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Off-chain trading for micro grid systems

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As micro grids and blockchain gained the interest and attention of both academia and the industry, the interaction between the two technologies seems inevitable. However, there are challenges to overcome in order to actually realize the integration between micro grids and blockchains. In this article, we review the solutions proposed to enhance micro grids with blockchains. We discuss the scalability challenges and the opportunities derived from the off-chaining computing techniques. In this context, we draft a design to implement a micro grid-based peer-to-peer local energy market, powered by an off-chain computing protocol called DIVERSITY. DIVERSITY aims to shift the computational burden from a main blockchain to an intermediate layer of nodes, aggregating data and executing smart contracts off-chain. We simulate different data logging approaches, and it is found that DIVERSITY allows an actual saving on fees and power consumption derived from using a public blockchain platform, such as Ethereum, in order to assure a truly decentralized renewable energy distribution at a lower cost.

KEYWORDS

micro grids, distributed energy resources, blockchain, off-chaining computing, energy trading, smart contract

1 Introduction

Anthropogenic global climate change has been proved by several research studies and investigations, urging actions by different stakeholders (e.g., international organizations, national governments, companies, and citizens) in the planning, management, and governance of human activities (as non-exhaustive examples cfr. On Climate Change (2021); Rosenzweig et al. (2008); Mikhaylov et al. (2020)). Greenhouse gases, and in particular carbon dioxide (CO_2), are responsible for the intensification of the natural process, called the *greenhouse effect*, that determines a threatening, potentially catastrophic, increase of the Earth's temperature. Energy is one of the sectors that contribute the most to the emission of greenhouse gases (Ritchie and Roser, 2020; IEA, 2021), with a 40% share of the total emission of CO_2 (Pavarini and Mattion, 2019).

In addition to the pollution and environmental impact due to intensive productions (i.e., industry, farming, energy generation, etc.), cities and urban areas are extensive exploiters of soil and natural resources, significantly influencing the energetic industry (Bakshi and Fiksel, 2003). There are approximately eight billion people living on Earth, of which more than 56% is living in urban areas, and population is growing +0.9% each year. At this pace, projections predict that there will be 10 billion people by 2050 (Dorling, 2021), with 68% of them living in cities (Ritchie and Roser, 2018). This determines, along with other factors, a constantly increasing demand of electricity coming from residential consumers (IEA, 2021). As for 2021, urbanized areas impacted 75% of global primary energy consumption and produced 70%–80% of global greenhouse gas emissions (Verma et al., 2021).

In this context, recognition of the environmental hazards and limits connected with urbanization is required. This contingency gives the opportunity to reconsider the idea of city to find possible improvements in citizens' health and quality of life, obtainable by means of a new governance approaches and urban planning towards *sustainability* (Quitzow and Rohde, 2021; Raco, 2020). With an attentive spotlight on *decentralization* and *optimization* of energy production, humanity may eliminate polluting, land consuming, and unsustainable power plants, especially those supplied by fossil fuels (Fonseca et al., 2021; Nyangon, 2020). The decentralization aspect has a focal importance in the implementation of the so-called "Smart Cities": cities connected with decentralized smart objects to help communities in the governance of their urban areas, promoting high quality of life and improving environmental health (Toan and Nhu, 2020).

The challenge is, therefore, to find the best fitting methods and techniques to realize cyber-physical systems capable of managing optimally the production, distribution, and utilization of energy sources.

As it will be discussed in Section 3, game theory and peer-to-peer (P2P) energy trading has been extensively utilized to optimize energy consumption and maximize the use of renewable energy and automatic trading in energy communities.

In game theory, the individual participant actions can optimize a community objective. For instance, in a smart grid, individuals can locally solve a load scheduling problem by using the prediction of others. Therefore, P2P energy trading platforms aim at matching the production and consumption, while setting the energy price with the help of game theory. Most of the conventional energy distribution platforms rely on a centralized platform for energy consumption reduction, trading, or payments. This poses problems of scalability and security. The use of blockchains, however, does not solve efficiently the problem of scalability, because of the costs (in terms of fees) to be payed in order to register transactions.

