Community Renewable Energy Systems

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Definitions

The term *Community Renewable Energy Systems* can be succinctly defined following Klein and Coffey (2016) as:

> *a project to service a group of people at the same geographic location (usually, town level or smaller) with a set of common interests, comprising a self-contained local energy supply system that distributes the energy produced locally (i.e., within the same area) by renewable energy resources; energy management systems and technologies; and methods to share the energy resources, costs, and benefits among all the stakeholders.*

Community renewable energy systems typically incorporate some form of peer-to-peer sharing of energy for enhanced efficiency, autonomy, and profits.

1 Introduction

Today, climate change and environmental pollution are significant challenges that endanger human existence, as well as the natural world. To mitigate their consequences, the global usage of energy, from production to distribution to consumption, must be radically and urgently revolutionized (United Nations, 2016). To achieve this transformation, governments, industries, and researchers are investing heavily into the development and utilization of clean, sustainable, and renewable energy sources (RES) and technologies. Since many RES such as photovoltaic (PV) panels are are distributed energy resources that can be installed locally, local communities and individual consumers are incentivized to participate in the renewable energy transformation. Community energy (CE) systems in which a community locally produces, shares, and utilizes RE have been proposed as a method to integrate and proliferate RES (Walker, 2008).

Community participation in energy systems has a long history, especially if we consider locally owned mills that harnessed and distributed the power of wind and water to the community (World Wind Energy Association (WWEA), 2016). In the 1970s, grassroots energy technology activism began to give strong impetus to establishing community energy, especially to encourage local community development and independence. However, these movements remained outside the scope of mainstream energy policies and supply systems in most countries. By the late 1990s, many governments and policy makers were beginning to realize the importance of RES and the necessity to encourage their proliferation. From around the early 2000s, community renewable energy (CRE) began to gain significant interest from governments and regulatory authorities (Walker et al., 2007).

Researchers and grassroots activists have strongly advocated and studied CRE systems (CRES) as models that emphasize and strongly encourage self-sufficiency, local determination, engagement, and empowerment (Walker, 2008). As a result, CE and CRE projects have been increasing rapidly across the world in the last decade. As of 2017, there were at least 2000 community energy projects in Europe alone (Scene, 2017; Hewitt et al., 2019). Today, community involvement in building the energy systems of the future is recognized as an important pathway for enabling an effective and inclusive energy transformation (International Renewable Energy Agency (IRENA), 2018).

This chapter describes and summarizes the current understanding of CRES. In Section 2, the basic principles of CRES are discussed, and CRES is defined and explained. Section 3 describes the benefits of CRES and the barriers that still prevent their implementation across the world. Section 4 describes the current status of scientific research and practical implementations. Section 5 concludes the chapter with a brief description of the future of CRES.

2 Principles of Community Renewable Energy Systems

2.1 Definition

CRES is essentially the economic participation, often including ownership, operation, and maintenance, of members of a defined community in a renewable energy project. Typically, CRES is limited by size and scope to smaller areas such as neighborhoods, villages, or small towns. However, this description is not sufficiently broad to explain the diverse features that characterize the numerous CRE projects and researches implemented across the world.

CRES has, in fact, been interpreted and defined in numerous ways across the world and in scientific literature, depending on the stakeholders, environmental conditions, and goals (Walker and Devine-Wright, 2008; Hicks and Ison, 2018). A report by World Wind Association (WWA), for example, proposes that the minimum requirement for a project to qualify as a CE project is that it must involve a combination of at least two of the following elements (World Wind Energy Association (WWEA), 2016):

1. Local ownership or stakeholding of the project;
2. All rights and voting control for community-based organisations; and
3. Local distribution of the social and economic benefits of the project.

However, such requirements to qualify as a CRE project could be more stringent or less stringent depending on the actual intentions and requirements to create a scalable, viable, and acceptable distributed renewable-energy-based CE project. Klein and Coffey (2016) evaluated many definitions and interpretations of the term "community renewable energy" that had been previously proposed in the literature and proposed the following all-inclusive definition:

"a project or program initiated by a group of people united by a common local geographic location (town level or smaller) and/or set of common interests; in which some or all of the benefits and costs of the initiative are applied to this same group of people; and which incorporates a distributed energy generation technology (for electricity, heat, or transportation) based on renewable energy resources (solar, wind, water, biomass, geothermal) and/or energy conservation/efficiency methods/technologies".

However, this definition misses an important component of CRES—the sharing of the RE resources among a group of people. Peer-to-peer (p2p) energy sharing enhances the community's autonomy and resilience and nearly always promotes the efficient usage of resources (e.g., by avoiding wastage). Moreover, the above definitions also do not allow for external stakeholders that have been envisaged by some researchers; Walker (2008), for example, suggested community projects to be either 100% owned by the community or developed in co-operation with the private sector. In the electricity sector, CRES may be developed by communities in partnership with governing authorities as well as private stakeholders such as retailers and utility companies (in open liberalized markets). Similar initiatives in other sectors may not only be possible but also critical for a CRE project's success.

