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Dissolving Metaphors in Peer-to-Peer Energy Trading: Towards a More Concrete Understanding of Metering, Legitimacy and Revenue Flows

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***Abstract*—Peer-to-peer *(P2P)* tokenised energy trading has seen much research interest in recent years. Despite this, the concrete physical workings of such marketplaces are rarely explained in the extant literature. This paper discusses notional P2P marketplaces with regard to their real-world implementation. The analysis of the physical/electrical layer and metaphorical token layer are kept distinct. Tokenised energy is conceptualised here as a dynamic *license to consume*, which serves as a *flow of legitimacy* for energy consumption in P2P schemes as typically proposed. Ledger structures, including centralised and decentralised/blockchain examples are examined. With the above points in mind, the workings of a notional blockchain-aware smart meter are described. The authors argue that while P2P energy trading may be a useful tool for regulators and for integration into smart token ecosystems, the drawbacks associated with decentralised tokenised energy markets may outweigh the apparent benefits at present.**

***Keywords*—blockchain, peer-to-peer energy, transactive energy, smart meters**

I. Introduction

With a rapidly increasing base of research, Peer-to-Peer *(P2P)* tokenised energy trading has been the subject of much interest in recent years [1]–[4]. At the time of writing, a search on *IEEE Xplore* for the phrase "peer to peer energy trading" returns 184 journal publications and 350 conference papers published since 2018. The same search terms on Google Scholar return over 16 500 results in the same period.

Despite this interest in P2P energy, there are few real-world schemes in operation [5]. Only a select number of start-ups and businesses have embraced the idea. For instance, [6] presents a framework for P2P energy, without any mentions of necessary hardware. Existing research, such as [7] and [8], has included hardware elements in electricity marketplace simulations, but only on a lesser scale. Some real-world commercial pilot studies exist, such as [9] in New York and [10] in the UK, but P2P energy trading has yet to see any mainstream adoption.

This paper will attempt to examine and discuss challenges in how P2P energy trading may be implemented on a more fundamental level. Regulatory arrangements, meter operation, and ledger structure are considered, with comparisons to existing examples. Through this established lens, P2P energy trading methodologies from extant work are examined and discussed. Centralised and decentralised/blockchain ledgers are compared, and notional hardware requirements are considered. Finally, the case for and against pure decentralisation will be examined, as well as alternative designs and market structures.

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II. Peer-to-peer energy trading

The notional P2P paradigm, as it is typically proposed in the above-mentioned studies, seeks to facilitate the unrestricted trade of energy between participating parties [1]. This is often suggested in combination with dedicated network-aware smart meters [11]. In these schemes, when a specified amount of electricity is produced (corresponding to a predefined *unit* of energy e.g. one kWh) by the generating party's renewable energy installations, the proposed meter detects this flow of current. The generated electricity is supplied to the grid. Notionally, the device then communicates with the network, crediting the generator's records with a token representing this unit of generated electricity [11]. These theoretical tokens can then be transferred, traded, and stored. P2P schemes often propose distributing these tokens on *exchanges* [3], similar to those used as cryptocurrency or Non-Fungible Token (*NFT*) marketplaces [1]. A consumer can hypothetically purchase any token from any generator for some form of currency. The proposed network facilitates this transfer, and the token is added to the buying consumer's record. The above description makes up the typical layout of existing P2P proposals, and is illustrated visually in Figure 1.

The consumer's meter hypothetically detects the presence of this token, and allows for the consumption of the equivalent quantity of electricity, thus "redeeming" and dissolving the token [2]. The token's function here may best be conceptualised as a dynamic *license to consume*, rather than a packet of transmitted electricity per se. In this scheme, the meter is the token's point of interaction with physical reality, by acting to continually verify the *legal legitimacy* of the consumed current flow.

Most of the extant literature in the space devotes minimal treatment to explaining the granular interaction of tokens with the real world or the physical process of "tokenising" energy. For example, Anoh *et al.'s* [12] simulation of P2P marketplaces is a well cited and rigorous study but does not discuss the physical layer of implementation. In reality, electricity itself *cannot* be tokenised. When generated, a unit of electrical energy must be consumed instantaneously. A unique packet of electricity cannot be physically transferred only between transacting parties [13].

