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FOSTERING SOCIAL AND ENVIRONMENTAL DEVELOPMENT IN EUROMED RENEWABLE ENERGY COMMUNITIES (RECS) THROUGH DISTRIBUTED LEDGER TECHNOLOGY (DLT)

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ECONOMIC RESEARCH FORUM
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CONTENTS

ABSTRACT

This article explores the integration of Distributed Ledger Technologies (DLT) within Renewable Energy Communities (RECs), with a focus on specific use cases from EuroMed countries. The research demonstrates how Blockchain-Based Affordances (BBA) can strengthen REC governance by enabling the application and automation of Ostrom's principles, effectively addressing issues like the Tragedy of the Commons (ToC). Furthermore, the study shows how BBA can enhance monitoring, reporting, and verification (MRV) of sustainable practices in RECs, ensuring compliance with EU renewable energy regulations and advancing progress toward the UN Sustainable Development Goals (SDGs). The findings provide valuable insights and policy recommendations that could be extended to RECs in the SouthMed region, broadening the scope of the study's impact.

RÉSUMÉ

Cet article explore l'intégration des technologies de registre distribué (Distributed Ledger Technologies – DLT) au sein des communautés d'énergie renouvelable (Renewable Energy Communities – REC), en mettant l'accent sur des cas d'usage spécifiques issus des pays euro-méditerranéens. La recherche montre comment les fonctionnalités fondées sur la blockchain (Blockchain-Based Affordances – BBA) peuvent renforcer la gouvernance des REC en permettant l'application et l'automatisation des principes d'Ostrom, contribuant ainsi à répondre à des problématiques telles que la tragédie des biens communs.

Par ailleurs, l'étude démontre comment les BBA peuvent améliorer les mécanismes de suivi, de reporting et de vérification (Monitoring, Reporting and Verification – MRV) des pratiques durables au sein des REC, en assurant la conformité avec les réglementations européennes en matière d'énergies renouvelables et en favorisant la réalisation des Objectifs de développement durable (ODD) des Nations unies. Les résultats apportent des enseignements précieux et des recommandations de politiques publiques pouvant être étendus aux REC de la région Sud-Med, élargissant ainsi la portée et l'impact de l'étude.

الملخص

داخل (Distributed Ledger Technologies – DLT) تتناول هذه المقالة دمج تقنيات السجلات الموزعة
، مع التركيز على حالات استخدام (Renewable Energy Communities – RECs) مجتمعات الطاقة المتجددة
محددة من دول منطقة اليورومتوسط. وتُبرز الدراسة كيف يمكن للخصائص القائمة على تقنية البلوك تشين
أن تعزز حوكمة مجتمعات الطاقة المتجددة من خلال تمكين (Blockchain-Based Affordances – BBA)
.تطبيق وأتمتة مبادئ أوستروم، بما يسهم في معالجة قضايا مثل مأساة المشاعات

كما تُظهر الدراسة كيف يمكن للخصائص القائمة على البلوك تشين أن تحسّن آليات الرصد والإبلاغ والتحقق
للممارسات المستدامة داخل مجتمعات الطاقة المتجددة، (Monitoring, Reporting and Verification – MRV)
بما يضمن الامتثال للوائح الاتحاد الأوروبي المتعلقة بالطاقة المتجددة ويسهم في تحقيق أهداف التنمية المستدامة
للأمم المتحدة. وتوفر النتائج رؤى مهمة وتوصيات سياساتية يمكن توسيع نطاقها لتشمل مجتمعات الطاقة المتجددة
.في منطقة جنوب المتوسط، مما يعزز من نطاق وتأثير الدراسة

INTRODUCTION

With vast renewable energy sources like solar and wind energy the Euromed region is well- positioned to harness these assets for economic growth and environmental sustainability. Renewable Energy Communities (RECs) have been at the forefront of sustainable economic development, particularly in the Euromed countries. According to the EU Directive 2018/2001, a REC is an entity characterized by open and voluntary participation, with a primary focus on delivering environmental, economic, and social benefits to its members, and the local communities it serves, rather than merely prioritizing financial gain[1]. RECs are generally rooted in specific geographical areas, such as neighborhoods, villages, or towns. In this research we focus predominantly on microgrid types of RECs (with few exceptions of REC who still follow a localized model). A microgrid is a localized energy system that integrates renewable energy sources and can operate autonomously or in conjunction with the main power grid. This localized structure makes microgrids particularly well-suited to the principles of RECs, where the goal is to produce, manage, and consume energy within a community framework.

In the Euromed region, wind and solar power plants are among the most competitive renewable energy technologies. However, these plants rely on variable renewable energy (VRE) sources with stochastic outputs. To address this variability, RECs require costly energy management and storage systems, significantly increasing both investment and operational costs[2]. As a result, despite their potential, RECs face challenges such as the 'Tragedy of the Commons,' where community members may overconsume or under-contribute to clean energy production, leading to free-rider issues. Another ongoing issue is 'greenwashing'[3], which can result from inadequate monitoring, reporting and verification mechanisms (MRV), which are necessary to reliably confirm that Renewable Energy Communities (RECs) are implementing authentic sustainable practices. Without these safeguards, claims of sustainability within RECs may lack credibility, leading to potential public mistrust.

These challenges highlight the critical need for investment in technological innovations to improve the deployment of renewable energy sources and enhance RECs management. However, many technological approaches tend to focus on optimizing supply-demand management and often prioritize

[1] European Parliament and Council of the European Union. (2018). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast).* Official Journal of the European Union, L 328/82. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001

[2] Technology Review. The $2.5 Trillion Reason We Can't Rely on Batteries to Clean Up the Grid; 2018.