Hence, following the lead of Klein and Coffey (2016), but allowing ownership by external stakeholders as well as internal p2p energy sharing, a CRES can be redefined more broadly as follows:

> *A project or program initiated to service a group of people who are united by a common local geographic location (usually, town level or smaller) and/or set of common interests; that incorporates a self-contained and self-sufficient local energy supply system characterized by distributed generation based on renewable energy resources (solar, wind, water, biomass, geothermal, etc.) and/or energy conservation/efficiency methods/technologies; and in which the produced energy resources, costs, and benefits as well as the project costs are distributed among all the stakeholders including customers, private players, governing authorities, and/or other investors based on some agreed criteria.*

There are two important points to note about this definition. First, the only restriction on how the energy resources, costs, and profits are to be shared is that there should be some form of agreement among all the stakeholders. Typical approaches would be to use some criteria such as fairness, justice, efficiency (cost or distribution), and societal welfare. Secondly, the role of local energy exchanges with some level of co-operation is emphasized. Figure 1 illustrates such a CRES.

2.2 Sharing of local energy

CRES is based on the generation and sharing of locally produced energy. There are two important ways in which RE can be produced locally, depending on the environmental and geographical conditions that dictate the most suitable type of RES for the locality.

Decentralized/distributed production Decentralized production is particularly applicable when the ideal local RES is PV. Customers who install PV panels and produce energy share their excess energy with other members of their community. Various models can be applied to provide appropriate remuneration to the community, depending on energy production and usage (Narayanan, 2019).

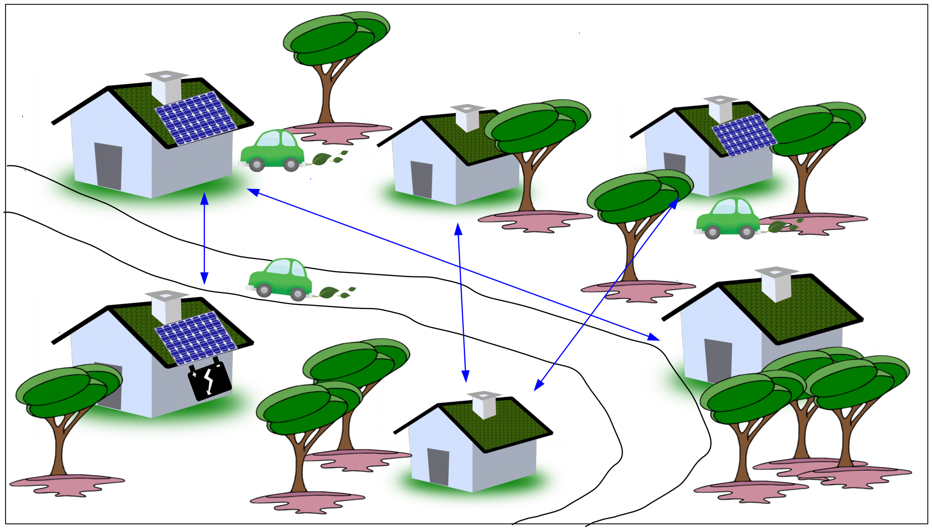

Figure 1: A community renewable energy system. Here, a local community participates in producing and distributing energy, often exchanging renewable energy among themselves.

Centralized production In cases where other forms of RE, such as wind energy or hydropower, are more appropriate, centralized power plants are established. Electricity is then distributed to the community similarly to the main electricity grid. The costs and revenue are shared among the participants.

In both cases, the locally produced energy can be shared using the available distribution infrastructure. The important question when energy is shared and used in this manner is as follows—how can the costs and revenues be distributed among the community participants? Several methods from broad fields such as game theory and auctions have been applied to enable the optimal distribution of the local resources (Narayanan, 2019). Theoretic approaches model the problem by considering cost minimization. For example, if we consider cost minimization in the case of a single customer, we have the following objective:

$$\sum_{i=1}^{n}\left(min\left\{\int_{t=1}^{t=T}(C_{cust_i}(t)-R_{cust_i}(t))dt\right\}\right) \tag{1}$$

where $C_{cust_i}(t)$ refers to the cost to the i^{th} customer in the community $(i = 1, ..., n)$ at time t, and R_{cust_i} refers to the revenue earned by the customer at t. Here, there are totally n customers, and each customer's cost is minimized separately.

The total customer costs can also be minimized as follows:

$$min\left\{\int_{t=1}^{t=T}\sum_{i=1}^{n}\big(C_{cust_i}(t)-R_{cust_i}(t)\big)dt\right\} \quad (2)$$

3 Benefits and Barriers

CRES have many well-known benefits and advantages over the traditional isolated distributed energy systems. In a comprehensive article, Walker (2008) described the benefits of (and barriers to) community-owned means of energy production and use. Brummer (2018) summarized the current knowledge gathered from practical implementations of CE projects in the United States, the United Kingdom, and Germany and presented the benefits and barriers that hinder CE in practice.

