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Fostering Energy Transition in Smart Cities: DLTs for Peer-to-Peer Electricity Trading

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***Abstract*—This paper explores the applications of Distributed Ledger Technologies (DLTs) in Peer-to-Peer (P2P) electricity trading. It highlights the challenges and trade-offs of applying three different DLTs: Blockchain, Directed Acyclic Graph (DAG), and Holochain. First, the study introduces the energy transition concept in the smart city context. Second, P2P electricity trading and its supporting trading mechanisms are introduced. Third, DLTs are defined and three different types of DLTs are introduced. Forth, possibilities, challenges, and consequences of applying DLTs in electricity trading are explained. Last, applying DLTs for P2P electricity trading from different aspects are discussed. This paper provides a benchmark for applying DLTs to foster energy transition in smart cities. It highlights how this type of technology can serve smart circular economy.**

***Index Terms*—Smart cities, DLT, blockchain, energy transition, P2P energy trading, ecosystem, token economy,**

I. INTRODUCTION

The European Union (EU) aims to be climate-neutral (i.e., to have an economy with net-zero greenhouse gas emissions) by 2050 [1]. The European Commission has set out this vision in 2018 which is at the heart of the European Green Deal and in line with the EU's commitment to the Paris Agreement [2]. As part of the European Green Deal, the Commission proposed in 2020 to raise its ambition in the 2030 climate and energy framework that includes EU-wide targets and policy objectives for the period from 2021 to 2030. Key targets for 2030 are: i) at least 55% cuts in greenhouse gas emissions (compared to 1990 levels); ii) at least 32% share for renewable energy; and, iii) at least 32.5% improvement in energy efficiency [3].

In this view, energy transition is associated with strategic trajectories of urban transformations in illuminating a path from 'status quo to the envisioned future' [4]. An important playingfield in achieving this transition is foreseen for the so-called 'smart cities' and their (active) citizens in capacity-building [5]. Several multi-actor models, such as Peer-to-Peer (P2P) trading [6], community self-consumption [7], [8], and transactive energy [9], can be detected that support citizen engagement in the energy transition in the smart city context. A common element between them is encouraging and incentivising citizens ('consumers' and 'prosumers'[1]) to have an active role in markets like energy but also electricity[2] [10], relating to the notion of value co-creation in smart cities. This is usually achieved by allowing prosumers to trade electricity or flexibility with other market participants such as other prosumers and grid operators in return for some (financial) incentives – the so called P2P electricity trading. Although initially introduced as a market model [10], it has the potential of a civic outlook alluding to P2P in terms of 'urban commons'.

P2P electricity trading, as 'civic', on the one hand, puts citizens in relation to their town, city, or local community and provides them with the opportunity for further engagement in value co-creation and energy/city governance. On the other hand, it requires cities to 'smarten up' to be able to capture this opportunity. Therefore, the application of smart devices and appropriate supporting technologies is warranted. Distributed Ledger Technologies (DLTs) can facilitate the roll out of token-based models that support building and (self-)governing communities and take up 'value' that is broader than merely an economic term (e.g., social contracts) [11], [12]. More precisely, these tokens could portray electricity itself as value, or generalize it more to represent fiat money. DLTs are also means for 'energy governance' – that is more equal and just, hence, fits the P2P ideals. Therefore, applying DLTs can enhance engagement and support the P2P electricity trading within a community (smart city).

A possible application of DLTs in P2P electricity trading could be to facilitate billing and settlements [13] without relying on trust-based models, which could be seen as a single point of failure, and have inherent weaknesses [14] such as data availability and privacy breaches [15]. Depending on the context, this trading could be done in a fully privacy-preserving manner while respecting regulatory mandates and capable of handling a large volume of transactions per second[3].

Given the context, this study explores the ways DLTs

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[1] Consumers who can also generate electricity

[2] Since a considerable share of energy (from any source) is being transformed into electricity before consumption, the interchangeable use of terms 'energy' and 'electricity' is justified in related debates.

[3] Hyperledger Fabric can scale up to 3500 transactions per second. Recent research has also improved its performance to handle upto 20000 transactions per second [16].

