Is it possible to develop a decentralized free energy market? An automatic literature review approach

Matteo Vaccargiu[1,2,*,†], Giacomo Ibba[1,†] and Roberto Tonelli[1,†]

[1]*Department of Mathematics and Computer Science, University of Cagliari, Italy*
[2]*Department of Computer Science, University of Camerino, Italy*

Abstract

The advent of decentralized energy markets has revolutionized the traditional energy sector by empowering consumers to trade energy directly with each other. Blockchain, on the other hand, has emerged as a secure and transparent platform for facilitating transactions without the need for intermediaries. By analyzing the current literature on the subject, this review explores the potential benefits and challenges of integrating blockchain technology into decentralized energy markets. Key themes include peer-to-peer (P2P) energy trading, grid optimization, transparency, security, and regulatory frameworks. The findings suggest that blockchain has the potential to enhance the efficiency, reliability, and sustainability of decentralized energy markets. However, several barriers such as scalability, interoperability, and regulatory concerns pose challenges to widespread adoption. Specifically, this paper is a preliminary study of the literature to assess the applicability of a free P2P energy market directly between prosumers and consumers. We present some practical projects and some theoretical solutions that could help addressing the challenges. Future research should focus on practical solution to address these obstacles, unlocking the full potential of blockchain in revolutionizing the energy sector.

Keywords

Blockchain, Decentralized energy market, SLR, Artificial intelligence, Large language model

1. Introduction

Rising costs, decreasing fossil resources, and the need to develop and spread the use of renewable resources has placed the energy market as one of the priorities of society today [1]. Decentralized energy markets have emerged as a promising solution to the challenges faced by traditional centralized energy systems [2]. The use of blockchain technology in these markets improved efficiency, transparency, and security in energy transactions. As the energy sector continues to evolve, the intersection of decentralized energy markets and blockchain technology is garnering increasing attention from researchers and industry professionals [3].

Nowadays, even decentralized markets always depend on a central entity for legislative and technical issues [4]. Total decentralization will occur when prosumers and consumers give free rein to agree on price and exchange energy with each other. We can define a free market as an economic system based on supply and demand with little or no government control. [5]

6th Distributed Ledger Technologies Workshop (DLT2024), May, 14-15 2024 – Turin, Italy

[*]Corresponding author.
[†]These authors contributed equally.
matteo.vaccargiu@unica.it (M. Vaccargiu); giacomo.ibba@unica.it (G. Ibba); roberto.tonelli@unica.it (R. Tonelli)
0009-0009-9461-6183 (M. Vaccargiu); 0000-0003-3087-1969 (G. Ibba); 0000-0002-9090-7698 (R. Tonelli)

This synthesis aims to provide a comprehensive review of the current literature on how decentralized energy markets are leveraging blockchain technology, the key challenges and opportunities in this space, and the impact of regulatory frameworks on their development and adoption. In addition, we want to evaluate the feasibility of developing a free energy market in which the selling price is agreed directly between prosumer and consumer based on a blockchain platform. To answer these questions, we conducted a systematic literature review using an automated tool, called SLR Automation Tool [6], based on AI and LLMs. Specifically, consider the following research questions:

RQ1: How are decentralized energy markets employing blockchain technology in the current literature?
RQ2: What are the key challenges and opportunities associated with decentralized energy markets and blockchain technology?
RQ3: How do regulatory frameworks impact the development and adoption of decentralized energy markets utilizing blockchain technology?

Addressing these questions provides an overview of the current use of blockchain technology in energy markets and allows us to discuss possible new challenges such as the peer-to-peer (P2P) free market. The paper is organized as follows: in Section 2 we present the results of the systematic literature review, in Section 3 we discuss the current status, challenges, and limitations of using blockchain in the decentralized energy market. Section 4 presents some practical projects and we discuss some possible theoretical solutions to meet the challenges of using blockchain in P2P energy markets; finally in Section 5 we draw some conclusions from our work and propose some future work.

2. SLR Automatic Analysis

In this section we present the article extraction methodology and results provided by the adopted systematic literature review (SLR) tool. The process of literature extraction and analysis is often lengthy and complex; in this paper, we present an alternative approach that leverages AI and LLMs for the extraction and interpretation of scientific papers.