Based on these and other studies, the benefits of CRES are summarized as follows:

1. **Economic benefits** (Klein and Coffey, 2016; Brummer, 2018):
   (a) *Decreased cost of energy*: Because of better energy utilization, energy sharing decreases the cost of energy for the customer.
   (b) *Income source*: Local producers can sell excess energy and gain additional income.
   (c) *Local employment*: CRE projects could potentially provide various employment opportunities to the community.
2. **Improved energy delivery** (Chakraborty et al., 2015; Mengelkamp et al., 2017):
   (a) *Better energy utilization*: Energy sharing improves energy utilization since it avoids wastage of surplus RE resources.
   (b) *Energy delivery networks*: CRES not only reduces the need for costly network expansion but also helps to reduce congestion in distribution networks (e.g., electricity transmission networks).
   (c) *Losses*: CRES can also reduce energy delivery losses. For example, if the community shares and utilizes electricity locally among themselves, electricity is transferred over shorter distances, thereby reducing power losses.
3. **Community building** (Brummer, 2018):
   (a) *Community identity*: By encouraging communities to become self-reliant and self-sufficient, CRES helps to build a stronger community identity.

(b) *Ownership*: Shared ownership and self-utilization of community resources can increase citizen partnerships in community activities and build a sense of co-operation and togetherness.

(c) *Autonomy and independence*: CRES are more autonomous because they do not rely on the main networks for energy. This can promote and improve a culture of independence and responsibility.

4. **Reliability and resilience**:

   (a) *Emergencies*: CRES are typically built to ensure that energy networks, such as electricity networks, can be seamlessly partitioned into self-sustaining island networks in emergencies (Yuan et al., 2017).

   (b) *Customer comfort and safety*: Because CRES can operate locally and independently from the main network, they can help to ensure customer safety and comfort during emergencies that pose risks to human life, such as storms.

5. **Promotion of sustainable energy**:

   (a) *Local investments*: CRES participants are encouraged to invest in RES such as PV panels because of potential monetary benefits. This increases the proliferation of RES, thereby enabling sustainable practices and a cleaner environment.

   (b) *Awareness*: CRES can lead to higher awareness of sustainable energy issues, leading to changes in societal norms, which, in turn, can facilitate the transition to a low carbon society.

6. **Social benefits**:

   (a) *Rural upliftment and energy poverty elimination*: Across the world, energy poverty is a bigger problem in rural areas than in urban areas. Often, this is because rural energy-connection programs receive low priority especially since it is challenging to connect less populated remote villages incrementally to existing networks. Rural communities can benefit strongly from localized CRES. Moreover, since the people in rural areas also typically tend to be very community-oriented, they are also likely to embrace them. Rural CRES, in turn, benefit the region and society as a whole.

   (b) *Equitable tariff systems*: Since CRES is localized, it is easier to establish equitable tariff systems that ensure that vulnerable customers have lower energy consumption bills or other benefits.

   (c) *Improved welfare*: Better, equitable, and accessible energy through CRES leads to improved health, well-being, and happiness. Moreover, CRES strengthens support networks and social infrastructures, reducing social and other ancillary costs.

Unfortunately, the implementation of CRES faces several barriers that can be classified into the following broad categories (Walker, 2008; Brummer, 2018):

1. **Institutional barriers**
   (a) *Legal problems*: It is often very difficult and time-consuming to obtain governmental permissions.
   (b) *Energy policies*: Current legislation and policies in many countries do not always support or encourage CRE projects and programs.
   (c) *Market regulations*: Energy market regulations in many countries do not always support or encourage the implementation of CRE projects.
2. **Economic barriers**
   (a) *Revenue adequacy*: Generally, communities themselves do not have sufficient financial resources to build a CRE project.
   (b) *Financial support*: Lending institutions are not always willing to support new and uncertain models like CRES.
   (c) *Billing and metering arrangements*: Complicated metering and billing arrangements often create entry barriers, especially in rural areas.
3. **Technical barriers**
   (a) Designing and implementing CRES while keeping the viewpoints of multiple stakeholders and their requirements, costs, and benefits is difficult.
   (b) More research is required to efficiently solve complicated issues such as fair distribution of the profits achieved by the community.
   (c) Achieving optimal economic and social outcomes is difficult, especially due to diverse preferences and behaviors.
   (d) Control methods and energy management systems required to manage local networks and ensure high quality of energy supply are not easy to develop or implement in practice.
4. **Stakeholder commitment**
   (a) Customers may be unwilling to co-operate or form a community due to social reasons such as conflicts or discrimination, or personal reasons such as individuality or privacy concerns.
   (b) Energy networks and providers (e.g., utility companies) may be unwilling to take risks in setting up an uncertain environment that may lead to technical network issues with insufficient compensation.
   (c) Private players are often unwilling to invest in unproven businesses, especially when there is no clear risk versus return analyses.

(d) Governments can be unwilling to risk failure, especially when other high-stakes events—such as elections—are impending.

Despite these barriers, CRE projects have become attractive to many stakeholders and market players. Several CRE projects have been implemented across the world, including experimental setups and on-field demonstrations.

4 Current Status

4.1 Introduction

More than 1200 publications on CES were published between 2004 and 2013 alone (Koirala et al., 2016). Moreover, there are now numerous operating CRE projects, ranging from small-scale solar energy projects in Germany, wind energy projects in Denmark, to small-scale, rooftop solar in Australia (Hicks and Ison, 2018). European countries, especially United Kingdom, Scotland, Germany, Denmark, and Spain, have become worldwide pioneers in establishing CE initiatives (REScoop, 2019). As of 2017, there were at least 2000 CE projects in Europe alone (Scene, 2017; Hewitt et al., 2019).