The present paper puts forward the view that tokens are better understood as a quasi-legal instrument; a *license to consume* or a *certifier of legitimacy*. Like cryptocurrencies and NFTs, tokens have *perceived societal value* i.e. they are digital assets. Rather than being *speculative* assets like cryptocurrency [14], energy tokens, like NFTs, are *backed* assets [15] owing to their potential to legitimise energy consumption [1]. Crucially, though, such legitimisation of energy consumption can only occur within a specific legal context established and upheld by regulators and grid operators. In this sense, energy backed tokens can be said to exist in the cyber-metaphorical realm, also called the control plane [16]. The control plane would be distinct from the physical layer that includes electricity generation and transmission systems, as well as electrical loads and smart meters. Smart meters would function as the means whereby these two planes interact.

Meters may also observe alternative supply scenarios, such as tokens representing portions of wind farm outputs, as in [17]. These scenarios, however, consider electricity supply in a different manner and are outside the scope of this document.

A. Models for dealing with illegitimate consumption

As discussed previously, energy tokens are assets underpinned not only by electrical energy but also by the relevant regulators and/or authorities that recognise their legitimacy. A user possessing a token is theoretically allowed to consume a measure of electricity. However, if an insufficient amount of tokens are present in the user's wallet and they wish to continue consuming electricity, action is required. Depending on rules and regulations, the user may be required to be flagged to the regulator for undesirable behaviour. Under some specific conditions, they could enter a state of illegitimate consumption, as confirmed by continued meter readings coupled with a lack of observed credit in their accounts or wallets.

In some scenarios the connection could be interrupted in the same manner as coin prepaid [18], [19]: a circuit breaker would simply disconnect the electricity supply. Meters could also draw from some emergency wallet maintained for such scenarios, similar to existing prepaid schemes [18] where users may maintain funds for such occasions on their accounts. A truly utilitarian approach could see the circuit breaker open as soon as the user's wallet is depleted and therefore supply is no longer permitted. However, a humanitarian approach would see some level of amnesty or leeway granted to consumers. For instance, New Zealand legislation prevents medically-vulnerable people who may be dependent on electrical equipment from being disconnected [19]. Such an arrangement would require regulator involvement to designate people as such. A 2007 study by the *British Electricity Commission* found that prepaid meters that self-disconnected upon credit depletion "*...were [not] an effective solution for low-income consumers*" and "*...hide the difficulty of low-income consumers*" [20]. Furthermore, research in [21] shows an increase in energy poverty and its consequences associated with a widespread roll-out of self-disconnecting meters.

Blockchain technologies could facilitate more compassionate and community-focused ways of dealing with electricity consumers whose wallets have become depleted e.g crowd-funded microloaning of energy tokens as in [22]. This methodology allows consumers to take out blockchain-enforced loans from one another, and can be replicated with energy tokens. Furthermore, blockchain reputation-based systems, as in [23], could be used to establish credit for lending scenarios.

[1] Energy tokens however, as in this proposal, differ from NFTs in that they are fungible

B. Ledgers for peer-to-peer energy trading

In proposed models for P2P energy trading, a ledger structure is required to keep track of token exchanges, serving to facilitate the *flow of legitimacy*. *Legitimacy* refers to the instantaneous state of electricity consumption. This is similar to current arrangements where a relationship with an energy provider guarantees some permissibility of consumption, even in overdraft cases. That is to say, even if a customer of an energy provider fails to continue bill payments while their electricity consumption persists, they retain some level of legitimacy in their consumption. The customer's trust that the relationship will continue is placed in both the provider's business architecture, as well as the legal system.

Existing studies propose the use of both centralised and decentralised ledgers [2]. Centralised ledgers exist on dedicated servers, usually operated by a governing entity, such as electric utility or commercial venture. Examples of studies proposing such arrangements include [24] and [25]. Both of these examples suggest a centralised model, with a dedicated regulator that serves as the market operator and governing authority.

