumers may run energy-intensive appliances during hours of solar energy peak production thereby creating incentive to adjust their energy consumption.

In summary, the potential impacts and benefits of blockchain for P2P energy trading include:

- Efficient, flexible, and robust renewable electricity trading market on a virtual P2P basis,
- Energy security both cyber security and security of energy supply,
- Energy cost reduction through energy optimisation, and
- Sustainability by facilitating renewable energy generation and low carbon solutions.

RENeW Nexus Project: P2P Energy Trading Case Study

The government of Western Australia is the first government to allow P2P energy trading across the grid through the RENeW Nexus project. The project is funded by the Australian Government through the Smart Cities and Suburbs Program (Sundararajan 2017). The aim of the project is to examine the value and efficiency of P2P energy trading in the City of Fremantle. As part of the RENeW Nexus project for P2P energy trading trial, electric smart meters have been deployed at 50 houses across the City of Fremantle. The energy data is collected at frequent time intervals (down to 5 seconds) and transmitted through IoT technology. The data comprises of energy imported from the grid, energy exported to the grid, energy generated from rooftop PV systems, energy consumption in households, etc.

During the research and development stage of the trial, the RENeW Nexus project uses a private consortium blockchain at zero transactional cost. However, for the purposes of this study, the cost of using a public blockchain is modelled as the RENeW Nexus may transition to a public network upon completion of the trial. In this report, energy production and consumption data is collected from the houses of 50 participants between 1 August 2018 and 28 February 2019 (i.e. 7 months) at 30 minute intervals. The aim of the analysis is to model the number of transactions, energy use and carbon emissions from blockchain mining, and the transactional costs compared across the two blockchain models (i.e. base layer model and second layer model). The analysis uses real data collected from the energy trading trial in the RENeW Nexus project.

Blockchain-based P2P Energy Trading Models

In traditional form of energy trading, households feed energy into the electrical grid or take energy from the grid depending on their energy use and production balance. Electricity retailers pay for the surplus electricity generated by households' rooftop solar as incentives at feed-in-tariff rate. In P2P energy trading, prosumers and consumers are directly trading the energy. 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. Consumers are also incentivised as they are able to purchase energy from their peers at a competitive tariff price using crypto-currency. The tariff price is set based on the supply and demand of the available renewable energy. The tariff price may be determined through a cryptocurrency trading market or via a fixed token supply and the variable availability of renewable energy. Where the demand for energy is greater than the available supply of energy on the P2P network, the energy wholesaler must feed the network above the market price. This further incentivises participants in the network to create excess renewable energy in order to drive down the price of energy and reward prosumers. It is important to note that prosumers can be both consumers and producers of energy. In this report, two blockchain models are explored for P2P energy trading i.e. base layer blockchain and second layer blockchain.

Base layer blockchain

In a P2P energy trading, payment transactions can be executed using a blockchain system. Payment transactions can be initiated 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. The smart contracts are executable programs that implement rules for energy payment calculation. The contracts act as agents that have a state and functionality and can be triggered automatically if a certain condition is met such as the trading agreement between consumers and prosumers is reached. Contract terms are written in computer language encoding legal constraints and terms of agreement (Swan 2015, Grewal-Carr V and S. 2016) thereby removing the intermediaries and reducing transacting, contracting, enforcement and compliance costs (Walport 2016).

Energy sharing commences between prosumers and consumers in a P2P trading manner. Payment transactions are initiated through smart contracts once energy sharing commences. Tariff and energy imports/exports will be parsed by smart contracts so that the payment price can be calculated. 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 (Wang and Kogan 2018), and forms a block. 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 to determine whether participants have sufficient funds to cover the cost of the transaction. If the available funds are sufficient, the transaction is then authenticated and validated by the network. A blockchain is formed by linking blocks together through the hash using common block signatures, which effectively maintains a record of past transactions in a linked list.

Second layer blockchain

As blockchain technology is still in its infancy, it remains unclear whether blockchain alone can support the transaction speed or volume required in existing energy markets. Second-layer solutions may increase transaction speed whilst volume can be significantly increased without sacrificing security or decentralisation. A generalised use-case for blockchain-based P2P energy trading using a second layer solution is outlined in this section. This model processes all transactions off-chain by recording them using a side-chain which uses network transaction fees as incentives to keep the network operating autonomously.