Researchers into CRES first proposed and established theoretical frameworks for achieving effective practical implementations. Subsequent research then kept pace with the increasing number of demonstrations and deployments, focusing on solving the social and technical challenges that hinder successful implementations (Koirala et al., 2016).

4.2 Social research

Social aspects and topics are an important focus of many researches (van der Schoor and Scholtens, 2019). For example, *public acceptance* has been a useful and widely applied framework to examine the impact of CE projects and the challenges. Is the community itself ready or willing to build CE-based systems and projects? The growing consensus is that even when people have strong preference for CRE, they are hesitant about installing RE infrastructure within their own communities, especially due to uncertainties regarding cost, viability, and other impacts. It is critical to build confidence among community members that the project is workable and more beneficial than the status quo. The chances of community acceptance are higher if the community already lacks energy access or if the costs are shared by another authority, e.g., the government (Bauwens and Devine-Wright, 2018; Woo et al., 2019; Schumacher et al., 2019).

According to Hewitt et al. (2019), another useful framework to examine CE projects is *social innovation*. Earlier, bigger companies and governments were driving CE innovation and projects. However, today, most CE models tend to be participatory and inclusive. They are often community initiatives or partnerships and closely tied to citizens' concerns around the democratization and decentralization of energy. New initiatives have also moved from focusing only on electricity, emphasizing holistic solutions such as waste reduction and circular economies. A motivator for this movement is that a clean environment enabled by renewable energy is a right that citizens should enjoy, rather than a market commodity that has to be traded (Hewitt et al., 2019).

4.3 Economic research

To realize CRES, it is necessary to answer a range of economic questions especially if they are based on p2p exchanges. An important question, for example, is the equitable and fair distribution of RES among the community members. In the case of centralized energy production, the costs of producing the RES must be shared among the community members in an equitable manner. In the case of distributed RES where some members produce energy to share with others, they should be compensated adequately for their investments. This question has been widely examined in the case of electricity. The most common approaches for pricing and exchanging electricity are (1) market-based approaches where the participants trade energy by participating in auctions (Mengelkamp et al., 2017; Sousa et al., 2019), (2) game-theoretic methods where some fairness or other social parameters are employed to allocate costs or profits, and (3) constrained optimization methods, where various optimization techniques solve for the desired objective (Chakraborty et al., 2015; Tushar et al., 2018, 2020). A brief overview of these methods is presented below; for a more detailed recent survey, see Tushar et al. (2020).

In the market-based approach, a highly flexible market platform is established to efficiently co-ordinate self-interested consumers, prosumers, suppliers, and any other stakeholders. Early researches drew heavily on economics literature focusing on p2p markets. In a seminal article on pairwise matching environments, Wolinsky (1990) considered a game with decentralized, bilateral trading where a constant population of traders enter and exit the market in each period. Then, in 2001, Blouin and Serrano (2001) proposed a detailed p2p local market mechanism with decentralized, randomized buyer and seller matching for local energy markets. For the pricing strategy, they assumed that the value of the product is binary so that buyers and sellers offer only two values (high or low) to each other. Golosov et al. (2014) examined the Pareto efficiency of the allocation of a similar model but with perfectly divisible goods. It continues to be a challenging task to apply the advances in economic theory to establish decentralized local energy markets, because it is not easy to model energy as a tradeable good.

The most common local energy markets design is to establish a centralized approach using auctions. Auction theory has a rich literature in economics theory, and numerous models have been examined (Kalagnanam and Parkes, 2004; Mochón and Sáez, 2015). A popular method is continuous double auctions (CDAs) where a moderator conducts double auctions based on bids—buy and sell orders—from the participants via a public order book. The pricing of the product—in this case, energy—is another problem in auctions that has also been studied intensively (Nicolaisen et al., 2001). Many non-strategic and strategic pricing strategies have been presented previously, especially for bidding to a centralized double auction market, such as the baseline zero-intelligence bidding strategy (Gode and Sunder, 1993), intelligent agent-based strategies, often using some form of adaptive learning techniques after every round of auction, etc. (Ramachandran et al., 2011; Mengelkamp et al., 2017).

Another typical tool used to deal with CRES is game theory. Game theory examines models and analyses of how self-interested participants would behave in strategic interactions and about how those interactions should be structured. Since game-theoretic tools can closely imitate and model interactions among independent rational players, game theory-based methodologies have a natural application to analyze interactions among energy stakeholders and have been explored extensively. For example, game theory has attracted attention as a key analytical tool in the design of the future electric power grid, including microgrids (Chakraborty et al., 2014; Tushar et al., 2018).

Constrained optimization methods such as linear programming (LP), mixed-integer linear programming (MILP), and nonlinear programming (NLP) have also been applied to solve different problems in energy sharing. In these cases, the problems are modeled as an objective function (similar to Eq. 2) that is to be optimized with respect to some variables that are constrained by the problem's requirements (Tushar et al., 2020). A very typical problem setup has cost minimization as the objective with constraints being electric power quality or reliability. In this manner, utilizing concepts from MILP, the energy generated from a rooftop PV with battery was optimized for p2p energy trading in Nguyen et al. (2018), whereas Long et al. (2018) used constrained NLP for achieving a two-stage aggregated control to realize p2p energy sharing. Optimization techniques are sometimes NP-hard (e.g., MILP) and, hence, are especially suitable for planning problems where time and computational resources are not limited. To solve operational problems, the problem may have to be be relaxed considerably.