[3] Good Energy. (n.d.). *Greenwashing: The truth about "100% renewable"* energy claims.Available at: https://www.goodenergy.co.uk/learn/greenwashing/ Pinsent Masons. (2021). *Energy suppliers wise to abandon REGO certificates amid greenwashing concerns.* Available at: https://www.pinsentmasons.com/out-law/news/energy-suppliers-wise-abandon-rego-certificates-greenwashing-concerns

profit-maximizing incentives, while overlooking the socio- economic fabric of RECs[4]. A purely technological solution risks failing to fully solve the 'Tragedy of the Commons' problem, as it may not adequately foster the collective responsibility and cooperation required within the community. Distributed ledger technology (DLT) has been proposed in the literature as potential solution to address these issues[5]. Arguably, DLT is well- suited for RECs because it enhances transparency while enabling secure, Peer-to-Peer (P2P) energy trading and alignment of community incentives with sustainable practices. Blockchains are today's most famous DLT, due to its decentralized model of governance with applications across financial, supply-chain, real estate, healthcare, etc. sectors. In this research we refer to Blockchain-based affordances (BBA) as the unique capabilities or features that blockchain technology enables, often enhancing transparency, security, and autonomy in various applications. This research focuses on evaluating whether DLT (through certain BBA) can effectively mitigate the "Tragedy of the Commons" problem within RECs in the Euromed. It also aims to explore the potential of DLT to improve monitoring, reporting, and verification of sustainable practices, such as clean energy production and consumption within RECs across the Euromed region. Additionally, the study examines the role of DLT in helping RECs in the Euromed region comply with EU renewable energy regulations and contribute to achieving Sustainable Development Goals (SDGs). In this paper, we refer to Distributed Ledger Technologies that follow a decentralized model of governance. To address these questions, we propose a methodology that involves selecting a set of RECs use cases in the Euromed region and analyzing them using Ostrom's governance principles. Additionally, our analysis extends the principles by integrating blockchain-based affordances (BBAs) and align these with the selected REC use cases based on various key variables. Results indicate whether and how DLT implementation can meet the criteria set by Ostrom's principles and help RECs avoid problems such as the Tragedy of the Commons. Other results will show the possibility of DLT to contribute to the improvement of monitoring, reporting, and verification of sustainable actions and compliance with current regulations and SDGs. Overall, this multidisciplinary research lies at the crossroads of economics, technology, governance, and environmental studies. It provides real-world solutions for managing RECs and contributes to advancing sustainable development in the Euromed. By bridging these disciplines, the study delivers both theoretical frameworks and actionable strategies for improving REC governance, adoption, and efficiency.

[4] Pacheco A, Monteiro J, Santos J, Sequeira C, Nunes J. Energy transition process and community engagement on geographic islands: The case of Culatra Island (Ria Formosa, Portugal). Renewable Energy. 2022;184:700- 11.

[5] Ramos, S., Mcmenamin, C. (2024). Privacy-Preserving Energy Trading with Applications to Renewable Energy Communities. Renewable Energy Resources and Conservation. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-59005-4_12

LITERATURE REVIEW

Recent advancements in blockchain technologies have been suggested as potential solutions to improve transparency, trust, and efficiency in energy transactions and governance in RECs. An EU report highlights that blockchain can significantly engage prosumers in the energy market, facilitating the creation of renewable energy communities[6].

Blockchains are Peer-to-Peer (P2P) ledgers where information is recorded in a decentralized, permanent, and verifiable way using cryptographic primitives[7]. A smart contract is a self- executing contract on a blockchain network where the terms of the agreement are directly written into the code[8]. These contracts automatically enforce and execute the terms when certain predefined conditions are met, without the need for intermediaries like lawyers or banks. As smart contracts run on a blockchain technology, they ensure that once deployed, they are transparent, immutable, and decentralized, meaning they cannot be altered or tampered with. By removing intermediaries and automating processes, smart contracts reduce transaction costs and increase efficiency in governance processes[9]. From a cybersecurity perspective, removing a 'central point of failure' also creates a more reliable, trustful and secure systems[10].

Besides other applications such as decentralized finance (DeFi), smart contracts and blockchains can be also used in the governance of Renewable Energy Communities (RECs), where they can help manage energy trading, enforce community rules, and ensure fair distribution of resources in line with community goals. The integration of blockchain technology within Renewable Energy Communities (RECs) offers substantial potential to improve their operational frameworks, providing benefits that are unattainable via centralized systems. Overall, blockchain's decentralized and transparent characteristics present innovative solutions to several critical challenges faced by RECs. For example, RECs often encounter the challenge of effectively monitoring and verifying sustainable practices to counteract 'greenwashing' and secure future funding, permits, and tax incentives. In this context, distributed ledger technology (DLT) has been proposed as a promising solution, offering greater transparency in the recording of sustainable actions. DLT tamper-proof nature ensures that records cannot be tampered with or altered by third parties[11].

Recent research has examined blockchain-based solutions for addressing various challenges faced by Renewable Energy Communities (RECs). For instance, a research study introduces a protocol utilizing

[6] EU Commission. Blockchain in Energy Communities; 2017.

[7] Nakamoto, S. (2009). *Bitcoin: A peer-to-peer electronic cash system.*

[8] Szabo, N. (1997). The idea of smart contracts.

[9] Ramos. S and Mannan, M. "Watch the Gap: Making code more intelligible to users without sacrificing decentralization?," *2022 IEEE 24th Conference on Business Informatics (CBI),* Amsterdam, Netherlands, 2022, pp. 133-139, doi: 10.1109/CBI54897.2022.10059.

[10] Ramos, S. (2024). *Blockchains in the Real World: An Interdisciplinary Perspective on Enhancing Security and Adoption.* University Pompeu Fabra

[11] Nakamoto, S. (2009). *Bitcoin: A peer-to-peer electronic cash system.* Retrieved from https://bitcoin.org/bitcoin.pdf

blockchain-based smart contracts to establish a peer-to-peer (P2P) energy market, enabling local producers to trade directly with local consumers[12]. However, this approach falls short in addressing the critical need for safeguarding user data privacy. Similarly, another study presents a blockchain-driven solution to optimize energy pricing through demand-side management and demand response mechanisms[13]. Furthermore, decentralized P2P trading through and distributed ledger technology (DLT) was suggested as a remedy for issues like free- riding within RECs, where members individually own production units and trade surplus energy in a market-oriented setting. Nevertheless, such mechanisms can unintentionally benefit wealthier members, leading to imbalances within the community and affecting its socio- economic structure[14]. In addition, while P2P trading facilitates direct energy exchanges among individuals, it also raises concerns about data privacy and confidentiality, which must be managed in compliance with existing regulatory frameworks[15]. Ramos et al. 2024 provide a theoretical solution to these issues pairing blockchain technology with cryptographic primitives. The research findings enhance coordination, privacy, and incentive alignment within RECs, while empowering them to establish a trustworthy reputation in the eyes of relevant external stakeholders. The privacy-preserving energy trading protocol enables secure communication of energy supply and demand. With tokenized incentives, users are encouraged to publish usage profiles and trade energy in a community-controlled public forum. This allows all users in the community to benefit from typically cheaper locally produced renewable energy, while also allowing the community (as a whole) to more effectively balance energy supply and demand, without compromising sensitive data confidentiality[16].