Participants enter a smart contract by first bonding a commitment payment plus a 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 transaction. 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. The multi-signature wallet is useful in this case due to trust-less nature of the joint funds. Authorisation of the transaction can be verified using the participant's public key. When both parties countersign a transaction, it is publicly verified that they have both approved the transaction. As long as the private keys remain in the sole custody of the individual participants, no other actor is able to 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 becomes the root of the side-chain.

Energy prices are calculated using the smart contract and transactions can be made between the parties as long as they do not exceed the value of the commitment payment. 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.

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 the transaction fees. The blocks are composed into a tree structure in the side-chain. The depth of the tree will grow as more participants begin trading with one another. A fraud-proof system enforces state transitions of the chain hierarchies (Poon and Buterin 2017). 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. The channel can be closed or settled cooperatively by the parties at which point the contract issues a refund to the participants based on their final balance, after the last transaction is complete.

The final transaction is settled by refunding the left-over funds to the relevant participants. 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. In order to record evidence of the side-chain transactions in a public blockchain ledger, only the Merkle root of the side-chain is recorded. This is the only requirement of the Merkle proofs which ensures 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 to be maintained 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 (Wang and Kogan 2018). The full side-chain ledger may be securely warehoused by the regulatory authority for the electrical grid.

The second-layer blockchain solution allows instantaneous, low cost transactions of just a few cents per transaction across a network of participants. The P2P electricity trading can be recorded and billed on the blockchain for any predefined time period, such as every five seconds or 15 minutes. The recording of transactions using a second layer allows the system to be instantly operated at a very low cost, allowing micropayment to be used to fund the 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 may be provided by an organisation operating a blockchain network.

The P2P energy trading incurs large numbers of small transactions between prosumers and consumers because the measured energy value is communicated and transacted in real-time. Hence, benefit of second-layer blockchain is that low-value transactions can be made cost-efficient for P2P trading and second-layer blockchains would ensure interoperability between transaction systems. Hence the energy trading marketplace would have low-cost authentication, validation, and settlement for low-value transactions.

In the event of fraudulent or faulty behaviour, the blockchain will penalise the faulty actor. A threshold can be set to settle transactions for a set time period (e.g. daily, fortnightly, weekly, or monthly), on a number of trading transactions, or where participants cooperatively determine a time, or a combination of these. Once a certain threshold is met, final settlement transactions will be sent to the blockchain for confirmation and consensus. Upon 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 whereby participants may be a blockchain node and agree to have no fees. However, this approach has some deficiencies 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. Rather, it is a 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 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 to 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, new regulatory policy would need to be written for the imposition of 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 may be applied.

Number of Transactions

The number of transactions reflects the energy balance between prosumers and consumers which is determined by the supply and demand of energy. If the amount of energy imported is greater than the energy exported, this indicates high levels of energy demand. In contrast, if the amount of energy imported is less than the energy exported, this indicates high levels of energy supply. An algorithm to calculate the minimum and maximum numbers of transactions is provided in the supplementary file. The 7-month RENeW Nexus minimum and maximum numbers of transactions are shown in Figure 1.

The distribution of the minimum and maximum numbers of transactions is shown in Figure 2. The minimum number of transactions falls primarily between 63 and 116 transactions while the maximum number of transactions falls primarily between 276 and 407 transactions.

Figure 1 Minimum and maximum numbers of transactions between 1st August 2018 and 28th February 2019

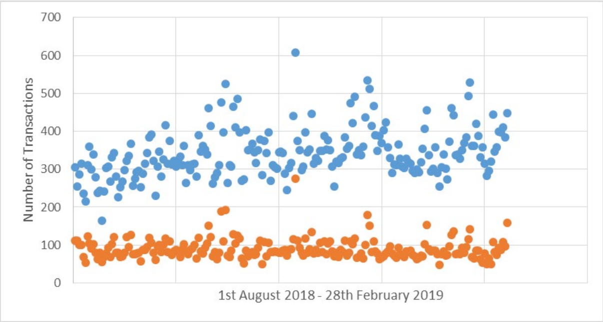
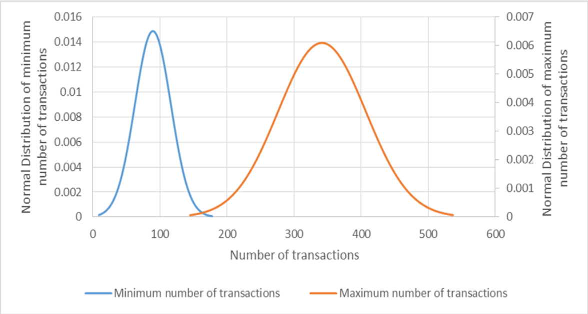


