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Case Studies on Energy Communities and Recommendations for Future Energy Communities

Yuchen Zhai

The Faculty of Engineering, The University of Hong Kong, Hong Kong, China
zyc11080921@gmail.com

Abstract. Developing Energy Communities is a crucial measure for energy transformation, which means that these communities take a leading role in achieving energy transition and climate goals within a specific range of communities by utilizing renewable resources. This research selects two European cases from the world's most representative energy communities: Samso Island in Denmark, the world's first island to achieve carbon neutrality, and the Magliano Alpi Community, the first renewable energy community established in Italy under the influence of European Union (EU) policies and the support of the Italian government. Due to energy scarcity in Africa, establishing Energy Communities within a certain range based on Distributed Energy Resources will have broad prospects. This research selects the developing Energy Communities in Africa as case studies to explore the current situation of African Energy Communities. By comparing and analyzing their differences between mature Energy Communities in the EU from multiple perspectives, the researcher will explore future development directions and provide recommendations for regions with scarce energy resources. Based on case studies from different regions, this research summarizes the key factors of Energy Community development, including policy issues, funding issues, technological issues, and community democratic co-creation issues.

Keywords: Energy Community, REC, DER, Co-creation

1. Introduction

Global warming has become a severe challenge faced by all humanity, with impacts covering multiple fields such as ecology, economy, and society. In response to this crisis, an international climate agreement, the Paris Agreement had been formulated in 2015, which clearly set the temperature control target of "Holding the increase in global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" providing a framework for global climate governance [1]. To achieve this goal, energy transformation is an inevitable method, which requires accelerating the substitution of renewable energy for non-renewable energy, as well as building efficient energy storage and distribution systems.

The concept of Energy Communities (ECs) has emerged in the context of global energy transition, and its definition varies in different countries and regions. Based on the scope of this research, Energy Communities is defined as the integration of distributed energy resources within a

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certain geographical area. Members of the community include residents, government organizations, and enterprises who cooperate to participate in the production, distribution, storage, and consumption of renewable energy. This research will conduct research and analysis based on those mature Energy Community cases worldwide. By summarizing the characteristics and development trends of mature Energy Communities, the research will provide suggestions for the construction of Energy Communities in more regions in the future.

2. Definition of energy communities

The European Union (EU) is the first region worldwide to establish a clear legal framework for Energy Communities. The Clean Energy Package for All Europeans was officially proposed in November 2016. This package categorizes Energy Communities into two types: Citizen Energy Communities and Renewable Energy Communities. Under the package, RECs can only adopt renewable energy technologies. Additionally, it stipulates that members and shareholders of RECs must be geographically close to the community, and small and medium-sized enterprises are permitted to administrate RECs, whereas CECs are restricted to the participation of small and micro-enterprises [2-5]. Because of its strictly narrow definition, in this research, Energy Communities are defined as: within a certain spatial range, using distributed renewable energy to replace traditional energy for energy supply. Community members, including residents, government authorities, and enterprises within the community, collaborate in the production, distribution, storage, and consumption of renewable energy. The renewable energy sources replace fossil fuels for power and heat supply, ultimately enabling the power grid and heat network in Energy Communities to be covered by distributed energy. Table 1 presents the types of distributed energy and related data available currently.

Table 1. Characteristics of DREs [6]

RET	Fuel Used	Size (kW)	Availability	O/P	Carbon Emissions
PVs	Sun	0.02–1000+	Location based	DC	Nil
Solar Thermal	Sun and Water	1000–30,000	Location based	DC	Low
Biomass Gasification	Biomass	100–20,000	-	-	Low
Geothermal	Hot Water	5000–100,000	Location based	Both	Low
Hydro (Small)	Water	5–100,000	Location based	AC	Nil
Wind	Wind	0.2–3000	Location based	AC	Nil
Ocean Energy	Ocean Waves	100–1000	Location based	AC	Low

3. Case study

3.1. Case study of Denmark - energy type: wind power

Denmark has established targets to attain complete carbon neutrality by 2045 [7]. This target far exceeds the EU's collective emission reduction target of 55%, which reflects the Danish government's robust climate and energy policies [8-9]. To achieve this objective, Denmark has vigorously developed renewable energy to replace traditional fossil fuels. Due to its geographical characteristics of being surrounded by sea and comprising numerous islands, the country possesses abundant wind resources, making wind power one of the key renewable energy sources being

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extensively developed. The installed capacity of wind energy in Denmark (CAP, unit: MW) has shown a continuous growth trend, growing from 5077 MW in 2015 to 7621 MW in 2024 [10].