4.4 Technical research

It is also necessary to solve a range of technical problems to realize CRES. Many researches have proposed several methods to solve some of the problems, but a coordinated complete solution is lacking. Moreover, most solutions tend to focus on electricity alone, while problems with other RES are ignored.

An important technical challenge is to ensure that the community members do not lose access to energy. Loss of access to energy, such as electricity, has strong impacts on economy, user comforts, and human lives. At the same time, RE is a variable source so that 100% dependence on RE can lead to many outages. Planners must ensure that such outages are managed by using secondary resources. A common secondary energy resource is storage systems. In the case of small local electrical networks (microgrids), an approach used to deal with outages is to enable both isolated (islanded) operational mode as well as grid-interactive mode. The microgrid operates independently as far as possible but connects to the grid when required, thereby making the electrical network more flexible and intelligent. However, there still remains several challenges to efficiently realize this switching capability in the case of CRES without affecting the quality of electricity supply (Planas et al., 2015). Power electronic devices and control algorithms must be appropriately designed to prevent any kind of grid stability.

Many energy systems also require some kind of control algorithm that coordinates and optimizes energy usage. In the first step, planning algorithms are used to initially optimize the energy structure so that the energy system can have high efficiency (Huang et al., 2015, 2017). Control algorithms, typically referred to as energy management systems (EMS), then have to achieve a target optimization such as cost optimization subject to multiple energy delivery constraints, for example, high reliability, quality, safety, etc. The most common EMS proposed in the literature is a hierarchical system in which the problem is separated into near-independent different parts, each of which is individually handled by different control algorithms (Xu et al., 2015; Paudyal et al., 2019). Often, as in the case of small electrical networks, the levels are decided based on the time scales of operations, the devices or equipment involved, the type of problem, and the nature of the stakeholders (Guerrero et al., 2011).

A recently proposed paradigm—Energy Internet—that leverages concepts from the Internet and Internet-based communication architectures is a potential way forward to make CES more efficient. Inspired by the data Internet, the Energy Internet proposes a cyber-physical system model that virtualizes the distribution grid management using discretized packets (Nardelli et al., 2019). This concept can be adapted to community energy systems, conceptually leading to an Energy Internet of networked microgrids as shown in Fig 2.

4.5 Practical implementations

As mentioned previously, numerous CRE projects have been developed across the world, with some European countries—United Kingdom, Scotland, Germany, and Denmark—pioneering their implementations. This subsection discusses practical CRE installations across the world, which have positively impacted the community.

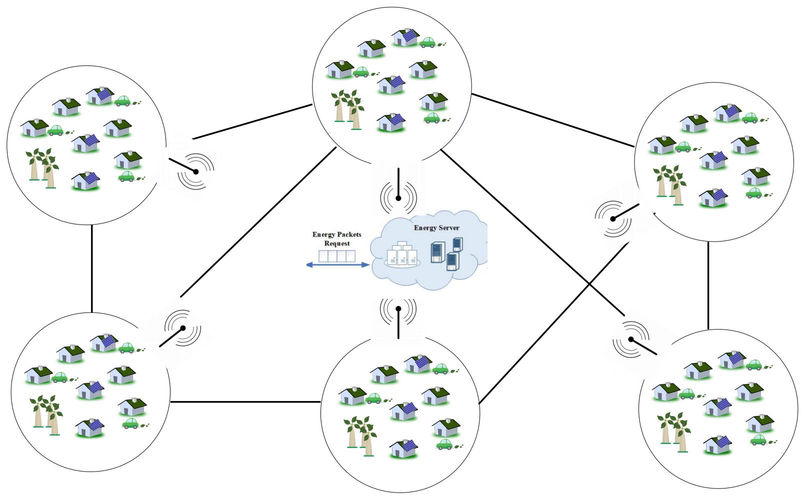

Figure 2: An Energy Internet of networked community energy systems. In this software defined energy network, the energy grid is managed using packetized energy management through a communications network infrastructure based on similar principles as the Internet.

United Kingdom In the United Kingdom (UK), the first co-operatively owned wind farm was established in Cumbria in 1996. Called Baywind Energy Co-operative, this community wind farm now has over 1,200 members (Baywind Energy Co-operative, 2019). Inspired by the success of this initiative, Energy4All was established in 2002 with the explicit aim of supporting renewable energy co-operatives (Energy4All, 2019). Energy4All now has 24 co-operatives—including wind power, solar power, biomass power and hydropwer—with more than 13,000 members. Edinburgh Community Solar Co-operative is an example of a solar-powered CRE project with 24 solar panels (generating capacity of 1.38 MW) that generate approximately 1.1 GWh of clean, renewable electricity for schools, community centres, etc. A fixed return on the members' investments is given annually to the members.

Denmark Many European countries were initially inspired by successful CRE initiatives in Scandinavian countries. Denmark, for example, has pioneered CRE by focusing on wind farms. The Middelgrunden offshore wind farm in Denmark is a large-scale CRE project that was the largest offshore wind farm in the world, when first constructed, with 20 turbines and a capacity of 40 MW. The Middelgrunden project is 50% owned by a community of 10,000 investors in the Middelgrunden Wind Turbine Cooperative (Sørensen et al., 2001).