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can be applied to foster energy transition in smart cities as 'urban commons'. It explores the possibilities, challenges, and consequences of applying DLTs for P2P electricity trading. The novel contributions of this paper are twofold: presenting possible applications for DLTs in P2P electricity trading and explaining associated challenges and consequences. More specifically, this study makes the following contributions:

- It produces new insights in the way DLTs can facilitate the roll-out of token-based models for P2P electricity trading, potential applications of DLTs in new electricity market models, the value proposition of applying DLTs for P2P electricity trading, and the effect of DLTs to the business ecosystem of electricity trading. In doing so, the study follows a future oriented qualitative approach.
- It utilises a business ecosystem perspective [17] as the theoretical lense to explore alternative urban governance models in support of the current energy transition push as 'civic cause'.

The remaining part of the paper is structured as follows. Section II covers a comprehensive background on three concepts: smart cities, P2P electricity trading, and DLTs. First the smart city concept is introduced and linked to energy transition and circularity. This is followed by an introduction of the traditional and P2P electricity tradingmarket models. Then, DLTs are defined and three types of DLTs are introduced: Blockchain, DAG, and Holochain. Section III compares the three types of DLTs, followed by presenting the applications of DLTs for P2P electricity trading. Section IV draws implications on investment requirements, democratization of the market, quality/reliability of services, and use cases of different types of DLTs. Finally, Section V presents opportunities for further research and concludes the paper.

II. BACKGROUND

A. Circularity through Energy Transition in Smart Cities

Today, navigating city life consists not only of planning, building and maintaining 'bricks and mortar' but managing and utilising 'algorithms and data' as well [18]. Captured by the momentum of the 'smart city' imaginary which has been associated with "the intersection of data technologies and urban environments", while "the unique a ordances of platforms are said to signal an evolution of the socio-technical relationship between citizens and cities" [19] (p. 116), what has been termed 'platform urbanism' [20], [21]. This can be manifested, for example, in patterns of consumption, socializing and service provision to, among others, reduce costs, spur innovation, enter new markets, and support sustainability goals [22]–[24]. More specifically, public and private entities are tapping value from this composite of growing assets, such as via new service models, by addressing and reconsidering action modalities, interventions, and the policies impacting the everyday life of many. One important motivation is to break away from path-dependent tendencies that have been driven unsustainable behaviours and choices in urban systems. In fact, there is an urgent need to transform urban landscapes, and shift them away from the 'take-make-dispose' paradigm around which many urban economic systems are currently organized. One example of system-level disruption can be found in the transformation from a large-scale fossil-fuel based energy system to decentralized small-scale renewable energy systems which also can underpin the promotion of urban circular economies which, when set into motion, can reverberate across the (smart) urban landscape.

Urban circular economies aim to extend the life of products and to limit the exploitation of natural resources [25]. It involves the development and use of innovative processes and technologies which promote the more responsible and sustainable use of materials. As technological advancements in renewable decentralized systems provide great opportunities to locally produce and consume energy in a sustainable manner – where systems align through smart grids that integrate local energy production, storage, and use in an efficient, sustainable, and economic way – urban circulair economies are, arguably, a transformation that may be instrumental for achieving more sustainable societies. In fact, an increasing number of (European) cities and regions can be seen to be experimenting with urban circulair economies [26], [27]. These experiments help society to gain knowledge about conditions under which urban circulair economies will succeed or fail, hence promote societal transformation through scaling up and out processes.

As with many smart city initiatives, one of the main challenges of establishing and sustaining an urban circular economy is buy in and resonance from citizens. Creating a culture around circularity is therefore among the main challenges of communities engaged in these experiments. However, the circular economy has so far been conceptualized as an ecological modernization of the current economy, keeping the creation of monetary value as its main goal [28], [29] and perpetuating the critical blind spot for social aspects [30], [31]. Elements of social justice, inclusivity and well-being are often left out of the discussion.

B. Peer-to-Peer Electricity Trading

The traditional paradigm of electricity generation and distribution is based on centralised electricity generation in power plants [32]. Power plants (still) mostly use non-renewable sources of energy. Centrally generated electricity passes through the high voltage transmission grid and after transforming to low voltage electricity is distributed via the distribution grid to the consumption sides. Centralized generation and one directional flow of electricity are the two main identifiers of the traditional paradigm [33]. The whole system have been resistant to change thanks to legal monopolies which until recently put a single (mostly state/government owned) entity in charge of the whole process [34].