The case selected here comes from Samsø Island in Denmark. The energy transformation of Samso island can be traced back to the economic crisis triggered by the closure of a local slaughterhouse on the island, with the pivotal shift centered on discontinuing fossil fuel imports. After 1997, the island vigorously developed renewable energy projects, especially utilizing wind energy. And the island had successfully achieved net energy exports by 2005.

Samsø Island demonstrates a very high degree of democratization, and all residents in the community can participate in the energy decision-making process. In fact, beyond being decision-makers, the islanders have more importantly become owners and beneficiaries of the Energy Community. In addition to meeting the energy demand of the island, the onshore wind turbines and offshore wind turbines, and other facilities installed on the island also generate surplus energy that yields financial returns. And this has enabled residents who actively participated in co-creation and invested in these facilities to become project beneficiaries, while these renewable energy projects have also contributed to local employment opportunities.

The asset ownership of the energy project on Samso island is also decentralized and diversified, including municipal authorities, external investors, and citizens in the community. From the regulatory perspective, the Samsø Energy Academy has played a role in guiding and supervising relevant decisions within the community in the process of Samso island's energy transformation [11-14]. Samsø Island, as a paradigmatic case of an Energy Community, offers a valuable exemplar reference for other Energy Communities.

3.2. Case study of Magliano Alpi, Italy— energy type: solar power

Italy's energy-related policies are largely guided by relevant EU policies. In accordance with EU legislation, Italy adopted the Integrated National Energy and Climate Plan (INECP) in January 2020, which set a target for renewable energy to account for 30% of total final energy consumption by 2030 [15]. In order to achieve this goal, solar energy has been vigorously developed. From a geographical advantage perspective, southern Italy benefits from its latitude and abundant sunshine, making photovoltaic power generation prevalent in the region [16]. By 2020, approximately 11% of Italy's electricity generation was derived from photovoltaic technology. It is estimated that by 2050, the installed PV capacity in Italy is expected to exceed 200GW. A significant portion of future photovoltaic power generation is likely to be realized through the establishment of new energy communities [17].

The case selected here is from Magliano Alpi, the first renewable energy community in Italy, which was established in December 2020. In the community, a photovoltaic power generation system is used to connect some public buildings, including schools, libraries, and municipal facilities, as well as private entities willing to participate in the distributed energy network. Due to the funding issues, the construction of the community depends on public funding. From the regulatory issues, the local municipal government participated in this process as a neutral guarantor. From the technical issues, a completely integrated system based on Internet of Things technology has been implemented in the community, which is composed of energy hub smart meters and smart grid management software. From the democracy and community co-creation issues, the community is based on the open and voluntary participation of Magliano Alpi community residents [18].

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3.3. Case studies from Africa

The challenges faced by Africa in the energy sector stem from both energy scarcity and inequitable energy distribution. Energy Communities present a viable pathway to address energy poverty in those regions. Communities lacking grid access can access electricity through the deployment of distributed renewable energy systems, such as solar and wind energy.

This study will study the cases of Energy Communities from South Africa, Malawi, Togo, Cameroon, and the Ivory Coast. By analyzing the current states of these Energy Communities, this research aims to summarize strategies for promoting the development of Energy Communities across Africa.