Germany Germany has primarily focused on CRE projects based on solar energy. A leader in renewable energy proliferation in Europe, Germany has enacted many legislative policies to enable and promote energy co-operatives and citizen energy companies (Yildiz et al., 2019). Citizen and energy cooperatives' projects often receive preferential treatment, such as reduced security payments and highest feed-in-tariffs. As of 2016, there were around 1500 RE-based citizen projects of which around 55% were community owned (i.e., co-operatives). For example, in Mainz, a citizen initiative UrStrom eG was set up in in September 2010 (Urstrom eG Bürgerenergiegenossenschaft, 2019). Today, the 300-member co-operative operates 12 PV panels, producing solar power for around 100 households.

Australia In Asia, many countries—e.g., Australia, China, and India—have implemented CRE projects, despite several legislative and financial barriers. Australia and China, in particular, have attempted to systematically and actively promote CRE initiatives. For example, the Coalition for Community Energy (C4CE) was founded in Australia with the objective of surmounting the barriers to CE and motivate the proliferation of CRE systems (C4CE—Coalition for Community Energy, 2019). Their guide to solar-energy-based CRE projects lists 10 case studies of successful community solar models and includes analysis and overviews of key technical, financial, and legal factors as well as tips and lessons from their experiences (Community Power Agency et al., 2017). For example, Bendigo Sustainability Group (BSG) is a community solar project in Victoria that was established in 2007; it comprises two PV systems—a 20 kW installation at the Bendigo Library and a 11-kW system at the Bendigo Discovery Centre (Bendigo Sustainability Group, 2019).

USA The US has fewer successful CRE projects than can be expected from its size and potential because of systemic barriers, especially legal frameworks and financial incentives, that hinder their deployment (John Farrell, 2016). As of 2010, less than 5% of the total installed wind power capacity was part of a CRE project; moreover, from 2010–2015, only 3% of added wind power capacity was community owned. Note that in contrast, 85% of Denmark's wind power generation is owned by the residents of Danish communities (as of 2015). In the case of solar energy, the US had just 70 MW of community solar projects by 2015. Nevertheless, a spate of new recent CRE initiatives promise to transform the CRE situation in the US. These projects often employ widely different models. For example, the Brooklyn Microgrid is a community of PV owners and customers in which electricity is traded using a virtual blockchain-based marketplace (Mengelkamp et al., 2018). This community-driven initiative began in April 2016 and is an example of a practical implementation of p2p energy transactions (Brooklyn Microgrid, 2017).

5 Future Prospects

CRES has been a popular pathway to achieve clean energy goals across the world, but some of the roadblocks mentioned in Section 3 raise questions about its continuing viability. Although most policy makers now recognize the need for CRES and flexible local transactions, CRES is far from becoming the mainstream source of energy production (Rommel et al., 2018). At best, CRES is a niche innovation (Roby and Dibb, 2019).

New innovative business models are required to push CRES into the mainstream energy area. Current investments continue to be focused on large-scale energy production and ignore local CRES projects, primarily because the monetary value of CRES projects is still unclear. At the same time, communities either do not have the expertise or economic resources to build CRES projects, or they lack the time and energy for taking the initiative. Industry–community partnerships must be established to make CRES projects the norm rather than the exception (Eitan et al., 2019). To achieve this, it is important to develop new models that can monetize locally produced energy.

To build more efficient and cost-effective CRES projects, it is also important to integrate various RE sectors such as transport, electricity, heat, gas, etc. Current research and practice inevitably focus only on one energy sector, typically electricity, but the need of the hour is the integration of different energy systems. Further, the flexibility in energy systems must be fully exploited together so that RE usage is maximized. If energy experts manage to frame and implement holistic approaches to implementing CRES, both economic and social goals could be realized (Krog and Sperling, 2019).

Finally, the future of CRES is unclear today not only because of social and technical barriers, but also because of the slowness of regulations to encourage local RES usage. The current regulatory framework continues to create challenges for decentralised and distributed forms of energy generation. CRES has significant potential to enable a smooth transition to 100% RES-based energy systems, which is a common goal for humankind today. As a result, it is imperative for regulatory bodies and energy policy makers to support and enable technological developments that are aligned with the socio-economic aspects of CRES.

The future prospects of CRES systems will depend on the pace of changes in legislative frameworks and new research innovation. Nevertheless, the distributed nature of RES suggests that community and co-operative energy production, supply, and management will continue to have an important role in ensuring a cleaner and sustainable environment for humankind.

References

Thomas Bauwens and Patrick Devine-Wright. Positive energies? An empirical study of community energy participation and attitudes to renewable energy. *Energy Policy*, 118:612–625, July 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.03.062.

Baywind Energy Co-operative. About Us. https://www.baywind.coop/about-us-3/, October 2019.

Bendigo Sustainability Group. About us, March 2019.

Max R. Blouin and Roberto Serrano. A Decentralized Market with Common Values Uncertainty: Non-Steady States. *The Review of Economic Studies*, 68(2):323–346, 2001.

Brooklyn Microgrid. About Brooklyn Microgrid. https://www.brooklyn.energy, December 2017.