In this frame, some techniques and solutions for ensuring scalability can be found. There are many ways to achieve such a goal such as payment channels, state channels, off-chaining computing, side-chains, and sharding. Between those, probably the most famous solution is Lightning Network (Poon and Dryja, 2016), a micro-payment channel for Bitcoin. It has to be investigated whether those scalability solutions for blockchains can obtain some groundbreaking outcomes in the energy sector. For example, while existing P2P systems only optimize individual costs, the new proposed platforms should aim at optimizing multiple global goals that include maximization of renewable energy use, minimization of the demand from the central grid, and cost reduction for individuals. Most importantly, all the trading should happen *via* energy-efficient blockchain, which improves availability and reliability of data, provides data immutability, and avoids the introduction of a centralized authority.

For this purpose, our contribution proposes a model to implement a local P2P energy market to cut losses in electric distribution, enhance the reliability of renewable electricity sources, and save on fees for the use of public blockchains in the accounting for energy exchanges.

In this study, we discuss the notion of *micro grids* and their integration with *distributed ledger technologies* (DLTs), such as *blockchains*. The following article contains a presentation of related works in the fields of micro grids, energy markets, and DLTs. Furthermore, we design a framework for local peer-to-peer (P2P) energy markets, enhanced by a blockchain, to implement in the framework of micro grids. The idea is to use a second-layer blockchain system to ensure correctness, transparency, fairness, and an optimal use of the generated electricity.

2 Background

2.1 Micro grids

A micro grid is an electric system composed by *producers* and *consumers* of energy (called *prosumers*, in case these roles are overlapping). Micro grids are characterized by three main ingredients: it is possible to determine the boundary of the system itself with respect to another power grid; the system operates as a whole entity, in which the single components are coordinated with each other; and a micro grid may function regardless if it is connected to a larger grid or not (*island mode*) Hirsch et al. (2018).

Micro grids have existed since the advent of electrification, that is, power grid in remote areas, but recently it is drawing more interest because of the proliferation of renewable electricity sources (RESs), that is, photovoltaic (PV), wind power, co-generation, storage, etc., and the need of a more stable, efficient, and manageable system to orchestrate all these decentralized energy resources (DERs) (Warneryd et al., 2020).

When some smart devices are installed in a micro grid, for example, smart meters, the micro grid can be, naively, labeled as a smart grid. Particularly, smart meters empower smart grids to be easily managed, and they give solutions for billing and P2P energy transfer concerns (Lai et al., 2021; Al Dakheel et al., 2020; Najafi-Ghalelou et al., 2018).

In fact, an optimal balance between the energy production and the actual electric load is an open problem for renewable energy sources (RESs). A solution for the producers connected to a main grid is to sell (feed-in) or store electricity in the grid, then retrieve it when it is needed, the so-called *net metering* (Schelly et al., 2017).

2.2 Decentralized ledger technologies

A DLT system, also called distributed ledger, is an immutable, consistent set of shared and replicated digital data disseminated across different machines (known as nodes, servers, or replicas). The main difference between a distributed database and a DLT is that the latter does not rely on a trusted third-party central authority to work but on a *consensus* algorithm. DLTs may be categorized by how participation is managed, such as in permissionless or permissioned frameworks. Permissionless DLTs are characterized by the absence of a control system on the access to the consensus: any device connected to the internet may join the blockchain and participate in the consensus. On the other hand, a permissioned DLT requires participants to be accepted by the already established network of peers; then, it can take part to the consensus process. Permissionless or permissioned is not related to the privacy of the network (public, private, or consortium), but it defines the security levels for the participation (Antal et al., 2021; Kannengießer et al., 2020).