Table 2. Basic information on the five energy communities

Country	Name of ECs	Energy Resources	Specific Governmental Policies that support ECs	Owners of the project/ Sources of funding/ Composition of the ECs	How are Values created and benefits
South Africa	Cookhouse Wind Farm	Wind	None found	African Infrastructure Investment Managers (AIIM) and the Local Community Trust, Old Mutual	Not mentioned
Malawi	Sitolo Community solar grid	Solar	None found	Malawi Government, UNDP & GEF	Not mentioned
Togo	Solar Microgrid Avetonou	Solar	None found	Togo Rural Electrification and Renewable Energy Agency (AT2ER)	Not mentioned
Cameroon	Togolese Smart Solar Kiosk	Solar	None found	EkoEnergy	Not mentioned
Ivory Coast	Mezam Division domestic biogas	Biogas	None found	UNDP	Not mentioned

Table 2 describes the basic information of the selected Energy Community cases.

The research has found that the development of Energy Communities in Africa adopts appropriate renewable energy sources based on local conditions. The five countries where the cases are located have policies related to renewable energy supported by the government. However, specific policies for developing Energy Communities utilizing renewable energy are lacking. This contrasts with the EU Energy Community cases, with clear policy guidance and standardized governance systems. In the process of advancing the construction of Energy Communities, the imperfect governance system may lead to various problems in the decision-making and implementation process of Energy Communities, and may also lead to confusion and misunderstanding among residents in the community. Meanwhile, these cases generally lack a clear governance system and defined approaches for value and benefit creation. Furthermore, the ownership, funding sources, and management entities of these community projects are predominantly government agencies, international organizations, or corporations, resulting in limited democratic participation and co-creation engagement from community residents [19].

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4. Problem analysis and prospects

4.1. Problem analysis

Based on a large number of case analyses and typical case studies, this study summarizes four core issues faced by Energy Communities, including regulatory issues, technical issues, funding issues, and democracy and community co-creation issues within the community.

4.1.1. Regulatory issues

The development of Energy Communities in different regions requires adaptation to local conditions, with adequate consideration given to the variations in politics, culture, economy, and other dimensions across the regions and countries where such communities are situated. The construction of Energy Communities must be based on the local business models and political-economic climates. As the core entity, Energy Communities should collaborate with other entities, including universities, real estate developers, business organizations, and local government organizations. Meanwhile, in addition to Energy Communities regulated by public sectors such as governments, other communities managed by residents' self-governance or commercial organizations need to establish more standardized management systems.

4.1.2. Technical issues

With the policy support and sufficient funding, how to solve the technical problems in the Energy Community and making better utilization of renewable energy within communities still pose certain challenges. The first is the technical challenge concerning the infrastructure for the distribution of renewable energy within communities. The transformation of traditional communities into Energy Communities faces huge challenges of grid access and upgrading. The underdeveloped communication infrastructure, along with the distribution of energy conversion devices and energy storage facilities, all present technical issues to Energy Communities. The second challenge stems from energy supply and accurate forecasting. Due to the instability and intermittency of renewable energy, how to stably supply energy to communities and accurately predict energy demand and supply have become technical issues to be overcome [20]. While ensuring a stable energy supply, the well-developed energy storage system in the community also needs to be innovated continuously. In the process of developing Energy Communities, it is necessary to combine advanced forecasting and machine learning to achieve the continuous upgrading of energy storage systems and the improvement of energy conversion efficiency [21]. There are still practical challenges in integrating energy management systems within the community, such as how to achieve a more reasonable energy distribution within the community through decentralized management [22].

4.1.3. Democracy and community co-creation issues

Whether in the EU—where mature Energy Community models have already existed—or in other regions such as China, energy systems have long been controlled by governments or large-scale centralized enterprises. The Energy Communities have achieved decentralization of control over a portion of energy resources, making local organizations and citizens in the community. This democratization of regional energy production can motivate citizens to actively participate in the development of Energy Communities. Within their daily living spheres, they can effectively play

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their roles, replace the combustion of fossil fuels with renewable energy, and thus actively drive energy transition and environmental protection.