2.1. Methodology

In this paper we propose an alternative approach to implement an SLR, taking advantage of AI and LLMs for extracting scientific papers from Scopus and analyzing their contributions using a tool called SLR Automation Tool [6]. The tool should be prompted with the research objective of interest and the associated number of research questions for that topic itself. Subsequently, the tool returns as output the possible research questions and a "Search String", which matches the research query that the tool will search on Scopus. Both AI-generated results can be edited and adjusted manually in the interface. The scientific papers were obtained by the tool scrapping using ScopusAPI from the query *"decentralized energy market" AND "blockchain"* provided by us. The tool manages one year at once and returns at most 15 papers for each year. Iterating from 2017 to 2023, we obtained 28 total papers. The results were validated by manually inserting the same query on the Scopus site. Once the papers were obtained, the tool through the use of OpenAI GPT 4 provides answers to the research questions and by using OpenAI GPT 3.5 summarizes the results and provides both an abstract and introduction. If used properly, ChatGPT may be a significantly helpful tool, already partly recognized by the scientific community, to conduct a Systematic Literature Reviews [7, 8]. The results obtained with artificial intelligence were then analyzed and interpreted by manual check by the authors and are the basis for the following discussion.

2.2. Results

From the data extraction process, we obtained 28 papers from 2017 to 2023. Figure 1 highlights the number of publications by country and Figure 2 the percentage of publications by continent.

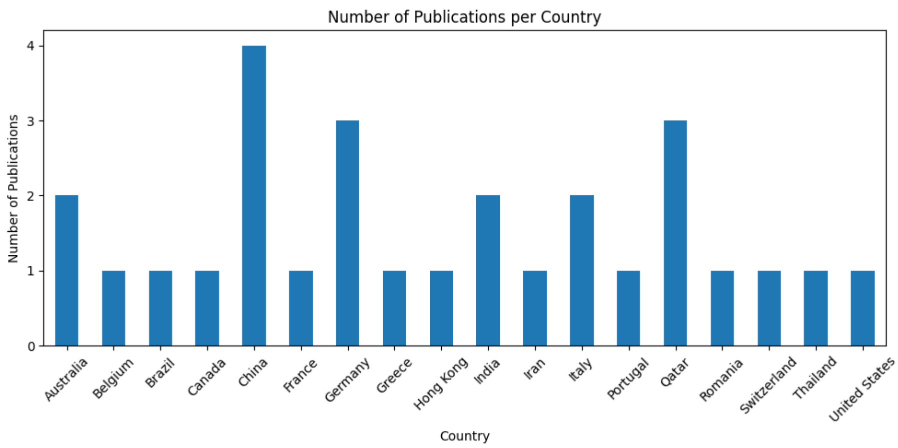

Figure 1: Barplot of the number of articles per country

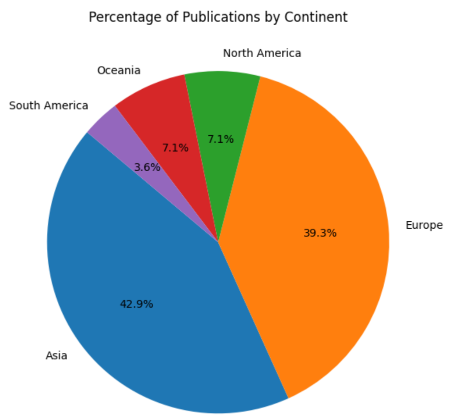

Figure 2: Pie diagram of the percentage of articles per continent

It can be observed from the barplot that China and Qatar, with 4 and 3 articles respectively, are the two countries with the most publications on the topic of using blockchain in the context of decentralized energy market. The first European country is Germany with 3 articles published. The result is also confirmed by the pie chart showing Asia with 42.9% of publications and followed by Europe with 39.3%. Another interesting fact is how European countries are in the majority among those published, showing a shared interest in the topic.