Likewise, blockchain technology offers several affordances that can function as trust mechanisms within decentralized peer-to-peer energy production networks, such as those found in Renewable Energy Communities (RECs). Monitoring in RECs is essential to ensure that all participants remain accountable and adhere to the community's established rules. In centralized systems, this function is often fulfilled through centralized surveillance, often not complying with data privacy regulations. However, decentralized systems, like those enabled by blockchain, offer alternative mechanisms. Specifically, blockchain allows for ex-post verifiability by recording encrypted, tamper-resistant proofs of actions. These records maintain privacy by limiting disclosure while allowing relevant third parties to verify the integrity of the data. This method preserves the necessary transparency for community governance without compromising individual privacy.

Furthermore, enforcement of mutually agreed community rules, typically handled ex-post in centralized systems, can be decentralized through ex-ante automation using smart contracts. Smart contracts can

[12] Wang X, Yang W, Noor S, Chen C, Guo M, van Dam KH. Blockchain based smart contract for energy demand management. Energy Reports. 2019.

[13] Wen S, Xiong W, Tan J, Chen S, Li Q. Blockchain enhanced price incentive demand response for building user energy network in sustainable society. Energy Reports. 2021;7:2704-12.

[14] Junlakarn S, Kokchang P, Audomvongseree K. Drivers and Challenges of Peer-to-Peer Energy Trading Development in Thailand. Energies. 2022.

[15] de Almeida L, Klausmann N. Peer-to-Peer Energy Communities: Legal Definitions and Access to Markets. 2021.

[16] Ramos, S., Mcmenamin, C. (2024). Privacy-Preserving Energy Trading with Applications to Renewable Energy Communities. Renewable Energy Resources and Conservation. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-59005-4_12

execute predefined agreements automatically, ensuring compliance without the need for an overarching authority. The combination of ex-post verifiability and ex- ante automation can enable blockchain to strengthen institutional trust and operational governance within RECs. It reduces the necessity for constant oversight while enhancing trust in the governance structures established by the community. By facilitating decentralized cooperation, blockchain technology fosters bottom-up collaboration and reduces reliance on centralized authorities, creating a more resilient and self-regulating community model[17] [18] [19].

[17] Rozas D, Tenorio-Fornes A, Diaz-Molina S, Hassan S. When Ostrom Meets Blockchain: Exploring the Potentials of Blockchain for Commons Governance. SAGE Open. 2021;11(1).

[18] Cila N, Ferri G, de Waal M, Gloerich I, Karpinski T. The Blockchain and the Commons: Dilemmas in the Design of Local Platforms. 2020

[19] Poux, Philémon and Poux, Philémon and Ramos, Simona, A Unified Framework for the Governance of the Commons with Blockchain-Based Tools: An Application to Customary Land Commons in Ghana (March 24, 2022).

CONTRIBUTION

The transition from centralized to decentralized energy RE systems has accelerated, with Renewable Energy Communities (RECs) being at the frontrun of these developments. This shift is particularly significant in the Euromed region, where citizen participation in renewable energy is growing, aligning with the EU's emphasis on sustainability and innovation.

The success of RECs depends on active member participation and effective coordination, yet they face challenges in governance, energy management, and regulatory compliance. Community-owned energy assets often struggle with fair resource allocation, exacerbated by the 'Tragedy of the Commons,' where members may overconsume or undercontribute RE. Traditional centralized systems for monitoring and verifying sustainable practices often lack transparency failing to address 'green washing' practices.

This research explores how distributed ledger technology (DLT) via BBA can enhance transparency in green action verification, mitigate free-riding issues, and support compliance with EU regulations and Sustainable Development Goals (SDGs). Despite these promising advancements, a significant gap remains in the research regarding how distributed ledger technology (DLT) can be effectively applied to real-world cases of Renewable Energy Communities (RECs) to mitigate the 'Tragedy of the Commons.' In summary, while there is substantial literature on the theoretical benefits of RECs and the potential of distributed technologies in energy systems, several critical gaps remain:

a) Practical Evidence on Implementation: There is a lack of case study analysis that demonstrate how blockchains can be effectively implemented in RECs to improve governance, MRV processes, and regulatory compliance while avoiding the 'Tragedy of Commons' problem.
b) Context-Specific Research: Most existing studies are situated in Western Europe[20] or North America, with limited focus on the unique socio-economic, regulatory, and environmental contexts of the Euromed region. This gap needs to be addressed to understand region-specific challenges and opportunities.
c) Policy-Oriented Analysis: While there is growing interest in the role of DLT in energy systems, there is insufficient research on the policy implications for supporting RECs in adopting these technologies, particularly in terms of developing supportive regulatory frameworks, cross-border collaboration, and community participation.

This research aims to fill these gaps by providing a comprehensive analysis of the potential application of distributed ledger technologies (particularly blockchains) in RECs through a selection of case studies in the Euromed region, offering both theoretical insights and practical implications.

[20] Hoops, B. (2023). *Two Tales of the Energy Commons Through the Lens of Complexity.* Groningen Journal of International Law, 11(4), 549–623.

METHODOLOGY

The methodology of this research is structured into two main parts: A) we analyse the selected use cases through the lenses of Ostrom's principles, and B) we match Ostrom's Principles with Blockchain-Based Affordances (BBA) and the selected REC use-cases. In the following section we describe the selection of a sample of ten use-cases, which we categorize according to the geographical location, size, type of renewable energy produced/used, the socio-economic conditions and the relevant technological infrastructure in place.