DLTs, and in particular blockchains (in which data are organized into blocks of transactions), started to have a huge impact with the introduction of Bitcoin (Nakamoto, 2008); in fact, blockchains received much attention from mainstream media and great interest from a vast audience. Because of its disruptive idea—that a digital currency could have some financial worth, even without a central bank "guaranteeing" its value—Bitcoin led the way to the development of DLTs. But it was with the launch of Ethereum (Buterin, 2017) that blockchains became more than a currency: the idea was to implement a world-wide computer on which algorithms, here called *smart contracts* (SMs), could be executed in a distributed fashion, without the need for an external central authority. From then on, decentralized applications (DApps) became more and more popular, especially for financial services, gaming, collectibles, and social media[fn1].

The downside of using these specific technologies, though, is the intensive use of electricity. Bitcoin and Ethereum both rely on the use of a consensus algorithm, known as proof of work (PoW), that is computationally intensive and, thus, energy demanding. Bitcoin alone, to keep the network working, requires the same amount of electricity that powers a small/medium-sized state (Rauchs et al., 2020). This is one of the reasons why other greener protocols to reach consensus in DLTs have been developed.

However, taking into account its popularity and both academic and company efforts to develop blockchains, this study will be focused on the integration between blockchain and micro grid.

3 Related work

Because of the need for decentralization in the management and optimization of the DERs, the convergence of micro grids and blockchain is no surprise.

There are already some well-known examples of micro grids integrated with a blockchain. Probably, the most famous one is the Brooklyn Microgrid (Mengelkamp et al., 2018) in New York (United States). However, there are also important examples in the European scene, for example, Prosume, a project implementing a decentralized, autonomous, independent, and digitized smart marketplace for different energy sources[fn2]. In addition to the technical effort made to combine these two technologies, it is worthy to point out the academic interest in the matter: there are several researchers studying and analyzing the topic, with the support of abounding literature reviews.

In the next paragraphs, we present a literature review, with the intent to group works with similar topics and affinities.

3.1 P2P and local energy markets

Literature reviews and surveys on P2P and local energy markets are fundamental entry-points for researchers approaching the topic. In particular, there are important classifications and comparative analysis (Zia et al., 2020), both for what concerns the market platforms (Zhang et al., 2017) and management algorithms (Moreno Escobar et al., 2021).

Different solutions have been proposed to build local energy markets and peer-to-peer grids. The proposed platforms may rely on several approaches, for example, game theoretical optimization processes (Zhao et al., 2019; Wen et al., 2021; Noor et al., 2018), market model optimization (Wang et al., 2021; Foti and Vavalis, 2019), multi-objective optimization (Tsao et al., 2021), hierarchical bidding and transaction structure (Yu et al., 2019), dynamic bidding strategy (Wang et al., 2020), ahead energy demand planning (Van Cutsem et al., 2020), or dynamic incentivization of optimized usage of energy (Yahaya et al., 2020).

3.2 Blockchain solutions in the energy sector

There exist a large variety of solutions and approaches proposed to integrate micro grids and blockchain to develop

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[1] DappRadar—https://dappradar.com/[Accessed 30 May 2022].

[2] Prosume—https://prosume.io/[Accessed 30 May 2022].

optimized energy communities while ensuring transparency, accountability, and sustainability. The interest of researchers translated into a continuous attempt to catalog, characterize, and summarize the state-of-the-art literature about the use of blockchain in the construction of micro grid environments (Chitchyan and Murkin, 2018; Andoni et al., 2019; Alladi et al., 2019; Siano et al., 2019; Mollah et al., 2020; Li et al., 2021; Baashar et al., 2021; Guo et al., 2022; Kirpes et al., 2019; Vieira and Zhang, 2021).

Together with literature review, related recent studies are covering important topics in the evolution of the micro grids enhanced by blockchain solutions. Proposals involve an energy trading platform to improve loss reduction and balanced self-consumption (Siano et al., 2019), optimization and physical constraints to implement an integrated cyber-physical system (Van Leeuwen et al., 2020; Iris and Lam, 2021), and the composition of emerging technologies such as blockchain and machine learning to develop fully autonomous, self-resilient Energy Internet grids (Yapa et al., 2021).

