Energy Communities-Challenge and an Opportunities for Energy Decentralization and Efficiency. A Comparison of PV Based Case-Studies with Different Control Strategies

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ABSTRACT: The global energy landscape is undergoing a significant transformation, driven by the increasing adoption of renewable energy sources and the emergence of decentralized energy production models. This transition towards decentralization challenges the traditional centralized energy infrastructure paradigm, offering opportunities for greater citizen involvement and participation in energy generation and consumption. Energy communities, as grassroots initiatives, have emerged as a promising collective organizational modality, enabling citizens to invest in clean energy, meet consumption needs, and contribute to environmental goals. This paper examines the evolution of energy communities, focusing on their regulatory framework, operational mechanisms, and potential impact on the energy transition. Drawing on case studies from Europe, particularly Italy, and leveraging concepts from the multi-level perspective theory, the paper explores the dynamics of socio-technical transitions in the energy sector and the role of energy communities as niche innovations driving systemic change. Furthermore, the paper discusses the integration of blockchain technology in energy communities, highlighting its potential benefits and challenges.
Blockchain holds the potential to facilitate peer-to-peer energy trading, optimize self-consumption, and enhance transparency in energy transactions.The transition towards renewable energy communities represents a fundamental shift in the energy sector, requiring collaboration between governments, businesses, and citizens. By promoting innovation, decentralization, and community empowerment, energy communities pave the way for a more sustainable and resilient energy future.
Through a comprehensive analysis, this paper aims to provide insights into the transformative potential of energy communities in shaping a more sustainable and democratic energy future

1 INTRODUCTION

The new European Directive on Renewable Energy (RED II), implemented in Italy by the "Milleproroghe Decree 162/2019", converted with Law no. 8 of 2020, establishes the possibility of creating communities between multiple subjects for the production and consumption of energy from renewable sources.

Energy Communities (CER) represent a virtuous socio-economic model of community in which community members - citizens, businesses and administrations - become prosumer (i.e. simultaneously producers and consumers) actively integrated into a participatory and democratic process to support the energy transition.

With CERs we move from a centralized energy system to a decentralized system, in which members share renewable and clean energy, in a peer-to-peer exchange, thanks to the innovation represented by Smart Grids. It is a decentralized digital electricity network, through which anyone who owns a photovoltaic system, connected to the grid, can share excess energy with other consumers, saving on bills and reducing the carbon footprint and energy waste.

By placing citizens at the center of the energy transition, CERs can be seen as a new collective organizational mode of access to energy resources, with open and participatory governance for the provision of benefits for members and the territory.

In fact, they allow the development of local production chains, providing networking and work opportunities for local communities and reducing energy dependence on other countries or regions. Furthermore, CERs also contribute to the fight against energy poverty through the reduction of energy consumption, the reduction of supply tariffs and a more equitable and accessible use of renewable sources.

Based on what has been said, it is clear that CERs are a regenerative model not only for individual communities, on a local scale but also on a territorial scale, underlining the role of communities as drivers of inclusive and sustainable development processes.

Despite this, CERs are not always welcomed with enthusiasm. In this regard, we would like to highlight the so-called NIMBY phenomenon ("Not In My Back Yard" or "Not in my backyard") which is also quite widespread for CERs; this phenomenon arises among civic committees, local communities, associations, political representatives who oppose the construction of quarries, landfills, waste-to-energy plants, power plants, etc. in their territories. In the case of CERs, these committees do not disdain renewable sources tout court but simply do not want to alter their landscapes, therefore, they clamor to install the plants in other areas. As a reaction to this phenomenon there is another: PIMBY ("Please in My Back Yard"), characterizes the attitude of individuals or committees who favorably welcome, in their territories, the photovoltaic systems because they consider them works of public interest.mThis contribution intends to propose an analysis of the state of the art of the practices relating to CERs already active in Italy. The methodology is divided into two phases: in the first phase, a cataloging of the selected practices is carried out, highlighting strengths and weaknesses at an economic, environmental and socio-cultural level. In the second phase, starting from the filing, we proceed with the identification of criteria and indicators for the quantitative-qualitative evaluation of the impacts produced by the practices analyzed and to allow their comparability. The result is the development of a first monitoring and evaluation

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framework, in order to define a tool adaptable to different contexts and implementable as the phenomenon evolves.