The study of 'traditional' commons-based communities, such as fisheries, and their governance processes using Elinor Ostrom's frameworks – including the Institutional Analysis and Development (IAD) – typically necessitates extensive time investment and direct engagement with these communities. Such engagement often involves methods like interviews, surveys, and observations to gather in-depth insights. This level of involvement was not feasible for the limited time of the present study, which represents a key limitation. However, despite this constraint, the unique characteristics of RECs, especially their governance structure dependent on the technical infrastructure and availability of public information, provide valuable insights for our analysis. For example, smart meters are an integral component of microgrids and localized renewable energy (RE) systems[21], enabling real-time monitoring of energy production, consumption, and distribution[22]. This technological capability aligns with Ostrom's principle of monitoring, as evidenced by case study analyses of interviews with energy communities[23]. However, the use of smart meters also raises privacy concerns, which could potentially be addressed through the implementation of blockchain-based tools (BBAs)[24]. This availability of smart meters was noted in all REC cases via publicly available information of technical documentation, white papers and scholarly articles[25]. Additionally, the necessity for prosumers to connect to a grid to produce and/or consume energy introduces the principle of clearly defined boundaries for participation, another principle of Ostrom's framework[26]. However, while grid access establishes clear boundaries, it does not entirely mitigate challenges such as free-riding, where individuals may still overconsume renewable energy

[21] E. J. Palacios-García et al., "Smart metering system for microgrids," IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 2015, pp. 003289-003294, doi: 10.1109/IECON.2015.7392607.

[22] European Commission. (n.d.). *Smart grids and meters*. Energy. Retrieved October 2023,

from https://energy.ec.europa.eu/topics/markets-and-consumers/smart-grids-and-meters_en

[23] Melville, E., Christie, I., Burningham, K., Way, C., & Hampshire, P. (2017). The electric commons: A qualitative study of community accountability. *Energy Policy, 106,* 12–21.

[24] Ramos, S., & McMenamin, C. (2024). Privacy-Preserving Energy Trading with Applications to Renewable Energy Communities. In: Pong, P. (Ed.), Renewable Energy Resources and Conservation. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-59005-4_12

[25] See references numbered in bibliography as: 3, 6-8,10,14,20,22-24,29,35-37-39, 42,44,47-48

[26] Stadler, M., Cardoso, G., Mashayekh, S., Forget, T., DeForest, N., Agarwal, A., & Schönbein, A. (2016). Value streams in microgrids: A literature review. *Applied Energy,* 162, 980-989. Melville, E., Christie, I., Burningham, K., Way, C., & Hampshire, P. (2017). The electric commons: A qualitative study of community accountability. *Energy Policy, 106,* 12–21.

resources without contributing equitably to their maintenance which is where BBAs could play a pivotal role with an added layer of verifiable identity and access management[27]. Likewise, although smart meters facilitate monitoring, BBAs could enable the automation of graduated sanctions (Ostrom's Principle 5) which was not directly inferable from the publicly available information hence not recorded as present in the tables below.

In performing the matching (Table 3.), we underline with 'X' principles that can be inferred as nearly automatic due to the underlying infrastructure or location in place. For instance, *monitoring* is enabled by the presence of smart meters in RECs; *well-defined boundaries* result the necessity to connect to the microgrid to access resources and in certain cases from the isolated nature of the location. Additionally, regulatory support within the EU not only enables but also aims to foster the development and local governance RECs, thereby facilitating the *minimal recognition of local rights to organize.* In a similar manner, RECs based on microgrids inherently satisfy Elinor Ostrom's principle of *Rules Adapted to Local Conditions* because they must be designed around the specific energy availability and energy needs of the local community[28] as noted in the cases of RECs explored. In cases where certain information was available but the specifications around the application were fully clear, the corresponding matches are marked in *red X*. For example, the Reshool Girona Renewable Community project emphasizes the significance and ways of empowering its members and fostering their proactive involvement relating to the *collective-choice arrangements principle and collective resolution mechanisms*[29]. In similar direction, active participation by citizens in decision-making and conflict resolution processes for local development was confirmed with onsite project surveys in Kythnos[30], however a direct inference of these principles would need a direct engagement with the community. Finaly, if no information was available, no mark was assigned on the table.

This study's inferences about the governance structures of Renewable Energy Communities (RECs) are based on publicly available information and interpretations of Ostrom's principles as applied to microgrid-based communities, supported by scholarly sources. The selected RECs, many of which are funded through public initiatives and EU projects, offer substantial information in the form of publicly accessible resources such as webpages, brochures, white papers, and technical documentation. These materials provide valuable insights into the design, implementation, and governance frameworks of RECs. While a sole reliance on such documentation limits the depth of contextual understanding that could be achieved through direct engagement, it nevertheless offers a meaningful perspective into the governance particularities of these communities. Likewise, we acknowledge that the case-by-case examination of publicly available information was feasible due to the limited sample size of Renewable Energy Communities (RECs) analyzed in this study. This approach, while effective for the scope of our research, may not be applicable to larger, more extensive studies.

[27] Agarkar, A. A., Karyakarte, M., Chavhan, G., Patil, M., Talware, R., & Kulkarni, L. (2024). Blockchain aware decentralized identity management and access control system. *Measurement: Sensors, 31,* 101032. https://doi.org/10.1016/j.measen.2024.101032

[28] Van der Schoor, T., & Scholtens, B. (2015). *Power to the people: Local community initiatives and the transition to sustainable energy.* Renewable and Sustainable Energy Reviews, 43, 666-675.

[29] Reschool. Girona demo case. Reschool Project. from https://www.reschool-project.eu/demo-case/girona/

[30] WiseGrid. Pilot sites: Kythnos. from https://www.wisegrid.eu/pilot-sites/kythnos

On the SouthMed: The use-case selection initially aimed to depict a bigger variety in the geographical location (selecting use cases from both the North and South Med) however information about RECs in SouthMed resulted to be scarce with limited and uncornfirmed sourses. In other words, although we were able to identify renewable energy communities in the SouthMed region, such as Zarzis, Siwa Oasis[31] and Oasis du Tafilalet[32], detailed information on their governance processes, energy exchange and equality important – the technological infrastructure in place was limited. Overall, most publicly available information on renewable energy initiatives in the SouthMed focuses on large-scale energy production, such as wind farms or solar parks. In these cases, the direct involvement of local communities in the operational governance and management of renewable energy is minimal, hence not relevant to our analysis.

Table 1. The table presents a comprehensive view of diverse Renewable Energy Communities from the Mediterranean region, showcasing different sizes, type of renewable energy, the socio-economic conditions and the relevant technological infrastructure in place.