Vasco Brummer. Community energy – benefits and barriers: A comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. *Renewable and Sustainable Energy Reviews*, 94:187–196, October 2018. ISSN 1364-0321. doi: 10.1016/j.rser.2018.06.013.

C4CE—Coalition for Community Energy. About C4CE. https://c4ce.net.au/, January 2019.

Shantanu Chakraborty, Takayuki Ito, and Tomonobu Senjyu. Smart pricing scheme: A multi-layered scoring rule application. *Expert Systems with Applications*, 41(8):3726–3735, June 2014. ISSN 09574174. doi: 10.1016/j.eswa.2013.12.002.

Shantanu Chakraborty, Shin Nakamura, and Toshiya Okabe. Real-time energy exchange strategy of optimally cooperative microgrids for scale-flexible distribution system. *Expert Systems with Applications*, 42(10):4643–4652, June 2015. ISSN 09574174. doi: 10.1016/j.eswa.2015.01.017.

Community Power Agency, Pingala, Starfish Initiative, Macedon Ranges Sustainability Group, The Hub Foundation in Castlemaine, CORENA, Repower Shoalhaven, Bvendigo Sustainability Group, and Environmental Justice Australia. Small Scale Community Solar Guide. Technical report, Coalition for Community Energy, Australia, 2017.

Avri Eitan, Lior Herman, Itay Fischhendler, and Gillad Rosen. Community–private sector partnerships in renewable energy. *Renewable and Sustainable Energy Reviews*, 105:95–104, May 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2018.12.058.

Energy4All. Our History. https://energy4all.co.uk/about-us/our-history/, February 2019.

Dhananjay K. Gode and Shyam Sunder. Allocative Efficiency of Markets with Zero-Intelligence Traders: Market as a Partial Substitute for Individual Rationality. *Journal of Political Economy*, 101(1):119–137, 1993.

Mikhail Golosov, Guido Lorenzoni, and Aleh Tsyvinski. Decentralized Trading with Private Information. *Econometrica*, 82(3):1055–1091, 2014.

Josep M. Guerrero, Juan C. Vasquez, Jose Matas, Luis García de Vicuna, and Miguel Castilla. Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization. *IEEE Transactions on Industrial Electronics*, 58(1):158–172, January 2011. ISSN 0278-0046, 1557-9948. doi: 10.1109/TIE.2010.2066534.

Richard J. Hewitt, Nicholas Bradley, Andrea Baggio Compagnucci, Carla Barlagne, Andrzej Ceglarz, Roger Cremades, Margaret McKeen, Ilona M. Otto, and Bill Slee. Social Innovation in Community Energy in Europe: A Review of the Evidence. *Frontiers in Energy Research*, 7:31, April 2019. ISSN 2296-598X. doi: 10.3389/fenrg.2019.00031.

Jarra Hicks and Nicola Ison. An exploration of the boundaries of 'community' in community renewable energy projects: Navigating between motivations and context. *Energy Policy*, 113:523–534, February 2018. ISSN 0301-4215. doi: 10.1016/j.enpol.2017.10.031.

Zishuo Huang, Hang Yu, Zhenwei Peng, and Mei Zhao. Methods and tools for community energy planning: A review. *Renewable and Sustainable Energy Reviews*, 42:1335–1348, February 2015. ISSN 13640321. doi: 10.1016/j.rser.2014.11.042.

Zishuo Huang, Hang Yu, Zhenwei Peng, and Yifu Feng. Planning community energy system in the industry 4.0 era: Achievements, challenges and a potential solution. *Renewable and Sustainable Energy Reviews*, 78:710–721, October 2017. ISSN 13640321. doi: 10.1016/j.rser.2017.04.004.

International Renewable Energy Agency (IRENA). Community energy: Broadening the ownership of renewables. Technical report, IRENA, Abu Dhabi, UAE, 2018.

John Farrell. Beyond Sharing: How communities can take ownership of renewable power. Technical report, Institute for Local Self-reliance, April 2016.

Jayant Kalagnanam and David C. Parkes. Auctions, Bidding and Exchange Design. In Frederick S. Hillier, David Simchi-Levi, S. David Wu, and Zuo-Jun Shen, editors, *Handbook of Quantitative Supply Chain Analysis*, volume 74, pages 143–212. Springer US, Boston, MA, 2004. ISBN 978-1-4757-1074-8 978-1-4020-7953-5. doi: 10.1007/978-1-4020-7953-5_5.

Sharon J.W. Klein and Stephanie Coffey. Building a sustainable energy future, one community at a time. *Renewable and Sustainable Energy Reviews*, 60: 867–880, July 2016. ISSN 13640321. doi: 10.1016/j.rser.2016.01.129.

Binod Prasad Koirala, Elta Koliou, Jonas Friege, Rudi A. Hakvoort, and Paulien M. Herder. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renewable and Sustainable Energy Reviews*, 56:722–744, April 2016. ISSN 13640321. doi: 10.1016/j.rser.2015.11.080.

Louise Krog and Karl Sperling. A comprehensive framework for strategic energy planning based on Danish and international insights. *Energy Strategy Reviews*, 24:83–93, April 2019. ISSN 2211-467X. doi: 10.1016/j.esr.2019.02.005.

Chao Long, Jianzhong Wu, Yue Zhou, and Nick Jenkins. Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid. *Applied Energy*, 226:261–276, September 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2018.05.097.