Figure 2 Distribution of minimum and maximum numbers of transactions



	Mean	Standard deviation	Mean – Standard Deviation	Mean + Standard Deviation
Minimum number of transactions	89.51	26.83	62.67	116.34
Maximum number of transactions	341.55	65.42	276.13	406.97

Energy Use and Carbon Footprint of Blockchain

In blockchain, miners are incentivised to validate transactions and ensure the integrity of the network thereby eliminating the need for a trusted third party. Blockchain creates a decentralised administrative data protocol. However, the validation process requires intensive computational and heightened electricity consumption. To accurately estimate the carbon footprint of blockchains, we study its power consumption and the carbon emissions produced by its mining activities. Carbon emissions from energy consumption to support the blockchain mining are evaluated against the reduction of carbon emissions from energy imported from the grid as results of P2P energy trading.

The methodology used to calculate power and energy required for mining blockchain in this report generally follows the process reported in (Bevand 2017, Krause and Tolaymat 2018). To calculate the amount of power consumed by the entire blockchain network, the daily network hashrate was multiplied by the power efficiency of the mining rig (computer hardware). Then the blockchain energy requirement was calculated by multiplying the blockchain power requirement with the time it takes to mine a block (block completion time). To determine the households' blockchain energy consumption, number of transactions in the RENeW Nexus project was multiplied energy required to mine blockchain and then divide by total number of transactions of whole blockchain network.

The energy consumption is a minimum energy requirement for a general blockchain network. It is important to note that the estimation of energy consumption for mining blockchain do not include energy used for cooling and maintenance aspects of running mining rigs.

With any electricity trading platform, electricity is traded in a P2P fashion which allows consumers to adapt their consumption to achieve desired objectives such as minimising electricity costs hence reduces grid imports and thereby reduces carbon emissions. Figure 3 shows the maximum and minimum energy consumed to mine blockchain grids daily, compared to the energy saved (household energy import).

Figure 3 Energy consumed to mine blockchain compared to household energy import (energy saving)