An important aspect in the blockchain context is the scalability problem and the unsustainable transaction fees to be paid in most of the public platforms. In general, different approaches have been proposed to address one or both issues, mostly through techniques known as *layer two* or *off-chain*. Specifically for the integration between blockchain and micro grids, Jeon and Hong (2019) proposed an off-chain hybrid blockchain, granting a secure channel to transfer energy between the prosumer and consumer without an intermediary. Pop et al. (2019) show how their second-tier solution combines the blockchain features, that is, tamper-evident, with the real-time record of energy data in an off-chain database.

3.3 NFT and gamification

To the best of our knowledge, Karandikar et al. (2021) are the only ones explicitly proposing the use of NFTs for a community-based energy infrastructure. The authors presented a model and related algorithms to encapsulate energy-related data into an NFT; thus, they encoded them in smart contracts for performance testing. They proposed a gamification system to incentivize the participants into the community energy infrastructure. At last, a comparison between the NFT and FT usage in the system shows that the performances of both implementations are commensurable for most major operations.

3.4 Conclusion

The vast amount of literature about micro grids, local energy markets, and blockchain assisted systems is generated by a significant interest from different parts in the energy sector, researchers, communities, and final users. In our summary, we review the existing literature about the integration of micro grids and blockchains, especially in a local energy market focus. We used three different categories, according to whether the work is more oriented to the problem of creating P2P and local energy markets, if it is centered on blockchain solutions for energy trading, and finally a mention on the use of NFT for energy trading, with an emphasis on the gamification of the process to incentivize the participation.

4 Methodology

In this section, we present the requirements to implement a blockchain solution for local energy trading by means of off-chaining techniques. Such a system would ensure correctness and transparency, and it is designed to reduce the fee cost derived from using a public blockchain platform, such as Ethereum.

Subsequently, we discuss what approaches can be used to store data on a blockchain and the resulting difference in terms of used gas, that is, the cost for saving the same amount of effective information on Ethereum.

4.1 Off-chain energy trading design

Our proposed design for local P2P energy markets relies on the idea that producers, consumers, and prosumers can maintain the data infrastructure to handle the energy exchange, without the need of a centralized entity. In the rest of the study, when it is not necessary to specify it, we use *prosumer* to indicate any participant in the market, irrespective of they actually produce/consume electricity exclusively.

There are two main prerequisites in this system: a physical electric connection between each prosumer (both for electricity and for information) and a network to handle the market for all the participants.

4.1.1 Electric infrastructure

The electric system must allow the transfer of electricity between any two prosumers in the micro grid: if we consider the electric scheme as a graph (where vertices are prosumers and edges are electric links), such a graph has to be complete.

We are assuming that the infrastructure includes cables, switches, and all the necessary devices to generate, accumulate, and transfer electricity.

We will discuss the constraints on the metering of the electricity exchanged in the network. Since the system is not based on a central and trusted authority, that, as an example, ensures the correctness of the billing, there must be some devices that cannot be accessed and manipulated maliciously by the prosumers. We expect that each prosumer installs a smart meter to register the produced and absorbed electric energy. Those smart meters have to be tamper-proof and not re-programmable;

they broadcast data to each participant in the network, ensuring that prosumers (or any other malicious actor) cannot compromise the correct functioning of the system.

4.1.2 Data infrastructure

For the network requirement concerns, instead, also because of the rich literature on the topic, we regard blockchains as an excellent solution to implement a decentralized P2P energy market.

In principle, any DLT that allows the use of smart contracts can be used as a distributed data network. However, in our implementation, we assume a second-layer blockchain, with node communication defined as a complete graph, analogous to the electric infrastructure described in sub Section 4.1.1. This choice comes from different factors: privacy, security, and costs. The first two aspects are strictly related to the network configuration, since nodes are needed to identify themselves to participate in the market, thus ensuring accountability and a restricted (not absent, though) disclosure of private data. Costs, instead, are connected with fees since transactions need to be submitted in a public blockchain: a tremendous amount of transaction fees would be needed in a straightforward implementation using public blockchains. In addition to the costs related to transaction fees, the possibility to aggregate and locally compute (off-chain) transactions reduces the energy consumption connected with the PoW protocol currently used by the most popular blockchain platforms.