Community	Size	Geographical Location	Energy Sources	Socio-Economic Conditions	Technological Infrastructure
Tilos[33 34 35]	Island	Greece	Wind, Solar	Rural, isolated, tourism-driven economy[36]	Advanced microgrid system (incorporation of smart meters, DSM, etc)
Magliano Alpi[37 38]	Town	Italy	Solar	Middle-income, Italy's first renewable energy community.[39]	Advanced microgrid system (incorporation of smart meters, DSM, etc)
Meltemi[40 41]	Town	Greece	Wind, Solar	Port and tourism-driven economy	Advanced Microgrid system (incorporating MAGIC[42])
Crete[43]	Island	Greece	Wind, Solar	Tourism-driven economy	Advanced Microgrid (REV-LAB, CELs System-of-systems Digital Twin)[44]
Kythnos[45 46 47]	Island	Greece	Solar	Rural, isolated island	Advanced Microgrid system (WiseGRID)[48]
Girona outskirts[49 50]	4 Villages as participants	Spain	Solar	Rural	Pilot EU-funded RESCHOOL project, microgrid system
Crevillent[51]	Town	Spain	Solar	Middle-income town	Pilot microgrid for EU-funded projects
Luče[52 53]	Village	Slovenia	Solar	Middle-income town	Pilot microgrid for EU-funded projects
Križevci[54 55 56]	Town	Croatia	Solar	Middle-income town	Pilot for EU-funded projects, solar city

[31] TaiyangNews. (n.d.). Egypt Seeking Bidders for Solar PV & Energy Storage Project in Siwa Oasis. https://taiyangnews.info/tenders/egypt-seeking- bidders-solar-pv-energy-storage-project-siwa-oasis

[32] United Nations Development Programme (UNDP). (n.d.). *Document Synthèse des réalisations POT.* https://info.undp.org/docs/pdc/Documents/MAR/Document%20Synth%C3%A8se%20des%20r%C3%A9alisations%20POT%20%20(1).pdf

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ALIGNING CASE STUDIES WITH OSTROM'S PRINCIPLES

Ostrom's 8 principles are a result of her empirical research using the IAD framework[57] to study real-world examples of successful resource management systems. Through this research, Ostrom identified recurring factors that contributed to the sustainable management of common-pool resources, which she distilled into the 8 principles. In this sense, the 8 principles can be seen as a practical subset or outcome of the IAD framework's analytical process, focusing specifically on the factors that lead to successful collective management of shared community resources such as the ones in RECs.[58] Table 2 below gives a clear explanation of Ostrom's principles, showing how they can contribute to achieving sustainable governance and practices of common based resources.

Table 2. Ostrom's principles for governing common goods explained

Principles	Description	Why it matters
Clearly Defined Boundaries	The community or group that uses the resource and the boundaries of the resource itself must be clearly defined. This ensures that everyone knows who has access to the resource and where the resource begins and ends.	Without clear boundaries, it's difficult to manage who can use the resource, leading to free-riding conflicts.
Rules Adapted to Local Conditions	The rules governing the use of the resource should be adapted to the local environmental, social, and economic conditions. These rules need to fit the specific context in which the resource is being used.	Local conditions vary greatly, and rules that work in one setting may not be effective elsewhere.
Collective-Choice Arrang.	Most individuals affected by the rules can participate in modifying them. This means that resource users themselves have a say in how the resource is managed and can adjust the rules as needed.	When people have a stake in rule-making, they are more likely to follow the rules and support collective action.
Effective Monitoring	Monitoring resource conditions and user behavior is essential. Monitoring ensures that rules are followed and that the resource is used sustainably.	Monitoring helps detect rule violations and resource depletion early on, allowing for corrective action before serious damage occurs.
Graduated Sanctions	Violators of the rules receive punishments that increase in severity depending on the seriousness and context of the offense. Initial sanctions are often light, such as a warning, but repeated or severe offenses lead to stronger penalties.	Graduated sanctions can provide flexibility and fairness, ensuring that unintentional violations are treated differently from willful noncompliance.
Conflict Resolution Mechanisms	Users and monitors have access to low-cost and efficient ways to resolve conflicts between users or between users and officials. Dispute resolution mechanisms should be accessible to all stakeholders.	Conflicts are inevitable when managing shared resources, and having accessible ways to resolve them helps prevent escalation and maintains cooperation.

[57] The IAD framework, co-created by the nobel prize winner Elinor Ostrom, is a well-established academic instrument for examining the governance of common-pool resources (CPRs).

[58] These principles became famous because they challenged the conventional wisdom that common resources are doomed to be overexploited, a concept popularly known as the "Tragedy of the Commons." Ostrom's groundbreaking work, for which she won the Nobel Prize in Economic Sciences in 2009, showed that local communities are capable of self-organizing and managing shared resources effectively without needing top-down regulation or privatization.

Local enforcement of local rules	The community's right to organize and govern the resource must be recognized by higher authorities (such as governments). Local users must have the autonomy to create their own rules without interference.	If external authorities undermine local governance, it can disrupt effective management and weaken local control.
Nested Enterprises	For larger common resources, governance activities are organized in multiple layers of nested enterprises. This means that smaller, local units manage their own sections of the resource but are part of a larger governance system that coordinates activities across scales.	Organizing governance across multiple levels can allow for more efficient and adaptable resource management.[59]

Ostrom's principles are highly relevant today, especially in areas like climate change, renewable energy management, and the global commons[60]. RECs managing renewable energy resources, often abide to Ostrom's principles (to a certain extent at least) to ensure fair and sustainable use of shared energy resources. As noted in the methodology section, after gathering relevant information on selected RECs, we aligned them with Ostrom's principles, as shown in Table 3 below. In Table 4 we show with greater detail the synergy between DLT and Ostrom's 8 principles, explaining how different BBA can help apply each principle on-chain.

Table 3. Matching of Use-Cases with Ostrom 8 Principles. The red X show a potential of the principle being applied in a specific REC however without clear evidences.