This paradigm, however, has gradually been changing [35]. The change stems from several reasons: renewable energy sources and batteries in high capacities and low cost, wide spread use of smart devices, and legal changes towards the liberalisation of the electricity market [36], to name a few.

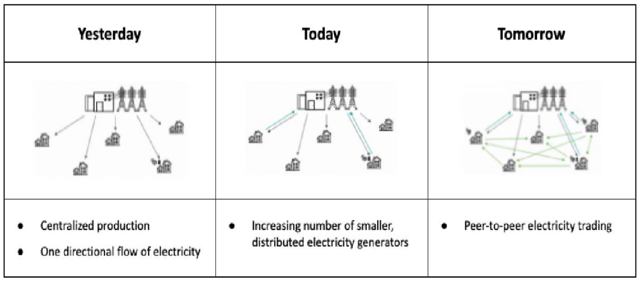

Fig. 1. Evolution of electricity production and trading [39].

Figure 1 shows this gradual change in the electricity production and trading paradigms.

Electricity markets witness the emergence of prosumers who expect to have high returns on their available resources by willing to take an active role in the energy transition process for the 'right' incentives [37] . P2P electricity trading is referred to trading of surplus renewable electricity produced at prosumers' sites with other prosumers or consumers (directly or through an intermediary) [36]. Figure 2 depicts a future scenario for P2P electricity trading which incorporates recruiting representatives to trade electricity on behalf of citizens. A broker facilitates the trading and clears the market [38]. A successful roll-out of the P2P trading requires overcoming several technical challenges. It entails the application of appropriate technologies.

In a more technical terminology, P2P electricity trading provides the possibility of mutual transactions between different entities to trade electricity in exchange for a fee [6], [40]. Traders in the P2P electricity markets may be of different sizes, i.e., residential houses, neighborhoods, microgrids, and local distribution networks [6], [41]. P2P electricity trading lets the smart grid benefit, operationally and economically, from demand side flexible resources [42]. The main and foremost objective of P2P models is to incentivise transactions that prioritise maximising the benefits of individual prosumers [43]. A selection of market mechanisms and appropriate technologies serves the mentioned purpose. Such models could involve intermediate parties that facilitate the trades among prosumers or support fully decentralised trades among them. The market mechanisms used in P2P models usually are set to optimise the trading based on algorithms with objectives of matching the excess supply of prosumers with the demand of consumers.

C. *Distributed Ledger Technologies (DLTs)*

The concept of DLT provides us with a P2P technology that can be used to store, distribute, and exchange data among multiple users over computer networks [45]. In a general categorization, DLTs can be divided into permissioned and permissionless. In a permissioned DLT, users or nodes need to have prior approval before joining the network, whereas, in a permissionless DLT, anybody can set up a valid node and start to participate in sharing data over the network [46].

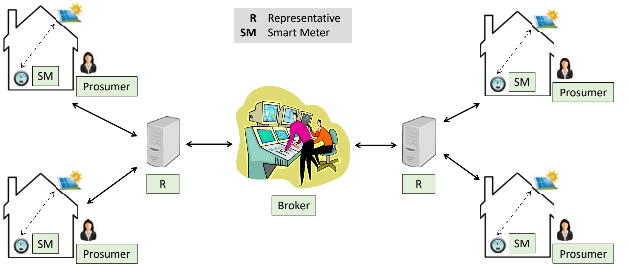

Fig. 2. Prosumers trade electricity with each other. The broker facilitates the trade of electricity between peers. Citizens may recruit a representative to trade on their behalf [44].

There exist different types of DLTs. Below we explain three technologies, named blockchain, Directed Acyclic Graph (DAG), and Holochain, that can be used to implement a distributed ledger. As most of the available DLTs are developed on top of the blockchain and DAG technologies, blockchain and DAC are a logical choose to analyse. Besides them, we will also discuss one of the newest DLTs, named Holochain, which is seen as a suitable candidate to be implemented in smart cities due to its lightweight nature.