The paper will analyze different case studies on blockchain technologies to manage and foster energy community diffusion in a decentralized way of energy production.

2 EVOLUTION OF ENERGY COMMUNITIES

Energy communities represent a paradigm shift in energy governance, moving away from centralized control towards decentralized, participatory models. This section explores the evolution of energy communities, highlighting key drivers, regulatory frameworks, and operational models. The European Commission's Clean Energy for All Europeans Package (2019) [1] has played a pivotal role in promoting the concept of energy communities, emphasizing the importance of citizen involvement in the future energy system. The implementation of energy communities in Italy, guided by legislative measures such as DL 162/2019 and Resolution 318/2020, serves as a case study to illustrate the regulatory framework and operational dynamics of energy communities.

2.1 Operational Mechanisms of Energy Communities

Energy communities operate based on principles of collective ownership, participation, and benefit-sharing.. Renewable energy communities, in particular, leverage renewable energy sources to meet consumption needs and promote environmental sustainability. The concept of shared energy, defined as the energy consumed within a community before accessing the grid, underscores the collaborative nature of energy communities..

2.2 Regulatory Framework and Governance

The regulatory framework plays a crucial role in facilitating the establishment and operation of energy communities.s. The European Commission's Clean Energy for All Europeans Package (2019) emphasizes the pivotal role citizens and collective initiatives will play in shaping the future energy system. Energy communities, grassroots movements investing in clean energy solutions, are emerging as key drivers of this transition. The European directive RED II (2018/2001/EU) has facilitated the proliferation of energy communities across Europe, with Italy embracing this trend through legislative measures such as DL 162/2019 and Resolution 318/2020/R/ee of ARERA.

According to the Renewable Energy Directive (RED II), a renewable energy community (REC) should maintain autonomy from individual members and other traditional market players, such as shareholders, who participate within the community. This autonomy is critical to ensure that the collective interests of the community prevail over the interests of any individual or corporate entity. Over the past two or three decades, the concept of locally and collectively owned energy production sites has gained traction. These forms of organization not only foster community involvement but also create a broader base of support, essential for the success of energy projects. By mobilizing local participation and contributions, such as financial shareholdings and access to land or properties, these communities can overcome significant barriers to project realization. Interestingly, the structure and organization of renewable energy communities vary between countries and regions, reflecting differing cultural, political, and regulatory contexts.

2.4 The concept of “shared energy”

Energy communities are putting into the energy distribution system the concept of shared energy [2]
Shared energy is defined under the regulation as the hourly minimum between the energy injected into the grid by the users and the energy consumed in a shared configuration (Figure 1).
The consumption of this kind of energy is also incentivized by the energy authority in order in this phase to support such a configuration.
Shared energy stays in between the pure production and user consumption, because actually it is a pool of energy that is directly produced and consumed by the community before having access to the grid, and as well as a pool for the grid of further power supply.

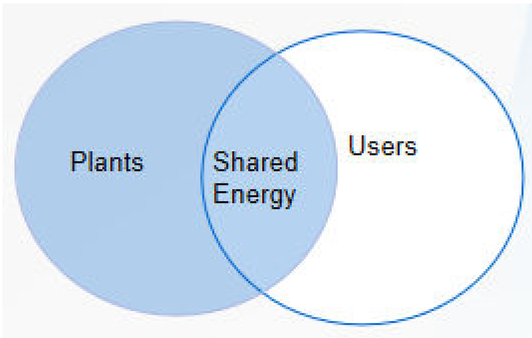

Figure 1: Conceptual model of Shared energy

. In particular, multi-energy districts, which are based on the advanced integration of energy storage technologies and polygeneration systems at the district level, are gaining a lot of interest from both research and industrial communities. Using energy storage systems and polygeneration technologies a smart district aims at better management of the variability of the local energy demand, to improve service reliability, and to promote optimal use of local renewable energy sources

2.5 Approaches to Analyzing Community Energy

Schreuer and Weismeier-Sammer (2010)[3] identified three main approaches to the analysis of community energy: microprocesses, public acceptance, and institutional conditions. Micro-level studies focus on interactions between community members and project organizers, highlighting the relationship between local people and external practitioners who facilitate community development [4,5] .