Community	**1. Clearly Defined Boundaries**	**2. Rules Adapted to Local Conditions**	**3. Collective-Choice Arrange-ments**	**4. Monitoring**	**5. Graduated Sanctions**	**6. Conflict-Resolution Mechanisms**	**7. Minimal Recognition of Rights to Organize**	**8. Nested Enterprises**
Tilos	X	X	X	X		X	X	
Magliano Alpi	X	X	X	X		X	X	
Meltemi	X	X	X	X		X	X	
Crete	X	X	X	X		X	X	
Kythnos	X	X	X	X		X	X	
Girona	X	X	X	X		X	X	
Crevillent	X	X	X	X		X	X	
Luče	X	X	X	X		X	X	
Križevci	X	X		X			X	

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OSTROMS PRINCIPLES AND BBAS

Principle	BBA
1. Clearly Defined Boundaries	Identity management & access control: Blockchain and cryptographical primitives can be leveraged to account of who is authorized to manage what in the REC, (e.g. use, produce, vote, transact, etc.) defining user participation boundaries.
2. Rules Adapted to Local Conditions	Smart contracts: Rules governing the REC use can be programmed into smart contracts that automatically enforce agreements and conditions, adapting to local or specific community needs.
3. Collective-Choice Arrangements	Decentralized decision-making & governance: Blockchain allows for decentralized decision making through the use of DAOs (Decentralized Autonomous Organizations) where all participants of the REC have a say in governance, reflecting collective-choice arrangements.
4. Monitoring	Transparency: Blockchain's transparent and immutable ledger allows recording of transactions and resource usage in REC without the need of central authority/third party.
5. Graduated Sanctions	Automated enforcement via smart contracts: Sanctions or penalties for rule violations can be embedded into smart contracts, where offenses trigger automatic penalties based on predefined terms (e.g., overuse of RE in RECs).
6. Conflict-Resolution Mechanisms	Decentralized dispute resolution: Blockchain-based platforms can provide automated decentralized conflict-resolution mechanisms, where disputes over resources are resolved transparently and fairly without the need of central authorities (e.g., Kleros). With the help of this BBA, each participant can have 'a say' in the REC management, helping achieve more democratic governance.
7. Minimal Recognition of Rights to Organize	Decentralization & autonomy: Blockchain can provide a system for self-governance in RECs, enabling the community to organize and manage its own resources the need for external interference. Likewise, the validity of records provided by DLT is in line with EU efforts to standardize REC operations and reduce 'green washing' practices, leading to higher recognition of local rules.
8. Nested Enterprises	Interoperability of multiple blockchain networks: Blockchain allows for nested and interoperable governance layers, connecting smaller community-based systems to larger governance frameworks in a transparent and accountable way.

INTEGRATION OF OSTROM'S PRINCIPLES WITH BLOCKCHAIN-BASED AFFORDANCES (BBA) AND RECS USE CASES

In the second phase, these principles are systematically matched with blockchain-based affordances (BBA), as discussed in the works of Rozas et al. (2021), Poux et al. (2020), and Poux and Ramos (2022). BBA encompass the technical capabilities of blockchain technology, which can be harnessed to operationalize Ostrom's principles and address the challenges associated with ToC. Key blockchain based affordances (BBA) under consideration in this article include Identity Management & Access Control, Smart Contracts, Decentralized Governance, Transparency & Real-Time Auditing, Automated Enforcement, Decentralized Dispute Resolution, Decentralization & Autonomy, and Interoperable Blockchain Systems. It is important to highlight that the classification by Rozas et al. (2021) incorporates Blockchain- Based Affordances (BBA) such as tokenization, smart contracts, decentralized autonomous organizations (DAOs), and the on-chain codification of trust. To enhance the clarity and relevance of these concepts in our analysis of Renewable Energy Communities (RECs), we adopt specific terminology for the BBAs.

In table 4 below we match the selected use-cases with the BBAs. This is logical continuation in analysing how BBA can enhance the management of RECs by aligning with Ostrom's 8 principles. In other words, the objective in this part is to explore how BBAs can be employed to fulfill Ostroms' principles in practical RECs settings. Additionally, the study addresses essential aspects of verifiable monitoring, reporting, and compliance, linking these elements to broader research questions concerning REC governance and the verification of sustainable practices. This methodology aims to provide an analysis of how blockchains can enhance the governance of RECs, contributing valuable insights both practically and theoretically to the fields of sustainable energy and RECs.

Table 4. Matching Use-Cases with BBA. Analysing how can BBA can enhance the management of RECs by aligning with Ostrom's 8 principles

Community	**Clearly Defined Boundaries** (Identity Management & Access Control)	**Rules Adapted to Local Conditions** (Smart Contracts)	**Collective-Choice Arrange-ments** (Decentralized Governance)	**Monitoring** (Transparency & Real-Time Auditing)	**Graduated Sanctions** (Automated Enforcement)	**Conflict-Resolution Mechanisms** (Decentralized Resolution)	**Minimal Recognition of Rights to Organize** (Decentra-lization)	**Nested Enterprises** (Interoperable Systems)
Tilos	X	X	X	X	X	X	X	X
Magliano Alpi	X	X	X	X	X	X	X	X
Meltemi	X	X	X	X	X	X	X	X
Crete	X	X	X	X	X	X	X	X
Kythnos	X	X	X	X	X	X	X	X
Girona	X	X	X	X	X	X	X	X
Crevillent	X	X	X	X	X	X	X	X
Luče	X	X	X	X	X	X	X	X
Križevci	X	X		X			X	X

INTERPRETATION OF RESULTS

As a general inference, a successful integration of Blockchain-Based Affordances (BBA) within Renewable Energy Communities (RECs) is contingent on the technological sophistication of the community and the governance structures of each REC. Advanced microgrid-type RECs, such as those found in the Greek islands, tend to exhibit more structured governance systems, with well- defined operational and resource management protocols enhanced by technological primitives in place (e.g., Microgrid REV-LAB, CELs System-of-systems Digital Twin in Crete REC or the Wise Grid in Kythnos). In contrast, a basic photovoltaic system may lack many of the governance features necessary for efficient REC management and do not possess the requisite technological infrastructure. Thanks to efforts by the European Union to promote local energy production and provide legal frameworks for RECs, Ostrom's seventh principle (*Minimal Recognition of Rights to Organize*) is well aligned with the opportunity for RECs to develop robust governance structures. While all RECs incorporate a level of consumption and production *monitoring*—through technologies such as smart meters—certain RECs as the ones in the Greek islands, have invested in highly advanced monitoring and management systems paving the way for an effective application of BBAs. The presence of *graduated sanctions* was not present in publicly available information. Significant member involvement in governance was observed in RECs such as those on the Greek islands and in Luče (underlining the principles of *Collective-Choice Arrangements*) with some public information indicating active citizen participation in energy governance and certain *Con ict Resolution Mechanisms*. Across all the cases studied, there was a consistent application of Ostrom's principle of *Clearly Defined Boundaries,* often implied by the installation of photovoltaic systems in specific areas (e.g., community) or connections to microgrid infrastructures. Lastly, the principle of *Nested Enterprises* was not observed in the selected use-cases, probably due to the nascent and localized structure of the selected RECs.