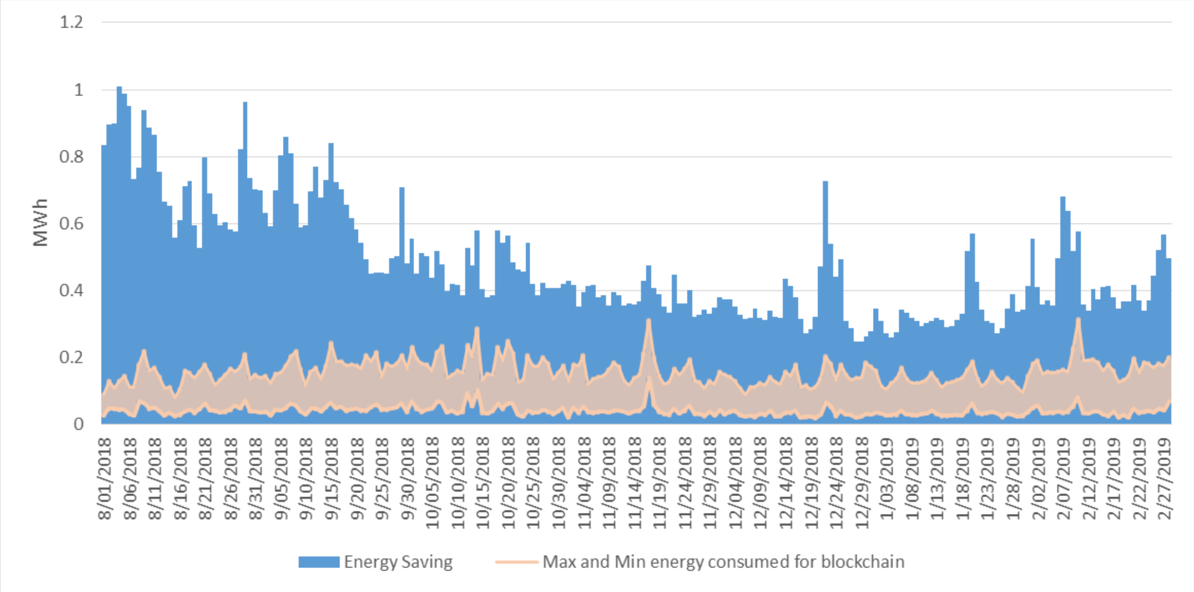


Figure 4 Blockchain's and household energy consumption in different seasons

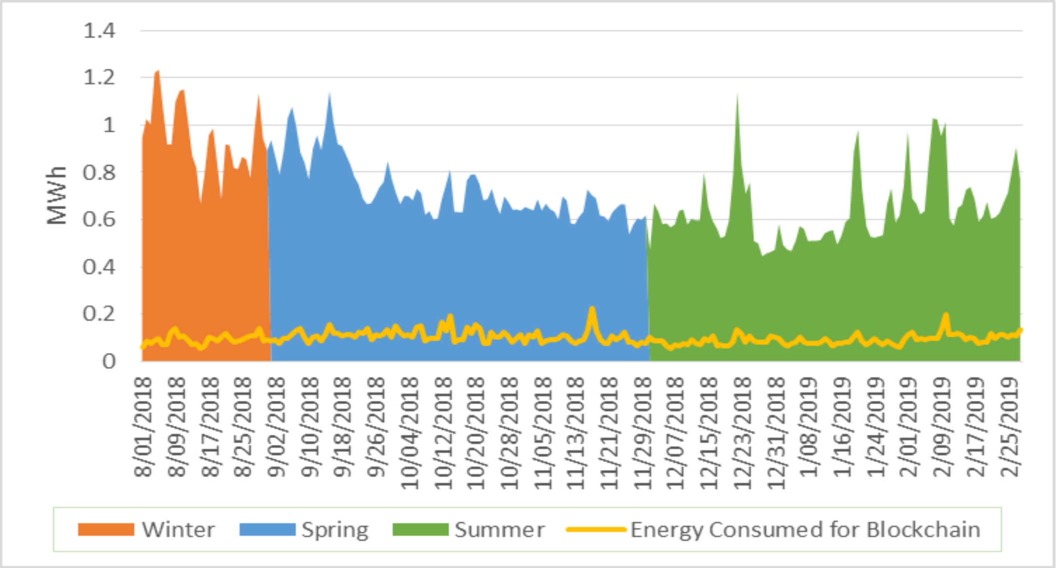
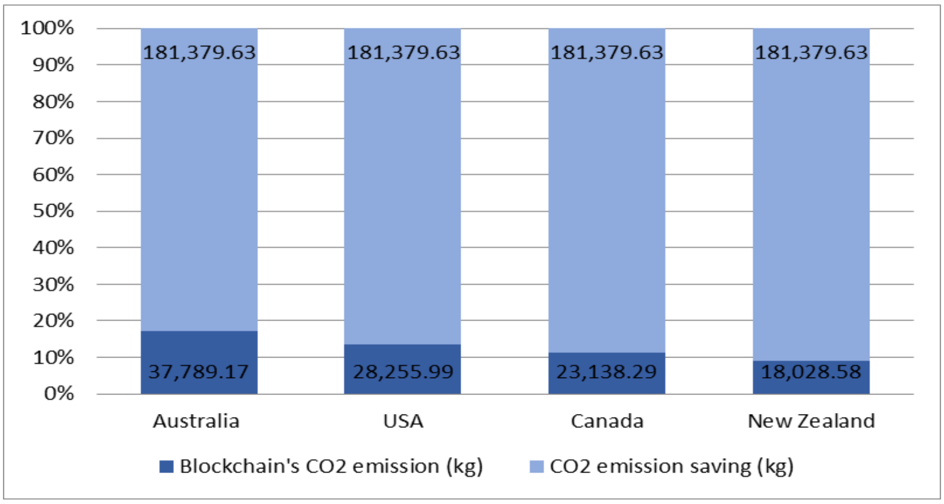


Figure 4 shows the average energy consumed in the blockchain compared with household energy consumption. While there are seasonal trends in household energy consumption, blockchain's energy consumption typically remains steady. Blockchain consumers use a maximum of 226 kWh (an average of 100 kWh) and minimum of 54 kWh of energy compared to household energy consumption at a maximum of 1,234 kWh (average of 724 kWh) and a minimum of 446 kWh. Blockchain consumed about 20 percent of energy saving and about 14 percent of household energy consumption.