More commonplace in the existing literature is the proposal of decentralised ledgers, with emphasis on blockchain technologies [2]. *Blockchain* refers to a decentralised, transparent, and immutable ledger that allows for secure transactions between parties: such database structures underpin cryptocurrencies. The trading of P2P energy tokens is sometimes proposed to be mediated by *smart contracts*, which are autonomous computer programs that reside and execute natively on the blockchain [26], and can impose business logic of arbitrary complexity on token transactions. Some works proposing or discussing a blockchain-based approach include [16], [27]–[32].

The adoption of blockchain energy marketplaces can be conceived of as a logical endpoint of the trend towards deregulation. Proponents of this arrangement often claim that the role of regulators and energy operators may be greatly reduced, mirroring cryptocurrency's goal of displacing traditional finance institutions and banks [14]. An alternative view may consider the role of regulators and authorities to be maintained, but with tokens serving as a means of legitimising energy consumption from them. This conceptualisation is discussed in more detail in section II-D.

C. Are decentralised ledgers worth it for P2P energy?

The hypothetical operation of P2P energy trading utilising blockchain begs the question of whether decentralisation is a true requirement in such trading arrangements. This section will discuss the pros and cons of both centralised and decentralised P2P markets, including the challenges of blockchain in general, and P2P-specific issues.

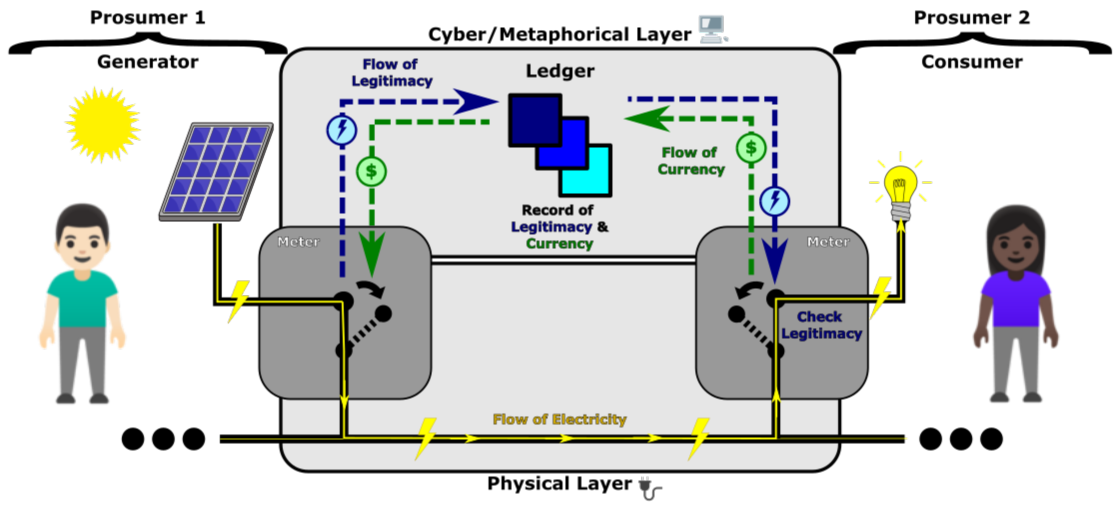

Fig. 1. Typical P2P trade process, with an explicit distinction shown between the physical and cyber/legitimising layers

1) General blockchain challenges: Much has been said about the increase in security associated with blockchain. Blockchain proponents claim that by having a trustless, decentralised ledger of transactions, the potential for fraudulent activities can be minimised [26]. However, it should also be noted that a public blockchain raises a number of security concerns, especially with somewhat sensitive data such as energy consumption trends. While a private blockchain could be employed, this somewhat defeats the point of achieving large-scale transparency and its associated benefits [26].

Blockchain has notoriously high energy consumption, especially in the commonly-occurring *proof-of-work* consensus mechanism [33]. Although this is partially solved by *proof-of-stake* and *proof-of-authority* validation methods, centralised ledgers are still likely to consume far less electricity.

2) P2P-specific challenges: Some studies proposed embedding mechanisms within tokenised energy trading that encourage electrically- and socially beneficial participant behaviour [34]. These mechanisms include limitations based on temporal [28], [35] and geographical location [36], [37]. Similarly, some studies such as [38] suggest the framework as a means of facilitating demand side management by autonomously handling bilateral trading arrangements while taking into account specific consumer preferences. While blockchain is proposed as a basis for these trading arrangements, they can be accomplished in the traditional centralised manner too.