These studies also explore conflicts that can arise between municipal representatives and active citizens regarding project control [6]. Local ownership plays a vital role in fostering public support and acceptance, particularly in renewable energy projects like wind power. Research suggests that large-scale commercial wind installations often alienate local populations due to a lack of ownership opportunities, leading to public opposition. In contrast, small-scale, community-based wind projects tend to receive higher levels of support from local residents [7].

3 CER as “Social Matryoshka”

CER can be considered a "Social Matryoshka", an inclusive community which, by connecting different actors, generates social benefits greater than those expected. In addition to the production and sharing of renewable energy, CER can become a context in which social initiatives are implemented that contribute to the regeneration of neighborhoods and the improvement of the living conditions of vulnerable social groups.
However, the creation of a CER presents difficulties, such as bureaucracy and regulatory uncertainty, which hinder the process and risk generating distrust among the population. Another risk is the lack of citizen participation and abandonment of the project. To overcome these barriers, a careful analysis of the territory and the inclusion of the most fragile subjects, often left on the margins of these initiatives, are essential.

Although the legislation provides that CERs mainly pursue environmental, economic and social, non-profit objectives, it is possible to think about broadening the scope of CERs to include indirect social benefits that promote social cohesion and the improvement of the quality of life in neighborhoods. For example, the CER can become a point of reference for the creation of "Formica Neighborhoods", characterized by solidarity and industriousness, where members engage in activities that go beyond the energy transition, such as youth crime prevention, school support and social inclusion.

Among the indirect social initiatives that a CER could promote are "repair cafés", meeting places where people collaborate to repair objects, promoting the circular economy. These spaces could also involve teenagers or adults with social problems, as part of recovery paths. Other activities could include the "wall of kindness", urban redevelopment projects and the installation of smart benches powered by solar energy.

In summary, CERs can be seen not only as tools for the production of renewable energy, but as multidimensional contexts in which active participation and citizenship are expressed in various spheres of society, contributing to creating safer, more inclusive and sustainable communities.

4 INTEGRATION OF BLOCKCHAIN TECHNOLOGY

The integration of blockchain technology into energy communities offers transformative potential, particularly in enhancing operational efficiency and ensuring transparency. As energy systems transition toward decentralization, blockchain emerges as a pivotal technology to facilitate peer-to-peer energy trading, smart contracts, and decentralized energy management. This section delves into these applications, supported by real-world case studies. The evolving energy landscape calls for new governance models in energy communities, particularly those that integrate traditional grid control methodologies with advanced technologies like blockchain. The smart grid paradigm, for example, emphasizes the need for greater power grid flexibility, where data and IT systems are used to remotely manage distributed energy generation and storage. This dynamic coordination allows energy systems to respond more effectively to fluctuations in demand and supply [8].

Blockchain technology, widely recognized for its potential in energy applications, offers various opportunities to enhance the efficiency and transparency of energy systems [9] . Some key applications include:

- Cost reduction through decentralized marketplaces
- Managing complexity, data security, and ownership within grids
- Engaging prosumers (consumers who also produce energy) in the energy market
- Facilitating peer-to-peer (P2P) energy transactions
- Enabling more efficient utility billing processes
- Issuing certificates of origin for renewable energy
- Supporting the decarbonization of energy systems
- However, the sustainability of blockchain technology in the energy sector is still being debated. While its potential for decentralization and transparency is clear, mainstream blockchain technologies like Bitcoin consume excessive amounts of energy per transaction, raising questions about their suitability as enablers for a more sustainable energy future [10].