1) Blockchain: In a blockchain, a ledger can be considered as a sequential chain linking data in a chronological order in the form of blocks. Each block contains a list of transaction records and a reference to an existing block. Therefore, each block has a parent block, except the first block which is called the genesis block. In order to add a new block to the blockchain, some nodes need to act as miners. Miners are responsible to gather transactions and organize them into blocks. Once a miner receives a transaction, he/she first needs to verify the validity of the transaction [47]. In order to do that, the miner needs to verify the signature of the node who has generated the transaction and check whether the new transaction is compatible with the last update of the blockchain. Once the transaction is verified, the miner can add the transaction to his/her transaction pool.

In order to mine (introduce) a new block, all the miners participate in a competition. First, they generate a reference to a previously mined block in the blockchain (usually the latest block) and add this reference to their to-be-mined block. Then, miners select up to a specific number of transactions from their transaction pools and add them to their to-be-mined block. As a next step, miners try to solve a cryptographic puzzle generated using their to-be-mined block. The miner who manages to solve the cryptographic puzzle earlier than the others is considered as the winner and the block that has been used to generate the solution will be added to the blockchain [48]. For solving cryptographic puzzles, miners usually need to consume a considerable amount of energy. To compensate for the miners' efforts in mining new blocks, a substantial amount of reward is paid to the creator of each block. Besides, in order to incentivize the miners to add transactions to their blocks, users who generate transactions pay a transaction fee to the miners.

TABLE I
COMPARISON OF THE DIFFERENT TYPES OF DLTS: BLOCKCHAIN, DAG, AND HOLOCHAIN.

	Blockchain	**DAG**	**Holochain**
Requirement	Miners for verification	-	-
Use of electricity	High (PoW) or Low (PoS)	Very Low	Very Low
Transaction fees	High (PoW) or Low (PoS)	N/A	N/A
Scalability (number of transactions)	Low	High	High
Immutability	Very High	Low	Low
Decentralized	High	Medium	High

Note that not all blockchains are based on solving cryptographic puzzles. The consensus mechanism used in blockchains with cryptographic puzzles is called Proof of Work (PoW) [49]. PoW, which is the most famous consensus mechanism used in blockchains, incurs a high cost in terms of computational power. It is worth mentioning that besides PoW, there exist other types of consensus mechanisms that aim to improve upon PoW limitations. The most popular alternative of PoW is called Proof of Stake (PoS) [50] that incurs substantially lower cost compared to PoW. In PoS, the miner who adds the next block to the blockchain is randomly selected among the list of stakeholders, and there is no need to perform heavy computations. In PoW, the miners who have access to more powerful computing devices have more chance to mine blocks. However, some argue that PoS can also be unfair as the miners who own more stake have more chance to become the leader in subsequent blocks [51]. For more detail about the different available consensus mechanisms, readers can refer to [52], [53].

2) DAG: This is another type of DLT. From a mathematical point of view, DAG is a graph with directed edges and no cycles. In a DAG-based DLT, every new transaction needs to reference some of the previous transactions in order to be added to the ledger. In contrast to blockchains, DAG does not need miners to verify the transactions, since in DAG, any node can become a verifier and easily add transactions to the ledger without requiring substantial computational resources. In order to add a transaction in DAG, the new transaction needs to verify at least one previous transaction available in the graph. Therefore, in this scenario, prior to adding a transaction, the node who has generated the transaction performs a PoW task [45]. The previous transaction which needs to be verified is selected using a specific algorithm that prevents nodes from only validating their own transactions [54]. In DAGs, nodes do not need to pay a transaction fee for their transactions to be added to the ledger.

3) Holochain: In contrast to blockchains, where each node maintains the same state of data, in Holochain, each node or agent generates and stores its own data in a journal called a source chain. All the entries of a source chain are cryptographically signed by the owner of the source chain and are immutable once written. In a Holochain network, each node shares the public entries of his/her source chain with a random selection of other nodes who are responsible to validate those entries and keep their copies. By implementing this idea, a Holochain network is able to construct a distributed database of all public data called a Distributed Hash Table (DHT). A Holochain network specifies validation rules for every type of entry. Using these validation rules, nodes can verify the validity of the entries they receive. If a node tries to propagate or validate false entries, that node is blacklisted, and a warning is sent to the other nodes [55].

III. DISCUSSION

In this section, we first present a comparison of the thee types of DLTs, followed by a discussion of their application to P2P electricity trading.