In this context, there is an increasing interest in the scalability of blockchain solutions, with regard to the off-chaining computation (Eberhardt and Tai, 2017; Eberhardt and Heiss, 2018; Gudgeon et al., 2019). Main challenges are connected with the establishment of blockchain properties (i.e., immutability, verifiability, decentralization, and secure multi-party computation) in a local and off-chain setting. To have an idea of the difference between on-chain and off-chain, the latter refers to all the techniques involving a second-layer protocol on top of a blockchain to achieve scalability and reduce fees.

Our design is based on the protocol described in Cacciagrano et al. (2021), called *DIVERSITY*. As represented schematically in Figure 1, DIVERSITY is a second-layer decentralized network that offers off-chaining computation of smart contracts, regardless of which blockchain platform is used.

In particular, this protocol allows a truly P2P contracting, with the possibility of multi-party execution of smart contracts. The innovative character of DIVERSITY is the reduction of on-chain operations, limited to the most critical aspects of contracting: open contract, aggregated data update, closing contract, and dispute. The last case, notably, is the key element in DIVERSITY: this protocol does not strictly achieve consensus; rather, it is a unanimous agreement on the executed computation. Indeed, it is enough to have a single honest participant in DIVERSITY to detect and disclose malicious behavior, since disputes are solved in a transparent way on-chain. Additionally, the time window structure that is implemented in DIVERSITY allows a smaller amount of memory to store data, since data in an undisputed temporal window might, in principle, be erased.

All these features makes DIVERSITY, in tandem with tamper-proof smart meters, a candidate for a practical tool to enhance local energy markets with the help of blockchains: it ensures accountability, security, and a cost-effective management of energetic assets. A comparison between the DIVERSITY and Bitcoin Lightning Network shows how the latter may be used for payment channels, but it cannot be used to handle energy data and thus compute the total due from the consumer to the prosumer.

The flexibility that can be achieved through DIVERSITY allows moving the attention of energy production control and trading onto the contracting part. This data infrastructure, in order to be fair and efficient, needs an attentive focus on the contract between the prosumers: a correct strategy, with incentivization mechanisms to ensure no waste of energy, is the central component in a local P2P energy market.

As a naive example, a contracting strategy may include discounts to buy electricity in surplus (hence, the need for an effective scheduling of energy-demanding activities), while penalizing the requests of energy when the supply is depleted, for example, during night time, if electricity is generated by photovoltaic panels.

Specifically, DIVERSITY allows the off-chain execution of smart contracts that make use of continuous streams of data. The execution of these smart contracts is performed by devices external to the blockchain called *intermediate nodes*. Each intermediate node has the role of constructing windows of sensor messages, perform computation on them, and eventually perform an action according to the previously computed result. Information about the computation to be performed by the intermediate nodes is stored in a smart contract previously committed to the blockchain. This information includes the parameters of the windows (e.g., size, starting point, and the number of windows); the specifics of the function to be applied to the windows of data; the intermediate nodes partaking in the execution of the off-chain smart contract; the sensors involved in the contract; and the reaction logic that specifies the action to perform at the end of each window (e.g., moving funds from the smart contract to a wallet). In our design, each prosumer has an intermediate node and a smart meter measuring the amount of electricity produced and used in a window of time. Sensor messages generated by the prosumers' smart meters contain the amount of electricity generated and the amount of electricity used within an hour's time span. Each smart meter sends these messages to every other intermediate node of the smart grid. The windows of data kept by the intermediate nodes are 2 months long. The off-chain function executed on each window of data is an aggregation function that returns the total amount of electricity generated and was used during 2 months by each prosumer. The reaction function