Questions arise as to the meter's behaviour if the internet connection is lost and it can no longer communicate with the blockchain. The meter could buffer consumption data while offline and update records when the connection is restored as in [39]. Finally, there are many advantages to having a dedicated entity that can be held accountable in the case of failures and malfunctions. A truly decentralised model would see any users experiencing problems left to fend for themselves.

D. Blockchain as a tool for regulators

Blockchain shows some potential as a tool for regulators. Although somewhat at odds with the above concepts of decentralisation, the transparent nature of the technology can serve as a way for existing energy providers to prove their compliance to regulators by establishing public records open to scrutiny. For instance, work in [40] suggests blockchain as a tool for regulators to keep track of the carbon allowance of generators. The technology's transparency in terms of public access could allow consumers to verify their fair treatment and rates, as in [41]. Blockchain could also function as a means of recording credit in public records in terms of bill payments, as in [42]. Thus, blockchain should be viewed as "*...not a trustless technology, but rather a confidence machine*" [43].

E. Blockchain token ecosystems

Perhaps the most notable advantage of a blockchain basis for tokenised energy is the potential for integration into a larger *token ecosystem* [27]. The example discussed in this work already includes a simple version of this concept, integrating energy and cryptocurrency within a single mechanism. Expansions on this concept can include decentralised funding arrangements [17], alternative energy supply scenarios [17], prediction markets [44], consumer preference-based supply [45], asset management [34] etc. Energy token economics translate into faster and more efficient interactions by allowing value transfer between economic systems, as in [34]. That is to say, multiple distinct ecosystems, including the electrical, financial, and physical layers could seamlessly interact. As an example, work in [17] proposes blockchain crowd funding for renewable energy projects. Investors are rewarded with tokens that entitle them to pro rata share of proceeds from generation in the form of cryptocurrency. Smart meters observe the plant's electrical generation. This example sees the interaction of tokens representing asset ownership, currency, and energy in a single ecosystem.

F. Smart meters and the Oracle problem

A recognised drawback of blockchain-based IoT systems is that of the *Oracle* problem [30]. While blockchains are a secure ledger of data [26], they can not organically pull or push external data [46]. That is to say, they must draw upon a trusted,

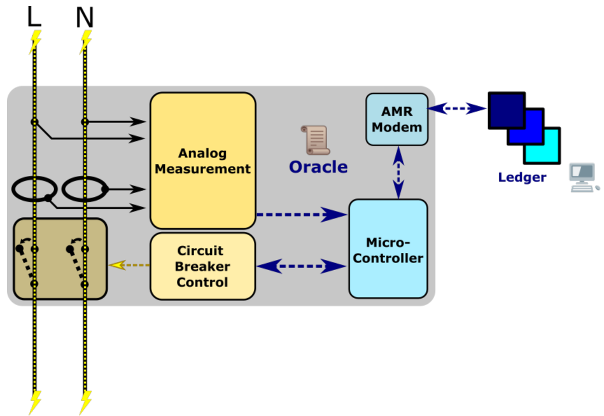

Fig. 2. Blockchain-aware smart meter design

usually centralised, source of data when communicating with the external world. A practical example of the Oracle problem occurs in supply chain management, a commonly-proposed use-case for blockchain technology. For instance, the work in [47] proposes managing seafood supply chains with blockchain. However, there is no guarantee that temperature sensors haven't been tampered with, or personnel have given due diligence to correctly inputting data along the chain. Although a data record on a blockchain may be immutable, this is a distinct property from being factually truthful.

In the case of a P2P energy example, this Oracle problem is most relevant to the prevailing metering arrangements. Electricity is a pure commodity with adequate regulation already in place. Meters can be viewed as Oracles of user consumption for the electricity supplier, legally protected by existing regulations. Trust must be placed in the meter installer. Despite legal protection, what steps can be taken to prevent meter tampering? What authority will enforce this? These points could be viewed as somewhat at odds with the decentralised vision of blockchain as energy tokens are dependant on these legal underpinnings.