3. Discussion

The use of blockchain technology within the energy market has grown significantly in recent years. This is witnessed by the literature review, which offers interesting insights into the present and future challenges. This integration addresses various aspects of the energy sector, including P2P energy trading, smart grids, renewable energy financing, and the creation of decentralized energy trading platforms. The literature provides a comprehensive view of how blockchain is being applied in these areas. Several papers focus on the application of blockchain in facilitating P2P energy trading. This model enables energy producers, often with renewable energy sources like solar photovoltaic (PV) systems, to sell excess energy directly to other consumers without the need for traditional intermediaries. Lopez et al. in [9] and Baig et al. in [10] discuss systems allowing for this kind of direct energy trading, emphasizing the role of blockchain in ensuring secure and transparent transactions. Kumari et al. in [11] further elaborates on a blockchain-based transactive energy management scheme for smart grid systems, highlighting the potential for enhanced grid management and consumer empowerment. Blockchain's application extends to smart grids and the financing of renewable energy projects as shown by Buccafurri et al. in [12].

Despite increasingly widespread use, the intersection of decentralized energy markets and blockchain technology presents a complex landscape characterized by challenges and opportunities. The first challenge is related to scalability and performance. Blockchain technology, while promising for decentralized energy markets, faces scalability issues. The technology must handle increasing transaction volumes as decentralized energy resources (DERs) proliferate. Westphall et al. [13] highlight concerns around blockchain privacy and scalability in decentralized validated energy trading, emphasizing the need for robust solutions to support the growing energy trading ecosystem. Other important aspects are related to regulatory and legal framework. Indeed, the integration of blockchain into energy markets raises legal and regulatory questions. These include the need for clear regulations around the use of blockchain for energy trading and the rights of prosumers within these markets. The lack of a supportive legal framework could hinder the deployment and acceptance of these technologies (Hermann et al. [14]). Finally, with several blockchain platforms and technologies in use, interoperability becomes a critical challenge. Systems require communication across different blockchain networks and with traditional energy systems to ensure smooth operation (Foti at al. [15]).

Regulatory frameworks influence significantly the development and adoption of decentralized energy markets utilizing blockchain technology. These frameworks can either foster innovation and market growth or pose substantial barriers to entry and scalability. From the provided list of papers, several key themes emerge that elucidate the relationship between regulatory environments and the blockchain-enabled decentralized energy sector. Wörner et al. in [16] likely discuss the importance of regulatory support for innovation in decentralized energy markets. Regulatory frameworks favorable towards blockchain technology can encourage experimentation and the development of new business models, thus accelerating the adoption of decentralized energy solutions. Delina in [17] explores the specific regulatory challenges and opportunities within a highly developed financial center. This context is crucial as it shows how regulatory environments in different jurisdictions can impact the deployment of blockchain in energy markets.

4. Examples of practical projects and possible solutions

4.1. Examples of decentralized energy market projects

The growth of theoretical models concerning decentralized markets has been followed by the development of several peer-to-peer energy trading projects, some still in the experimental stage, across different global regions. Some significant examples are presented in this subsection.

Piclo [1], founded in the UK in 2014 by Open Utility and Good Energy, uses blockchain technology to create a decentralized energy market where commercial consumers directly purchase electricity from local renewable sources. The platform employs real-time meter data and consumer preferences to match supply and demand every half-hour, allowing prosumers control over their electricity sales and providing consumers the possibility to choose their electricity sources based on location and preference. This system not only increases transparency but also enhances consumer engagement and satisfaction through the provision of detailed data visualizations and analysis.

SonnenCommunity [2], initiated in Germany in 2015 by sonnenBatterie, integrates blockchain with energy storage solutions to facilitate an energy-sharing community among sonnenBatterie owners. This community bypasses traditional energy suppliers by allowing members to share surplus energy through a virtual energy pool, accessible during low production periods. The sonnenCommunity's use of centralized software to connect members helps maintain energy balance, highlighting the project's focus on sustainability and self-sufficiency, contrasting with Piclo's emphasis on consumer choice.