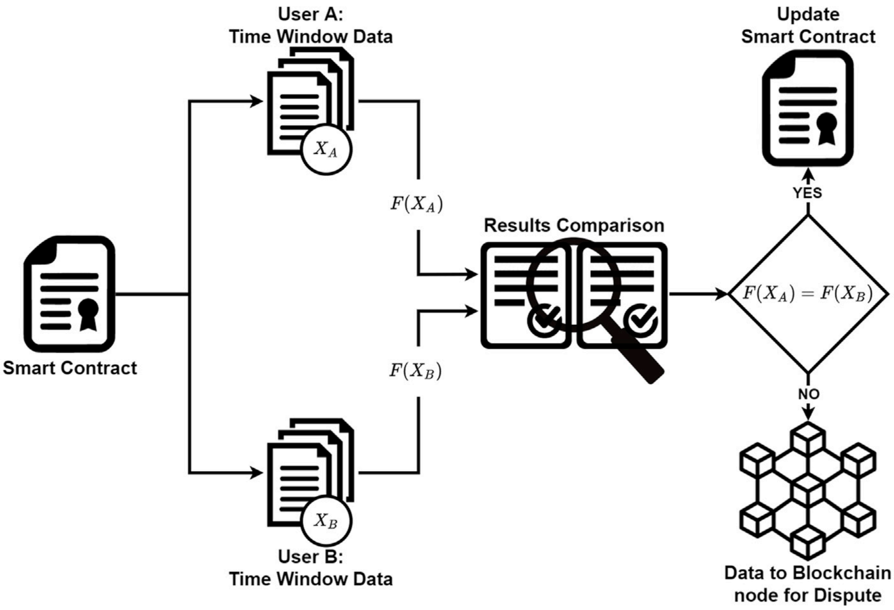

FIGURE 1
DIVERSITY off-chain execution for user A and B.

redistributes part of the funds previously locked on the contract to the prosumers according to the result computed by the off-chain function and to the electricity prices previously agreed upon. Our off-chain approach enables the prosumers to automatically perform the economic transactions involved in a smart grid system without incurring the costs of using a straightforward on-chain approach while avoiding the introduction of a trusted third party at the same time.

4.2 Simulation settings

There are three approaches to store data on a public blockchain: raw data application (RDA), session application with trace (SAT), and session application (SA). RDA means that each time there is an event generating data, that information is stored on the blockchain. In SAT, data are stored in sessions, reporting all the events that triggered a data generation in that session. It could be regarded as an event logging technique with some data aggregation policy. SA sends the total amount of events in a given session, without reporting each single event in the session. DIVERSITY operates in this configuration.

Simulation settings, that is, virtual machines used and number of nodes composing the blockchain, are borrowed from Cacciagrano et al. (2021) since the only difference in simulation is the artificial dataset.

Our artificial dataset is elaborated from electricity consumption data in Italy. We retrieved the Italian electricity market load from *Terna spa*[fn3]. Using data from EIA[fn4] about total electricity consumption per capita, we calculated the average consumption profile for Italian citizens.

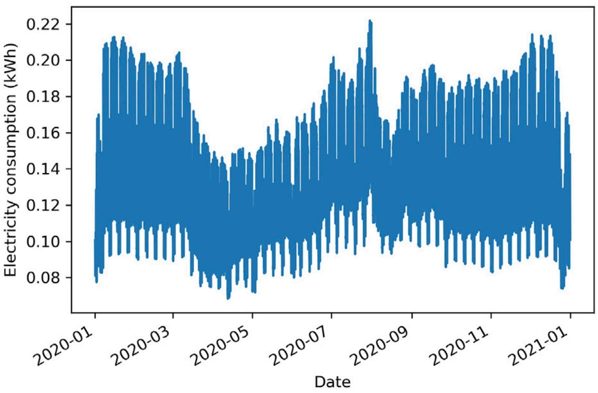

FIGURE 2
Average electricity consumption profile for Italian citizens in *kWh* from 2020-01-01 to 2020-12-31.

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3 Terna—https://www.terna.it/en [Accessed 30 May 2022].