IMPLICATIONS OF BBA IN THE SELECTED USE-CASES

Clearly Defined Boundaries: All the use-cases analyzed demonstrate naturally imposed "Clearly Defined Boundaries" such as being part of an island or a community or/and technically imposed boundary such as having installed a photovoltaic to participate in the REC. In more advanced REC setups with more complex governance structures, blockchain could ensure transparency by securely documenting "who does what" within the energy system. For larger RECs, such as Crevillent, or where governance becomes more complex, blockchain infrastructure could facilitate the management of identities and access rights, ensuring that only authorized members can generate, store, consume energy, or vote and be involved in specific roles within the REC. This could be extended with managing voting rights in settings where governance structure allows it.

Smart Contracts and Local Conditions: While the generation and management of renewable energy in these RECs is shaped by local conditions (e.g., isolated islands vs. urban environments), blockchain can further enhance these operations through smart contracts. Blockchain can automate the enforcement of community-specific energy rules. For instance, in a REC like Magliano Alpi, blockchain could streamline local energy agreements, adjusting distribution and pricing based on solar availability or community demand without the need for human intervention.

Collective-Choice Arrangements: In cases where there is a significant focus on member involvement, BBAs could further decentralize decision-making by enabling community members to vote or reach consensus on different internal and external governance issues. This decentralized system could increase transparency and empower communities to shape their energy futures more directly.

Monitoring: All of the RECs incorporate smart meters in the technical infrastructure in place allowing for monitoring of energy usage and production. However, blockchain could add an important value by ensuring transparent yet privacy preserving tracking of energy generation, consumption, transactions etc. By storing all energy-related data on an the blockchain ledger, BBA can ensure every transaction is verifiable and immutable, which is especially valuable in preventing free-riding or disputes over energy use. The application of cryptographic primitives together with DLT can ensure privacy and security for REC members when needed. This can help prevent conflicts over resource use and prevent free-riding.

Graduated Sanctions: The data didn't show a clear application of Graduated Sanctions within RECs. Graduated Sanctions is considered a crucial element in effective management of Commons as noted by Ostrom[61]. Blockchain could enable smart contracts to automatically enforce such sanctions in cases of rule violations, such as overuse of RE. For example, in communal buildings like those in Girona, blockchain could prevent free-riding by automatically reducing energy access for repeated offenders.

Conflict-Resolution Mechanisms: Blockchain can also play a role in conflict resolution by providing transparent records of all energy transactions, potentially reducing disputes over resource use. In technologically advanced RECs, such as Crete, blockchain-based mechanisms for decentralized conflict resolution (e.g., via DAOs) could be implemented. For other RECs, external blockchain-based arbitration platforms like Kleros could offer alternative dispute resolution mechanisms.

Nested Enterprises: The RECs analyzed in this study dealt mostly with the governance of the Renewable Energy (RE) and did not extend into additional 'Layers' of governance such as to the management of clean water or waste (as in other successful RECs such as Culatra). In order to boost this principle, blockchain could facilitate the integration of a more complex governance system within the REC as well as an interoperability between local RECs and other entities. REC examples such as Crevillent, Girona, and Križevci demonstrate the potential for blockchain to support larger, interconnected energy systems.

[61] Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action.* Cambridge University Press.
In this foundational work, Ostrom discusses the role of sanctions and graduated penalties as key principles for managing common-pool resources effectively, helping to prevent overuse and ensure compliance among users.

In conclusion, while most of the analyzed RECs show the possibility of integrating BBA through blockchain, its implementation is highly dependent on the specific governance structures and technological readiness of each community. Blockchain can significantly enhance the transparency, efficiency, and autonomy of these energy communities, particularly in more technologically advanced REC systems. By implementing DLT, REC can ultimately mitigate issues such as free-riding and Tragedy of the Commons. In terms of the potential of Distributed Ledger Technology (DLT) to enhance monitoring, reporting, and verification (MRV) of sustainable practices, including clean energy production and consumption across the Euromed region, our analysis indicates that DLT could be a pivotal enabler. Integrating successfully with smart meters and other sensor technology, BBAs can offer transparent, secure and immutable records of energy flows, significantly strengthening the existing MRV of renewable energy initiatives, thereby helping to curb issues like "greenwashing". The integration of smart meters with blockchain technology can enable accurate tracking of energy generation and consumption, while also verifying the source of renewable energy. This combination of transparency and immutability ensures that data on sustainability practices is reliable and tamper-proof, thus fostering trust in the adoption of green energy solutions and providing verifiable proofs for external auditors.

Overall, DLT can facilitate RECs' compliance with EU renewable energy regulations and help them contribute to achieving Sustainable Development Goals (SDGs). DLT can particularly support RECs in contributing to SDG 7 (Affordable and Clean Energy) by promoting equitable access to clean energy and ensuring its sustainable production. Furthermore, it can contribute to SDG 13 (Climate Action) by reducing energy waste and improving the efficiency of renewable energy systems. Likewise, the integration of DLT in RECs can directly contribute to SDG 11 (Sustainable Cities and Communities), which focuses on creating inclusive, safe, and sustainable cities. Through improved energy management and the promotion of local renewable energy production, blockchain enables cities and communities to become more sustainable and energy-resilient. Additionally, DLT can empower citizens to take part in energy governance and decision-making processes, contributing to the development of decentralized, self-sustaining energy communities. Furthermore, in line with SDG 8 (Decent Work and Economic Growth) , RECs supported by DLT can foster local ownership of energy resources, thereby creating new opportunities for economic participation. By promoting local renewable energy production, DLT-driven RECs can also reduce energy costs, increasing disposable income and contributing to local economic growth.

OVERALL POLICY IMPLICATIONS & RECOMMENDATIONS

The integration of blockchain technology into the governance of Renewable Energy Communities (RECs) offers significant opportunities for more efficient, transparent, and decentralized energy management. However, for these benefits to be fully realized, appropriate policy frameworks need to be in place. These policy implications are particularly relevant to local, national, and international governance bodies interested in promoting decentralized energy systems and enhancing the role of communities in renewable energy transition efforts. Here are some of the key policy implications:

A) Promoting Decentralized Energy Governance
One of the primary advantages of using blockchain in RECs is its ability to support decentralized decision-making and governance, empowering local communities to manage their energy resources autonomously, including fortifying monitoring and graduated sanctions. Granting local energy communities the legal recognition and autonomy to self-organize are crucial. This aligns with Ostrom's principle of collective-choice arrangements, where communities can directly participate in rule-making and governance.