A. Comparison of DLTs: Blockchain, DAG, and Holochain

In contrast to the PoW-based blockchains, DAGs and Holochain networks reduce the need of substantial resources, i.e., the extensive use of electricity. This is due to the relaxed transaction verification requirements. Besides, unlike in blockchains, users in DAGs do not need to pay transaction fees as there is no need to incentivize miners.

Moreover, the most important advantage of DAGs and Holochain networks is that they are highly scalable and can handle a large number of transactions in a relatively short time. Blockchains usually have lower transaction throughput. Note that, in the cases where the number of transactions is too low, DAGs are vulnerable to attacks [45].

Another important point is that the blockchains have better immutability than DAGs and Holochain networks [45]. This means that once a transaction is added to the blockchain, with a high probability, we can be sure that the transaction will not be changed or deleted in the future. Compared to blockchains, DAGs enjoy a lower level of immutability. On the one hand, this can make DAGs susceptible to different attacks such as a parasite chain attack, which aims at threatening the immutability and irreversibility of the transactions [56]. On the other hand, some DAG-based DLTs can use this property to provide controlled mutability, which means no malicious node can alter the records without everyone knowing, but the DLT can modify regulations or bugs [57].

Another drawback of DAGs is that they are not fully decentralized. DAGs usually use a coordinator to prevent malicious activities, especially at the beginning when there are not enough transaction nodes to perform validations [54]. Blockchains, on other hand, can provide us with a fully decentralized network. Table I summarizes the differences mentioned above.

B. Applying DLTs for Peer-to-Peer Electricity Trading

The application of the three introduced DLTs is the same in essence, which is 'enabling multiple parties to contribute to a single purpose'.

One of the applications of DLTs in electricity trading could be to facilitate billing and settlements without relying on Trusted Third Parties (TTPs). There could be two types of billing and settlement financial transactions in P2P electricity trading markets: (i) transactions amongst the peers (prosumers or consumers), as explained in [58] and (ii) transactions amongst the other, more traditional, energy market participants to deal with the transmission and distribution grid charges, as explained in [59]–[61]. The peers can use DLTs to transfer money among each other. This trading could be done in a fully privacy-preserving manner while respecting regulatory mandates and capable of handling a large volume of transactions per second [62].

Another application of DLTs could be implementing decentralized secure auctions. The previous works such as [63], [64] that propose secure protocols for holding auctions in smart grids are designed either without considering the financial transactions amongst peers or are based on the assumption of having a TTP. However, by using DLTs, we can move towards implementing decentralized and secure auctions without the need for a TTP. Users can publish their bids through blockchains, and trading prices as well as winners can be determined using smart contracts.

IV. IMPLICATIONS

Considering the technical differences and benefits of the introduced DLTs, the following implications can be drawn.

A. Investment Requirement at Peers' Sites

Based on the type of DLT that is going to be implemented in the grid, the peers' investment may differ. In the cases that blockchains are used as DLT, peers can be divided into two separate groups. The first group consists of peers who will play the role of miners/verifiers, and the second group consists of ordinary peers who will just use DLT to exchange information. In this scenario, the miners/verifiers need to invest a considerable amount of money to take part in extending the blockchain. If the consensus mechanism used in the blockchain is PoW, the term investment refers to computational power, and if the blockchain is based on PoS, the term investment refers to stakes or coins generated through mining new blocks. In addition to investing in computational power or stakes, miners/verifiers need to store the whole system's data to be able to verify all the transactions. However, moving towards using blockchains does not change the investment requirement for other peers who are not interested to be miners/verifiers. The reason is that the amount of data that is shared by the use of blockchains is the same as using the centralized platform.

It is worth mentioning that implementing blockchains opens a window of opportunity in the electricity trading market which is the possibility of becoming a miner. In general, feasible scenarios are imaginable in which investment return is appealing for some private and corporate entities to seek the benefits of a miner.

If DAGs are used as DLT, all the peers will play the role of verifiers. As mentioned before, prior to submitting any transaction in a DAG, the owner of the transaction needs to verify at least one of the previous transactions. In order to do that, peers need to store all the system's data and have enough computational power to verify the other transactions. Compared to miners/verifiers in blockchain-based grids, peers in a DAG-based network need a considerably lower amount of investment. However, compared to ordinary peers in blockchains, who are not responsible for verifying transactions, peers in DLT need more computational and storage power.