Miners can locate electricity anywhere; ideally, where the cost of electricity is cheap and/or areas where renewable energy sources are available (for example, Iceland). As the location of miners cannot be determined, the contribution of emissions in this report is estimated using emission factors from selected countries (i.e. Australia, USA, Canada, and New Zealand). The calculation of carbon emissions is provided in the supplementary file. Figure 5 shows the percentage of carbon emissions produced by blockchain mining in different countries compared with carbon emission saving in Australia within the P2P energy trading model.

Figure 5 Carbon emission from blockchain mining in different countries comparing with carbon emission saving from Australia in the P2P energy trading model.



Blockchain Cost

In order to estimate the cost of blockchain transactions on a public blockchain, the Ethereum blockchain and its associated costs were used in the analysis. The Ethereum blockchain is a public network which uses Ether or ETH as its cryptocurrency to pay the transaction costs of using the network. The Ethereum blockchain network uses ‘gas’ as a unit to measure the computational work of conducting transactions or smart contracts. The computational work is a measure of time spent and the costs of electricity and computing hardware used to execute the codes and finalise the transactions. Gas price, which refers to the cost per unit of gas, is a crucial element for the execution of transactions in the Ethereum. The gas price in Wei units is converted into ETH units and then into USD based on the current exchange rate. The amount of gas used in this report was 21,000 units of gas for a single transaction (Zainuddin). The blockchain cost is then multiplied by the projected number of transactions.

With a standard Western Australia tariff rate of 28 cents per unit, household electricity costs are calculated. Figure 6 shows the average blockchain cost compared to household electricity costs. It is important to note that on 19 February 2019, the average blockchain cost on the Ethereum network increased to a rate even higher than total household electricity cost that day. This could be a mistake made by an Ethereum developer as there were four transactions that took place on the day with a coding error from the same wallet address. Within four hours, one spent over half a million dollars in transaction fees which was the most expensive transaction fees spent for a cryptocurrency payment (WILLIAMS 2019). It is believed that the developer confused the gas price with the transaction value and then made a mistake (Sukhomlinova 2019).

Figure 6 Average blockchain cost comparing with household electricity cost

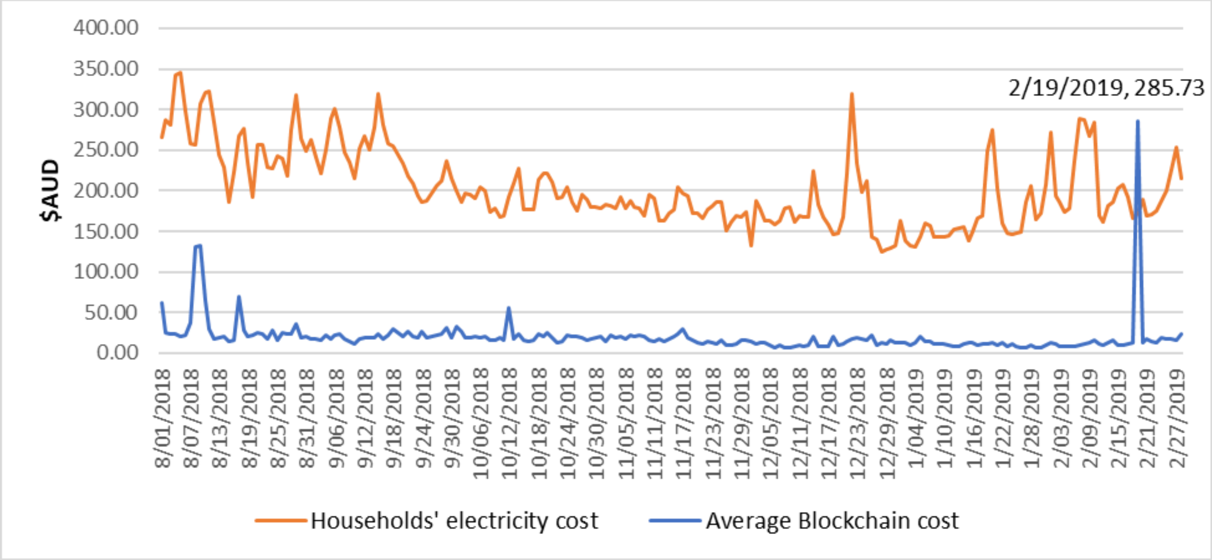


Figure 7 Box-and-whisker plots of household electricity cost comparing with minimum and maximum blockchain costs