Vandebron [3], launched in the Netherlands in 2013, offers a platform similar to Piclo but with a unique pricing structure independent from third parties, allowing consumers to purchase energy directly at producer-set prices. This approach not only promotes price transparency but also supports independent producers by ensuring they receive a fair price for their energy, which is particularly beneficial in a decentralized market structure. As of December 2018, the number of households powered by wind, biomass, and solar energy reached 100,000 [18]. To date, 200,000 households are part of the grid.

The Brooklyn Microgrid (BMG) [4], a project by LO3 Energy started in 2017 in Brooklyn, New York, focuses on creating a resilient energy trading platform that addresses local grid

[1] https://www.piclo.energy
[2] https://sonnengroup.com/sonnencommunity
[3] https://vandebron.nl
[4] https://www.brooklyn.energy

reliability issues during severe weather events. BMG uses blockchain to enable peer-to-peer energy trading among residents with solar panels, enhancing community resilience and control over local energy supply[19].

These projects illustrate diverse applications of blockchain in decentralized energy markets. Piclo and Vandebron focus on direct consumer-producer connections to vary electricity pricing, whereas SonnenCommunity emphasizes energy self-sufficiency through storage. BMG highlights resilience, providing a model for local grid stability and community empowerment. Each approach, as pointed out by Zhang et al. in [20], reflects different strategic priorities within the broader context of blockchain's potential to transform energy markets.

4.2. Possible solution to support the adoption of blockchain in decentralized energy markets

To effectively support blockchain adoption in decentralized energy markets, regulatory frameworks must evolve alongside technological advancements [21]. Clear regulations and the introduction of interoperability standards can reduce system fragmentation and boost efficiency. Regulatory sandboxes could foster innovation by allowing developers to test new technologies under relaxed conditions. Additionally, government incentives like tax breaks and subsidies could encourage the uptake of blockchain technologies by lowering barriers for new entrants [22].

Addressing scalability issues is crucial, as blockchain technology must handle high transaction volumes in energy markets. Solutions like off-chain transactions and state channels can manage multiple transactions off the main blockchain while ensuring accurate ledger updates. Sharding, which divides the blockchain into smaller segments, can also significantly improve throughput [23].

Drawing on case studies from similar sectors, such as financial services or IoT, can offer insights into implementing these technologies effectively. For example, the financial sector's use of layer-two solutions, like the Lightning Network, provides a model for handling large-scale, real-time transactions in energy markets. These adaptations help meet the specific needs of energy markets, ensuring scalability, security, and transparency [24].

Incorporating these strategies will help overcome current challenges and promote a smooth transition to blockchain-powered decentralized energy systems.

5. Conclusion and Future Works

A thorough examination of 28 papers revealed that decentralized energy markets are actively integrating blockchain technology to drive innovation and improve the overall energy ecosystem. The findings highlight the multifaceted benefits of this integration, including enhanced efficiency, transparency, and security in energy transactions. To answer RQ1, decentralized energy markets are utilizing blockchain technology for peer-to-peer energy trading, smart grids, renewable energy financing, and decentralized energy trading platform development. The review identifies key challenges and opportunities in this dynamic landscape, underscoring the need for a nuanced understanding of the complexities involved. As highlighted by RQ2, crucial challenges concern scalability, regulation issues, and opportunities, including enhanced grid management and consumer empowerment. Additionally, the synthesis emphasizes the pivotal role of regulatory frameworks, which is a key point for RQ3, in shaping the trajectory of decentralized energy markets utilizing blockchain technology, showcasing how regulations can facilitate market growth or present significant barriers to entry.

Overall, the synthesis provides valuable insights into the current state of research and practice at the intersection of decentralized energy markets and blockchain technology, setting the stage for future advances in this evolving field. We can also conclude that the role of the central agency changes from managing the entire process to supervising the market.

From the analysis of the projects it is interesting to note that although from Figure 2 Asia is the largest country with scientific publications at the theoretical level, no advanced projects are implemented there. Given that this initial query provides only 28 papers, in order to have a complete overview of the literature in this field the first future work is to consider different search queries so as to have more cross-cutting topics and at the same time analyze platforms other than Scopus. Further future research should focus on exploring scalability solutions, conducting regulatory impact studies, investigating interoperability solutions, undertaking longitudinal studies, and engaging with stakeholders to advance the adoption and effectiveness of blockchain technology in decentralized energy markets while examining its impact on fostering free market principles and competition.