In terms of meter installer credibility, individuals could include their information in the public blockchain. Clients could then provide transparent reviews. This is somewhat similar to blockchain reputation systems as in [23].

To prevent tampering, a meter is required to "prove" that its measurement is taken from the correct source. For instance, it may take a snapshot of grid conditions at regular intervals e.g. power in certain harmonics, exact voltage and frequency. This can autonomously be verified against other users' measurements, reaching consensus. Previous attempts at solving the Oracle problem in DeFi have suggested using the medians and aggregates of different sources so as to decrease the chances of receiving inaccurate information. An example is that of MakerDAO *Medianizer*, that provides the median of cryptocurrency prices taken from various feeds [48]. A final thought should be given to the current legal status of metering tampering. The Oracle issues become less problematic when legislation is in place explicitly prohibiting the tampering with meters, as is common in home metering systems [49]. Thus, while controlling authorities continue to exist, the electrical meter is somewhat protected from the Oracle problem, at least compared to open-ended and complex industries like seafood supply chain management.

III. Notional Metering Design

As mentioned above, very few existing studies and programs have considered the real-world physical layout and infrastructure required for the implementation of typically-proposed P2P trading schemes. The required hardware and how it functions is rarely discussed. This section will explain the notional workings of a smart meter required for P2P trading schemes as described above. Blockchain is selected as the ledger's basis.

For parties participating in these P2P energy trades, the smart meter serves as the vessel whereby tokens interact with reality. A notional single-phase smart meter design is shown in figure 2, corresponding to the description and discussion below. Existing studies assume that such meters are present in all market participants' premises, and can observe all consumed and generated data. Analog measurement is communicated to the meter via pulse output. The microcontroller communicates with a dedicated modem through a serial connection, likely RS485 or similar. Information exchange will conform to the European EN 62056-3-1 standard [50]. The modem is similar to existing GSM/GPRS models used in established smart metering systems, but are formatted in such a way as to communicate with the blockchain. The microcontroller can thus function as a full node for the blockchain, helping to maintain the integrity of the network [26], [51]. The circuit breaker is a standard polarised latching relay as in most smart meter applications.

Existing pilot projects often suggest using extant blockchain platforms like *Powerledger* or *Hyperledger Fabric* [29], [52]. The former is a unique blockchain running on the efficient *Solana* network. Owing to Solana's *proof of stake/proof of authority* model [29], energy usage is reduced and transaction rate is greatly increased.

The blockchain is required to have a short block time, and thus be able to handle multiple continuous transactions [26]. When a producer meter reads a new unit of electricity generated for export, the meter communicates with the blockchain and records this information on the subsequent block. This includes all relevant information, including the producer's ID, amount of energy exported, and the consumer's information. As in the popular existing literature, smart contracts will likely perform the role of market operators, allowing for the exchange of energy tokens, facilitating transactions, and imposing any necessary restrictions (as in [28], [36]). The consumer meter observes the presence of the energy tokens in their private wallet. This is interpreted as a license to consume the relevant amount of energy. When tokens are sold or traded the relevant financial exchanges are handled automatically, with buyers being debited and sellers being credited. In the case where consumer credit is depleted, the circuit breaker can be opened, as discussed previously.

IV. Conclusions

Peer-to-peer tokenised energy marketplaces, while the subject of much research attention, have yet to see mainstream adoption and implementation. The functional requirements of the smart metering required for energy tokenisation is rarely discussed. Centralised and decentralised ledgers are both explored as potential options for P2P energy trading, with each presenting its unique advantages and disadvantages. Questions about P2P's implementation, including market operation, hardware requirements and operation, and ledger types have been critically examined and discussed. The case for and against the popular decentralisation scenario has been made. Based on the above, the paper then shows a potential design for a notional metering setup.

The above questions and unknowns presented leave the authors sceptical of the true advantages of the P2P paradigm as it is typically proposed. The concept's true advantages may arise out of supplementary mechanisms and token ecosystems, likely when paired with blockchain technology. Alternatively, regulators could embrace the technology as a tool in existing operational models. In its current state, P2P's potential problems and unknowns potentially outweigh the benefits.

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