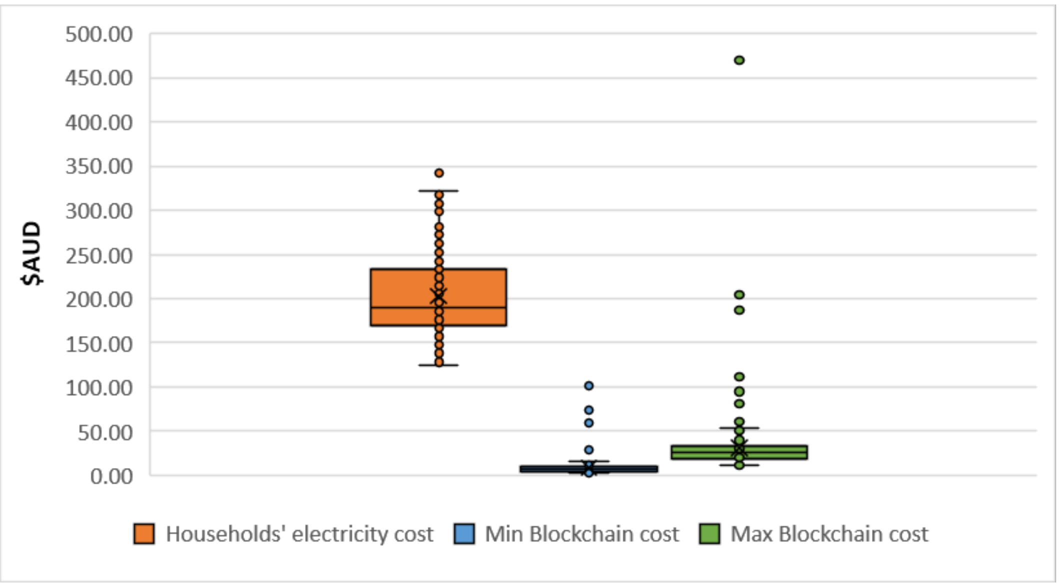


Figure 7 shows box-and-whisker plots of household electricity costs compared with minimum and maximum blockchain costs. There are some outliers in the blockchain cost plots. The maximum blockchain cost on 19 February 2019 is higher than the highest electricity cost of households. However, the minimum blockchain cost on that day is still less than the lowest electricity cost of households for the whole period. Other than those anomalies, the cost of blockchain is typically lower than household electricity costs.

Given that the cost of blockchain can be very high at certain points, the second layer approach presents an ideal solution. The block finality time (i.e. time to put transactions on the chain) can be set to bypass the computation cost for every single transaction being recorded in the blockchain. This results in a great cost saving.

Table 1 shows the minimum and maximum base layer blockchain costs compared with second layer solution costs for monthly block finality time. The second layer solution yields a minimum saving of AUD $1,749.67 and a maximum saving of AUD $5,682.00.

Table 1 Base layer blockchain costs comparing with second layer blockchain solution costs

Month	Min base layer blockchain cost ($AUD)	Max base layer blockchain cost ($AUD)	Min second layer solution cost ($AUD)	Max second layer solution cost ($AUD)	Min Saving ($AUD)	Max Saving ($AUD)
August	503.19	1,614.13	6.53	203.80	496.66	1,410.32
September	266.19	967.56	4.68	48.33	261.51	919.24
October	272.95	1,007.14	4.44	80.48	268.51	926.65
November	219.42	800.40	4.02	41.27	215.39	759.13
December	145.28	623.73	2.25	37.22	143.02	586.51
January	136.02	550.06	2.06	34.34	133.96	515.72
February	233.17	1,034.36	2.56	469.86	230.61	564.50
TOTAL	**1,776.21**	**6,597.38**	**26.55**	**915.31**	**1,749.67**	**5,682.07**

Figure 8 Cost comparison between base layer blockchain and second layer blockchain solution