Acknowledgments

This work was partially funded by Ministero dell'Università e della Ricerca (MUR), issue D.M. 351/2022 "Borse di Dottorato"—Dottorato di Ricerca di Interesse Nazionale in "Blockchain e Distributed Ledger Technology", under the National Recovery and Resilience Plan (NRRP).

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.5—Call for tender No. 3277 published on 30 December 2021 by the Italian Ministry of University and Research (MUR) funded by the European Union-NextGenerationEU. Project Code ECS0000038—Project Title eINS Ecosystem of Innovation for Next Generation Sardinia—CUP F53C22000430001-Grant Assignment Decree No. 1056 adopted on 23 June 2022 by the Italian Ministry of University and Research (MUR).

This work was partially supported by project SERICS (PE00000014) under the MUR National Recovery and Resilience Plan funded by the European Union-NextGenerationEU.

This work was partially supported by Regional Development Program 2020-2024 - RAS Strategy 2 - Economy Identity Project 2.1 - Research and technological innovation project "BandzAI+" - Announcement Aid for Research and Development Projects - ICT Sector , CUP project: F23C23000230008/G27H23000270002.

References

[1] Incentives and strategies for financing the renewable energy transition: A review, Energy Reports 7 (2021) 3590–3606. URL: https://www.sciencedirect.com/science/article/pii/S2352484721004066. doi:https://doi.org/10.1016/j.egyr.2021.06.041.

[2] C. Liu, Z. Li, Comparison of centralized and peer-to-peer decentralized market designs for community markets, IEEE transactions on industry applications 58 (2021) 67–77.
[3] Systematic analysis of the blockchain in the energy sector: Trends, issues, and future directions, Telecommunications Policy 48 (2024) 102677. URL: https://www.sciencedirect.com/science/article/pii/S030859612300188X. doi:https://doi.org/10.1016/j.telpol.2023.102677.
[4] S. Johnstone, Secondary markets in digital assets: Rethinking regulatory policy in centralized and decentralized environments, Stanford Journal of Blockchain Law & Policy 3 (2020).
[5] I. Bremmer, Article commentary: the end of the free market: who wins the war between states and corporations?, European View 9 (2010) 249–252.
[6] A. M. Sami, Z. Rasheed, K.-K. Kemell, M. Waseem, T. Kilamo, M. Saari, A. N. Duc, K. Systä, P. Abrahamsson, System for systematic literature review using multiple ai agents: Concept and an empirical evaluation, 2024. arXiv:2403.08399.
[7] M. Waseem, A. Ahmad, P. Liang, M. Fahmideh, P. Abrahamsson, T. Mikkonen, Conducting systematic literature reviews with chatgpt [chatgpt for slrs: A proposal], 2023.
[8] S. Anjomshoae, A. Najjar, D. Calvaresi, K. Främling, Explainable agents and robots: Results from a systematic literature review, in: Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems, International Foundation for Autonomous Agents and Multiagent Systems, 2019, p. 1078–1088.
[9] H. K. Lopez, A. Zilouchian, Peer-to-peer energy trading for photo-voltaic prosumers, Energy 263 (2023) 125563. URL: https://www.sciencedirect.com/science/article/pii/S0360544222024495. doi:https://doi.org/10.1016/j.energy.2022.125563.
[10] M. J. A. Baig, M. T. Iqbal, M. Jamil, J. Khan, Blockchain-based peer-to-peer energy trading system using open-source angular framework and hypertext transfer protocol, Electronics 12 (2023). URL: https://www.mdpi.com/2079-9292/12/2/287.
[11] A. Kumari, U. Chintukumar Sukharamwala, S. Tanwar, M. S. Raboaca, F. Alqahtani, A. Tolba, R. Sharma, I. Aschilean, T. C. Mihaltan, Blockchain-based peer-to-peer transactive energy management scheme for smart grid system, Sensors 22 (2022). URL: https://www.mdpi.com/1424-8220/22/13/4826. doi:10.3390/s22134826.
[12] F. Buccafurri, G. Lax, L. Musarella, A. Russo, An ethereum-based solution for energy trading in smart grids, Digital Communications and Networks 9 (2023) 194–202. URL: https://www.sciencedirect.com/science/article/pii/S2352864821001012. doi:https://doi.org/10.1016/j.dcan.2021.12.004.
[13] J. Westphall, J. E. Martina, Blockchain privacy and scalability in a decentralized validated energy trading context with hyperledger fabric, Sensors 22 (2022). URL: https://www.mdpi.com/1424-8220/22/12/4585. doi:10.3390/s22124585.
[14] A. Hermann, T. Teich, S. Kassel, D. Kretz, T. Neumann, S. Leonhardt, S. Junghans, Blockchain in decentralized local energy markets, in: I-ESA, 2018. URL: https://api.semanticscholar.org/CorpusID:169391324.
[15] M. Foti, D. Greasidis, M. Vavalis, Viability analysis of a decentralized energy market based on blockchain, in: 2018 15th International Conference on the European Energy Market (EEM), 2018, pp. 1–5. doi:10.1109/EEM.2018.8469906.
[16] A. Wörner, V. Tiefenbeck, W. Ketter, Blockchain-enabled markets: a literature review with