4.1.4. Funding issues

The funding for Energy Communities typically comes from three sources, which are closely linked to the development stages of the communities. First, in the initial construction phase, the funding for Energy Communities typically comes from policy-driven funding provided by public sectors such as governments. In the case study of this research, the funding for the Magliano Alpi community originated from the Italian government's relevant incentives for renewable Energy Communities. Moreover, after formulating relevant policies and regulations about Energy Communities, the EU also invests substantial funding in related projects. Next, in the process of Energy Community development, the co-creation with community residents will bring about participatory funding raised by members within the community. In the case of Samsø Island from Denmark noted previously, the wind turbines within the community are jointly owned by the municipal authority, community residents, and small shareholders. Therefore, the case study reveals that when community residents actively participate in community co-creation and become beneficiaries of renewable energy generation facilities within the community, self-raised funding from internal members will constitute an important part of the funding. In addition, the economic benefits demonstrated as Energy Communities become more mature will continue to attract market-oriented funding. As the profit model of an Energy Community gradually matures with development, it can attract private capital and investments from financial institutions to achieve technological innovation and scale expansion, thereby further advancing the community's energy transition goals. For example, when large-scale community projects such as community microgrids need to be built or the community's integrated energy system needs to be optimized, new funding can be obtained through this channel.

4.2. Exploration of atypical energy communities in China

As a major energy consumer, China actively responds to international climate and energy policies, promotes energy transformation, and vigorously develops renewable energy. However, in the exploration of Energy Community cases, cases in China that are similar to the concept of European Energy Communities are neither typical nor numerous. Based on the analysis, it can be summarized as three main reasons, namely, the differences in energy systems and development priorities, variations in the maturity of market mechanisms, and disparities in community awareness and democratic levels.

First, the EU has clear policies and legal frameworks for the Energy Community. But China's energy policies mostly focus on the construction of large-scale renewable energy projects, such as the expansion of nuclear power plants, wind power generation, and the construction of large-scale photovoltaic projects.

From the perspective of electricity market mechanisms, the EU has achieved a high degree of internal market integration, with most end-users possessing the right to choose their electricity suppliers. In contrast, China's electricity market is currently in a stage of reform, where relevant mechanisms remain underdeveloped. For instance, transaction mechanisms for distributed energy resources in China's current electricity market lack sufficient flexibility, making it difficult to achieve efficient energy sharing and trading comparable to that in EU Energy Communities.

In terms of energy democracy and community co-creation, the EU Energy Community case emphasizes the broad participation of citizens in the community. Citizens should play significant

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roles in decision-making, investment, and operation of community energy projects. On the contrary, most similar practices in China are implemented in rural areas, where residents' cognition of the concept of Energy Community is relatively low. These initiatives are predominantly driven by government or corporate entities, resulting in low levels of resident participation in community co-creation.

5. Conclusion

This research examines typical case studies of Energy Communities in EU region and Africa, providing a comparative analysis of their developmental experiences and encountered challenges. The study reveals that Energy Communities in the EU, particularly in Western and Northern Europe, have well-established practices. These communities have developed within a robust policy framework and an environment of energy democracy, actively co-created by local governments, residents, and commercial developers. In the African case studies, the lack of a governance system and regulation, technological development constraints, and the lack of participation in democratic co-creation will restrict the development of Energy Communities.

Based on the case studies, the development of Energy Communities in the future needs to be guided by systematic policy guidance at national, regional, and governmental levels and under the strict supervision of local authorities and communities, combined with the integration of continuously innovating energy technologies into new Energy Communities and to enhance the participation of residents in the democratic co-creation of communities, so as to prioritize regional energy transition through distributed renewable energy sources within communities. The stable and sustainable funding needed for the development of Energy Communities will be derived from two primary sources: stakeholders with interests in future Energy Communities, and capital attracted by Energy Communities operating within scientifically systematic frameworks.

Furthermore, this study explores the atypical development of Energy Communities in China, concluding that disparities in energy systems and development priorities, varying degrees of market mechanism maturity, and differences in awareness of community democratic co-creation bring obstacles for Energy Community development in China. Pilot programs should be selected based on regional development characteristics to explore differentiated and localized approaches for Energy Communities.

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