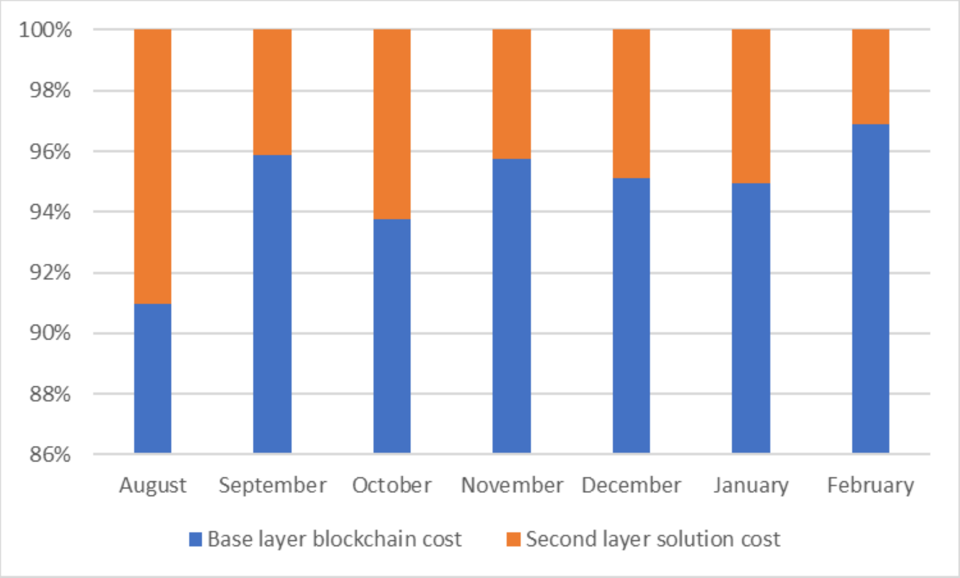
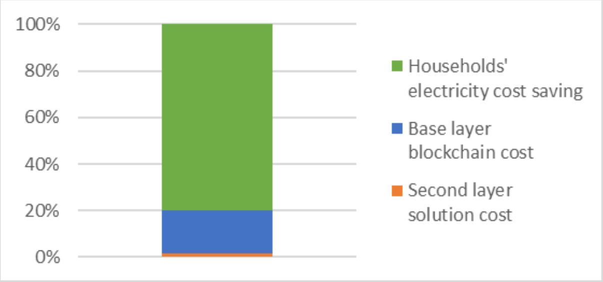


Figure 8 shows the percentage of savings with the highest saving in February where the base layer blockchain cost increased significantly. The lowest percentage of saving is still high (i.e. above 90%). The second layer solution yields a significant cost saving.

Figure 9 illustrates a comparison between household electricity cost savings from P2P trading with base layer blockchain and a second layer solution. The second layer solution costs almost nothing compared to household electricity cost saving from P2P trading.

Figure 9 Percentage comparison of household electricity cost saving, base layer blockchain cost, and second layer solution cost



Conclusion

Blockchain is a significant distributed ledger technology with a great potential for P2P energy trading. Given the significant interest in using blockchain and distributed technology for P2P trading, this report explores and evaluates blockchain based P2P energy trading. Scalable, robust, and secure P2P energy trading is still in its infancy however, blockchain technology presents a promising innovation for energy trading and the distribution of energy.

To ensure the success of blockchain-based energy trading, important economic, legal, and regulatory parameters need to be considered. For example, the cost of processing trading transactions is lower than current coordination costs, energy can be traded more frequently than contemporary 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.).

The carbon footprint of blockchain technology and its associated costs are the areas of concern for blockchain-based energy trading. This report investigates the efficient implementation of blockchain technology for P2P energy trading from the view of costs and benefits. This report compares energy saving in the upscale P2P energy trading against energy consumed to support blockchain systems.

This report also outlines carbon emission savings from P2P trading against blockchain carbon emissions. As mining activities can be conducted anywhere in the world, it is ideal if it is to take place in areas where the cost of electricity is cheap and/or where electricity is generated from renewable energy sources. Blockchain achieves an approximate 20% saving of carbon emissions if energy is mined in Australia 15% in the USA, 12% in Canada, and 9% in New Zealand.

To examine the cost of blockchain, we compare the cost between two models (i.e. base layer blockchain model and second layer solution model). The second layer solution model yields a significant cost saving (above 90%) compared to the base layer blockchain. Therefore, the second layer solution costs approximately 1% and the base layer blockchain costs approximately 23% of current household electricity costs.

Data Availability

All data analysed and algorithm developed in this report are provided in the supplementary file.

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