In the cases that Holochain is implemented, all the peers need to perform a specific number of verifications, but there is no need to store all the system's data. Each peer is responsible for maintaining a small amount of the whole system's data. Therefore, compared to DAGs, in Holochain networks, peers need to have access to almost the same computational power but less storage capacity.

B. Democratization of the Market

Shifting from a centralized network to a decentralized network using DLTs can enhance the democratization of the market. Previous monopolies which legitimize DSOs in the traditional electricity markets will dissolve by this characteristic. In DAGs and Holochain networks, all the peers play the role of verifiers, and thus, in these types of DLTs, all the peers rather than a limited number of authorities are responsible for verifying and auditing the market. In blockchains, although not all the nodes indeed act as verifiers, there exists the possibility of becoming a verifier for all the peers, and the only requirement is having the incentive and making the required investment as well as technical expertise.

DLTs are tied to the elimination of regulations. The concerns regarding the governance shift from the regulation to rule-based instructions which are less likely to be biased. The legislator is not a single party and a single party cannot stop the existence of the DLTs.

C. Quality/Reliability of Services

The application of DLTs increases the quality/reliability of service in the electricity market. It makes the whole system more transparent, hence, the whole data is public, therefore, demand and supply are predictable. It leads to easier balancing and a more robust system against prediction failures. Another advantage of using DLTs is data availability, i.e., by having access to a distributed ledger, we can be sure multiple copies of data are distributed over several nodes, and therefore there are no concerns if a limited number of peers go offline. In blockchains and DAGs, verifiers keep a copy of the last update of data, and in Holochain networks, for each piece of data or entry, there exist multiple peers who are responsible for storing that entry.

It is worth mentioning that reliability costs privacy in P2P electricity trading. Increased transparency enhances the reliability of the service but at the same time increases the privacy threats against the participating peers [65], [66]. In this sense, in the European context, it may infringe the General Data Protection Regulation (GDPR) [67]. As a solution for this problem, one can think of using anonymous blockchains to reduce the amount of information that can be revealed through blockchains. Anonymous blockchains not only can provide immutability but can preserve the users' privacy by disconnecting the link between the transactions. However, anonymous blockchains usually impose higher computational requirements on the verifiers compared to ordinary blockchains.

D. Use Cases of Different Types of DLTs

As mentioned before, blockchains can provide us with a high level of immutability and security. Once a transaction is added to a blockchain, we can be almost sure that it will not be deleted or changed in the future. Therefore, a malicious peer cannot perform attacks such as double-spending. With this in mind, for the case of transferring fees among different peers, it is highly recommended to use blockchains. Another important point to mention is that energy-consuming blockchains are in contrast with the nature of P2P electricity trading which is increasing energy efficiency. In order to solve this problem, one can think of using other types of blockchains that are based on more efficient consensus mechanisms such as PoS.

However, for the applications that scalability matters more than security, such as sharing information about the grid condition, we can use other types of DLTs rather than energy-consuming blockchains.

V. CONCLUSIONS AND OPPORTUNITIES FOR FUTURE RESEARCH

The paper explains how P2P electricity trading supports energy transition in smart cities and how it relates to the notion of circularity. Furthermore, the applications of three different DLT types, blockchain, DAG and Holochain, in P2P electricity trading are discussed, and associated trade-offs and the comparison of different applications are explained. We also discussed the amount of investment required to implement different types of DLTs and the effects of DLTs on market democratization as well as service reliability. Besides, we emphasized on the fact that blockchains can provide a high level of immutability, while DAGs and Holochains can provide a high level of scalability. Therefore, for different applications to be implemented in smart cities, we need to choose a DLT that is most compatible with the application requirements.

The study also identifies interesting opportunities for future research. Considering the conflicting nature of the smart grid values which has the energy efficiency in its heart, with the PoW-based blockchain technology due to the increased energy consumption, it would be fruitful to research on developing a type of technology which complies with the sustainability goals of the smart grid while providing the technical benefits. It will require new consensus mechanisms. Evaluating the feasibility of investments both for the citizens and for the potential miners/versifiers is another void for future studies

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