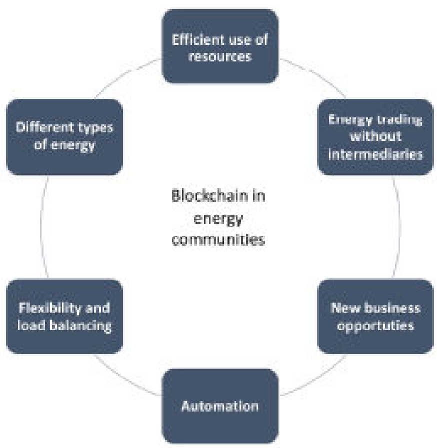

Figure 1: Role of Blockchain in energy communities

4.1 Peer-to-Peer Energy Trading

Blockchain's most significant contribution to energy communities lies in facilitating peer-to-peer (P2P) energy trading. Traditional energy markets rely on centralized entities to regulate the production and distribution of energy. In contrast, blockchain technology enables direct transactions between energy producers and consumers within a decentralized framework. By using smart contracts on a blockchain platform, energy consumers can trade surplus energy seamlessly with their neighbors. This approach not only promotes efficiency but also reduces reliance on centralized grid systems. As Tushar et al. (2020) [11] explain, blockchain-based P2P energy trading enhances market accessibility, giving consumers more control over their energy sources and prices.

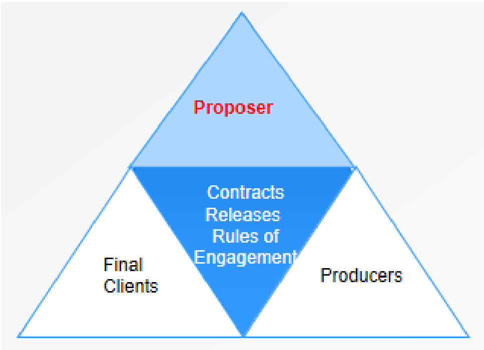

Figure 2: Application of Blockchain to support smart contracts in energy communities

4.2 Smart Contracts for Automation and Trust

Smart contracts play a critical role in automating and enforcing agreements between parties in energy communities. These are self-executing contracts with the terms directly written into code, making them tamper-proof and highly transparent [12]. In the context of energy communities, smart contracts can govern energy exchanges, automate billing, and ensure compliance with regulations without intermediaries. The automated nature of smart contracts significantly reduces transaction costs and enhances trust among participants, particularly in complex transactions involving multiple parties.

4.3 Decentralized Energy Management

Decentralized energy management is another area where blockchain demonstrates immense promise. Energy communities are increasingly moving towards decentralized models, where local energy generation, such as solar or wind, plays a central role. Blockchain provides a robust platform to manage this distributed network efficiently. Through blockchain, energy generation data can be recorded in real time, ensuring data integrity and preventing manipulation. Furthermore, the decentralized nature of the blockchain itself aligns with the principles of energy decentralization, creating a more resilient and transparent energy system [13].

4.4 Case Study: Blockchain Grid in Austria

The Blockchain Grid project in Austria stands as a practical example of how blockchain can revolutionize energy communities. Launched to test the viability of blockchain technology in energy trading, the project allowed participants to trade energy directly within their community using blockchain-based platforms. The results demonstrated increased efficiency in energy distribution, lower costs, and higher transparency in energy exchanges [14]. This project is a key example of how blockchain is shaping the future of energy communities across the globe.

5 DISCUSSION

Despite their transformative potential, energy communities face various challenges, including regulatory barriers, technical complexities, and socio-economic considerations. Future research and policies should investigate the potential benefits of adopting a holistic approach to integrate technological innovation, regulatory reform, and community engagement.

As energy communities continue to grow in prominence, innovative solutions such as blockchain could redefine the governance and operational models of these communities. However, careful consideration must be given to the energy consumption and sustainability of blockchain technologies in energy markets. The balance between technological innovation and environmental sustainability will be crucial for the future of decentralized, community-based energy systems. In this context, blockchain technology offers substantial opportunities for enhancing the efficiency, transparency, and resilience of energy communities. Through applications such as P2P energy trading, smart contracts, and decentralized management, blockchain can fundamentally transform how energy is produced, managed, and distributed. The Blockchain Grid project in Austria exemplifies the practical potential of this technology, suggesting broader applications in future energy markets.

6 CONCLUSIONS

Energy communities represent a novel approach to energy governance, fostering decentralization, democratization, and sustainability. Through collective ownership and participation, energy communities empower citizens to actively contribute to the transition towards renewable energy and sustainable development. While challenges persist, the growing momentum behind energy communities signals a promising path towards a more resilient and inclusive energy future.

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