Potential Implementation: National energy regulatory bodies can create pilot programs that test decentralized governance models, providing insights for future policy refinements and granting of 'special' rights.

B) Supporting Blockchain Adoption in Energy Markets
Blockchain technology enables transparent, secure, and tamper-proof energy transactions, which are essential for RECs. Likewise, Blockchain offers RECs the ability to access main grid energy markets and participate in energy trading more efficiently. By using smart contracts, RECs can set up automatic energy transactions with local or national grids, ensuring fair prices and seamless energy trading.

Potential Implementation. Policymakers need to encourage the adoption of blockchain by developing standards and guidelines for integrating blockchain into existing energy systems. Regulatory bodies should create standards for blockchain interoperability in the energy sector, ensuring that RECs can participate in national energy markets. Policymakers should also explore incentive programs that promote the development and deployment of blockchain solutions in energy communities. Energy regulators can collaborate with blockchain developers to establish compliance standards that ensure compatibility with national energy infrastructures. Governments can introduce blockchain-based pilot projects in energy markets to test scalability and efficiency.

C) Ensuring Data Privacy and Security
Blockchain's transparent and immutable nature offers significant advantages in terms of monitoring and accountability in energy communities. However, it also raises concerns about data privacy and the security of sensitive information, especially as blockchain can provide a permanent record of energy

usage and transactions. Policymakers need to balance the benefits of transparency with the need to protect personal and community data from misuse. Data protection laws such as the GDPR may be updated to account for the unique privacy features posed by blockchain. This could include guidelines for anonymizing energy data while still allowing for transparency in energy use. In line with the NIS directives, governments could also establish cybersecurity standards for blockchain implementations in the energy sector to safeguard against potential breaches.

Potential Implementation: Legislators can mandate privacy-enhancing blockchain technologies, such as zero-knowledge proofs, to protect users' energy data. Additionally, regulatory agencies can introduce certification programs to ensure blockchain platforms used in RECs comply with cybersecurity best practices.

D) Incentivizing Sustainability and Inclusivity

Overall, RECs can be particularly valuable in promoting sustainable production and consumption of energy. Likewise blockchain powered RECs can be particularly helpful is isolated areas where main grid energy is scarce/expensive. Therefore, governments should establish economic incentive programs that support the deployment of blockchain in underserved areas, ensuring that these communities can benefit from blockchain-based governance. Additionally, funding for research and development in the blockchain-energy sector can be increased to ensure that sustainable energy projects are scalable and accessible to a wider population.

Potential Implementation: Policymakers can create grant programs specifically for blockchain- powered RECs in remote or underserved areas. Furthermore, governments can offer tax incentives for companies developing blockchain applications that enhance energy accessibility and sustainability.

RESULT IMPLICATIONS FOR THE SOUTHMED

Although data access on Renewable Energy Communities (RECs) in SouthMed countries was scarce and didn't allowed for an in-depth analysis of particular use-cases, the results from NorthMed RECs can provide a valuable base for extrapolation. The NorthMed cases demonstrate how the combination of governance structures and technological readiness can significantly impact the effectiveness of RECs further helping reduce issues such as ToC. By analyzing the possible implications for SouthMed countries, we can offer insights into how they might benefit from the integration of BBAs, assuming similar socio-economic and environmental challenges but also key regional differences.

Governance Structure and Policy Support: NorthMed RECs show that the successful adoption of blockchain technology depends largely on the presence of robust governance systems strongly underpinned by 'friendly' EU regulatory frameworks. In SouthMed countries, policymakers will need to prioritize the development of governance structures that facilitate citizen involvement, collective decision-making, and the establishment of clear operational rules for energy distribution and consumption. Overall, legal frameworks similar to those provided by the EU (e.g., the RED-II Directive) would also need to be created and adapted to local conditions, fostering the growth of RECs in a structured and sustainable manner.

Technological Readiness and Infrastructure: In NorthMed RECs, the presence of smart technologies (e.g., smart meters) showed to be pivotal for monitoring and enabling a further application of a DLT based system (which can further enforce energy agreements, and enable decentralized energy management). For SouthMed regions, where infrastructure might be less developed, efforts should focus on building the necessary technological foundation, including the deployment of smart metering, energy storage, and decentralized digital platforms for energy management. This would ultimately empower local communities to manage energy autonomously and reduce dependency on national grids.

Citizen Involvement and Local Governance: NorthMed examples such as the Greek Islands highlight the importance of citizen involvement in REC governance. Active participation leads to better energy management and a sense of ownership among community members. In SouthMed countries, fostering such involvement may face challenges due to political, social, or cultural barriers, but there is significant potential for grassroots movements to play a key role in building sustainable energy communities.

Scalability and Interoperability: The ability of blockchain to facilitates the integration of local RECs with larger grids, suggests that SouthMed countries could benefit from scalable blockchain solutions. Given the growing interest in energy communities, SouthMed regions could use blockchain to connect multiple small-scale RECs with national or regional grids, ensuring efficient energy distribution and trade of surplus RE.

While SouthMed countries face distinct challenges compared to their NorthMed counterparts, the results from NorthMed RECs can provide a roadmap for the potential success of blockchain technology in local energy communities. By focusing on governance, infrastructure development, citizen participation, and technological innovation, SouthMed countries could leverage blockchains to create more resilient, transparent, and efficient energy communities aligned with the unique environmental and socio-political landscapes of the region.

CONCLUSION

Blockchain technology holds significant potential for Renewable Energy Communities (RECs), paving the way for more sustainable development by enabling decentralized, transparent, and autonomous governance of renewable energy. This study highlights how Blockchain-Based Affordances (BBAs) can enhance the governance of RECs by facilitating the application and automation of Ostrom's principles, effectively mitigating challenges like the 'Tragedy of the Commons.' By improving the monitoring, reporting, and verification (MRV) of sustainable practices within RECs, BBAs can support compliance with EU renewable energy regulations and help further progress toward the United Nations Sustainable Development Goals (SDGs). Therefore, by encouraging blockchain adoption in RECs, policymakers can help speed up the shift toward sustainable, community-led renewable energy systems. As renewable energy remains essential in the fight against climate change, blockchain-enabled RECs can present an innovative model for local energy production, management, and trading. This model not only fosters socio-economic growth within communities but also contributes to global sustainability efforts.

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