4 EIA—https://www.eia.gov/[Accessed 30 May 2022].

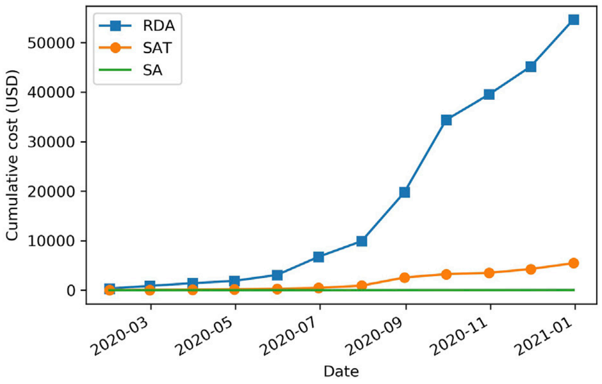

FIGURE 3
Cumulative cost comparison between the different blockchain data storing approaches: RDA (blue line with squares), SAT (orange line with circles), and SA (green solid line).

5 Results

In this section, we present the results supporting our claim regarding the use of DIVERSITY to save on fee costs in building a micro grid powered by a blockchain solution.

Our artificial dataset is represented in Figure 2. The figure depicts the Italian average electricity consumption profile per capita (5,000 $kWh/year$) from 2020-01-01 to 2020-12-31. Measurements are taken every 15 min, returning a timestamp and an energy value expressed in kWh.

From the implementation of the three different logging techniques—RDA, SAT, and SA—we can calculate the cumulative cost of each implementation for solutions based on an Ethereum blockchain. For each smart contract implemented to store the data, the length in bytes is computed, and the number of bytes is used to calculate the cost in USD to submit a transaction, when this is requested by the logging technique: for RDA, this would happen as soon as a measurement is performed, while for both SAT and SA, a transaction is sent at the end of each month, in a way similar to an electric company's billing.

As shown in Figure 3, there is an important difference in terms of cost when using the three different approaches to log data in an Ethereum blockchain. Over the time span of a year, RDA is the most expensive application (≈ 54690 USD), followed by SAT (≈ 5455 USD), and the cheapest approach to register data in a public blockchain is SA (≈ 23 USD), as in DIVERSITY.

Therefore, DIVERSITY actually reduces costs in terms of fees paid to register data in a public blockchain, saving more than 2,000 times the amount with respect to RDA and more than 200 times with respect to SAT.

It is worthy to note that although RDA and SAT may look like similar techniques, in the computation of the cost, they have a critical difference: in an Ethereum implementation, as described in Wood et al. (2014), there is a considerably high fixed cost to submit a transaction; therefore, even though in both the approaches all the data are registered, SAT is shown to be greatly cheaper than RDA.

6 Conclusion

In our study, we present challenges and opportunities connected with the decentralized renewable energy production and trading, especially in an urban context. We recognize the important role of micro grids in defining a framework in which peer-to-peer local energy markets may lead to a new governance and management of energy resources: decentralized and environment-friendly. Blockchains are playing an important part in empowering this change in paradigm, giving a secure infrastructure in which energy is traded safely .

The literature on the topic is rich, but we find that there is a relatively small amount of research in developing second-layer solutions for smart grids. Our proposal tries to fill this gap by presenting a layer-two platform to create a local energy market enhanced by a blockchain solution. Specifically, the effort to develop an off-chaining protocol is justified because it relies on the security and decentralization of public blockchains, while ensuring a concrete saving on fees. Although the construction of a private blockchain may seem a suitable solution, the investment to build and to maintain such a platform may be quite demanding (Yang et al., 2020). We propose a local energy market based on a micro grid in which a novel second-layer decentralized network protocol, DIVERSITY, is the engine to run off-chain smart contracts. DIVERSITY, if backed by a tamper-proof smart meter, guarantees a correct, secure, and transparent billing in energy transactions. At the same time, our system would greatly reduce the cost in terms of fees and energy consumption associated with computation executed on-chain.

A natural extension to our research is the development and implementation of smart contracts to use in our platform. A main focus should be the study and modeling of an optimal strategy in managing the energy exchanges, to be encoded in the smart contract. In this way, more than the infrastructure of the local energy market, there it would be developed the logic to execute the actual trading through those smart contracts.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization, MM, LM, and DC.; writing—original draft preparation, MM; writing—review and editing, MM and

LM; supervision, LM and DC. All the authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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