a focus on decentralised energy markets, 2023, pp. 315–340. doi:10.4337/9781802201864.00021.

[17] L. L. Delina, Fintech re in a global finance centre: Expert perceptions of the benefits of and challenges to digital financing of distributed and decentralised renewables in hong kong, Energy Research Social Science 97 (2023) 102997. URL: https://www.sciencedirect.com/science/article/pii/S2214629623000579. doi:https://doi.org/10.1016/j.erss.2023.102997.

[18] J. Lee, Y. Cho, Estimation of the usage fee for peer-to-peer electricity trading platform: The case of south korea, Energy Policy 136 (2020) 111050. URL: https://www.sciencedirect.com/science/article/pii/S0301421519306378. doi:https://doi.org/10.1016/j.enpol.2019.111050.

[19] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, C. Weinhardt, Designing microgrid energy markets: A case study: The brooklyn microgrid, Applied Energy 210 (2018) 870–880. URL: https://www.sciencedirect.com/science/article/pii/S030626191730805X. doi:https://doi.org/10.1016/j.apenergy.2017.06.054.

[20] C. Zhang, J. Wu, C. Long, M. Cheng, Review of existing peer-to-peer energy trading projects, Energy Procedia 105 (2017) 2563–2568. URL: https://www.sciencedirect.com/science/article/pii/S1876610217308007. doi:https://doi.org/10.1016/j.egypro.2017.03.737, 8th International Conference on Applied Energy, ICAE2016, 8-11 October 2016, Beijing, China.

[21] A novel decentralized platform for peer-to-peer energy trading market with blockchain technology, Applied Energy 282 (2021) 116123. URL: https://www.sciencedirect.com/science/article/pii/S0306261920315373. doi:https://doi.org/10.1016/j.apenergy.2020.116123.

[22] Y. Yin, M. Yan, Q. Zhan, Crossing the valley of death: Network structure, government subsidies and innovation diffusion of industrial clusters, Technology in Society 71 (2022) 102119. URL: https://www.sciencedirect.com/science/article/pii/S0160791X22002603. doi:https://doi.org/10.1016/j.techsoc.2022.102119.

[23] D. Strepparava, L. Nespoli, E. Kapassa, M. Touloupou, L. Katelaris, V. Medici, Deployment and analysis of a blockchain-based local energy market, Energy Reports 8 (2022) 99–113. URL: https://www.sciencedirect.com/science/article/pii/S2352484721014293. doi:https://doi.org/10.1016/j.egyr.2021.11.283.

[24] G. A. F. Rebello, G. F. Camilo, L. A. C. de Souza, M. Potop-Butucaru, M. D. de Amorim, M. E. M. Campista, L. H. M. Costa, A survey on blockchain scalability: From hardware to layer-two protocols, IEEE Communications Surveys & Tutorials (2024).