Esther Mengelkamp, Philipp Staudt, Johannes Garttner, and Christof Weinhardt. Trading on local energy markets: A comparison of market designs and bidding strategies. In *European Energy Market (EEM), 2017 14th International Conference on The*, pages 1–6. IEEE, 2017.

Esther Mengelkamp, Johannes Gärttner, Kerstin Rock, Scott Kessler, Lawrence Orsini, and Christof Weinhardt. Designing microgrid energy markets: A case study: The Brooklyn Microgrid. *Applied Energy*, 210:870–880, January 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2017.06.054.

Asunción Mochón and Yago Sáez. *Understanding Auctions*. Springer Texts in Business and Economics. Springer International Publishing, Cham, 2015. ISBN 978-3-319-08812-9 978-3-319-08813-6. doi: 10.1007/978-3-319-08813-6.

Arun Narayanan. *Renewable-Energy-Based Single and Community Microgrids Integrated with Electricity Markets*. Doctoral thesis, Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland, November 2019.

Pedro H. J. Nardelli, Hirley Alves, Antti Pinomaa, Sohail Wahid, Mauricio De Castro Tome, Antti Kosonen, Florian Kuhnlenz, Ari Pouttu, and Dick Carrillo. Energy Internet via Packetized Management: Enabling Technologies and Deployment Challenges. *IEEE Access*, 7:16909–16924, 2019. ISSN 2169-3536. doi: 10.1109/ACCESS.2019.2896281.

Su Nguyen, Wei Peng, Peter Sokolowski, Damminda Alahakoon, and Xinghuo Yu. Optimizing rooftop photovoltaic distributed generation with battery storage for peer-to-peer energy trading. *Applied Energy*, 228:2567–2580, October 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2018.07.042.

J. Nicolaisen, V. Petrov, and L. Tesfatsion. Market power and efficiency in a computational electricity market with discriminatory double-auction pricing. *IEEE Transactions on Evolutionary Computation*, 5(5):504–523, October 2001. ISSN 1089778X. doi: 10.1109/4235.956714.

Priti Paudyal, Prateek Munankarmi, Zhen Ni, and Timothy M. Hansen. A Hierarchical Control Framework with a Novel Bidding Scheme for Residential Community Energy Optimization. *IEEE Transactions on Smart Grid*, pages 1–1, 2019. ISSN 1949-3053, 1949-3061. doi: 10.1109/TSG.2019.2927928.

Estefanía Planas, Jon Andreu, José Ignacio Gárate, Iñigo Martínez de Alegría, and Edorta Ibarra. AC and DC technology in microgrids: A review. *Renewable and Sustainable Energy Reviews*, 43:726–749, March 2015. ISSN 13640321. doi: 10.1016/j.rser.2014.11.067.

Bhuvaneswari Ramachandran, Sanjeev K. Srivastava, Chris S. Edrington, and David A. Cartes. An Intelligent Auction Scheme for Smart Grid Market Using a Hybrid Immune Algorithm. *IEEE Transactions on Industrial Electronics*, 58(10):4603–4612, October 2011. ISSN 0278-0046, 1557-9948. doi: 10.1109/TIE.2010.2102319.

REScoop. Community Energy Map—European Projects. https://www.rescoop.eu/european-projects, November 2019.

Helen Roby and Sally Dibb. Future pathways to mainstreaming community energy. *Energy Policy*, 135:111020, December 2019. ISSN 0301-4215. doi: 10.1016/j.enpol.2019.111020.

Jens Rommel, Jörg Radtke, Gerrit von Jorck, Franziska Mey, and Özgür Yildiz. Community renewable energy at a crossroads: A think piece on degrowth, technology, and the democratization of the German energy system. *Journal of Cleaner Production*, 197:1746–1753, October 2018. ISSN 0959-6526. doi: 10.1016/j.jclepro.2016.11.114.

Scene. Energy Archipelago—A Global Community Energy Platform. https://scene.community/blog2/the-end-for-now-energy-archipelago, November 2017.

K. Schumacher, F. Krones, R. McKenna, and F. Schultmann. Public acceptance of renewable energies and energy autonomy: A comparative study in the French, German and Swiss Upper Rhine region. *Energy Policy*, 126:315–332, March 2019. ISSN 0301-4215. doi: 10.1016/j.enpol.2018.11.032.

Hans Chr Sørensen, SPOK ApS, Jens Hansen, Per Vølund, and Haslev Denmark. Experience from the establishment of Middelgrunden 40 MW offshore wind farm. page 5, 2001.

Tiago Sousa, Tiago Soares, Pierre Pinson, Fabio Moret, Thomas Baroche, and Etienne Sorin. Peer-to-peer and community-based markets: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 104:367–378, April 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2019.01.036.

Wayes Tushar, Chau Yuen, Hamed Mohsenian-Rad, Tapan Saha, H Vincent Poor, and Kristin L Wood. Transforming energy networks via peer to peer energy trading: Potential of game theoretic approaches. *arXiv preprint arXiv:1804.00962*, 2018.

Wayes Tushar, Tapan K. Saha, Chau Yuen, David Smith, and H. Vincent Poor. Peer-to-Peer Trading in Electricity Networks: An Overview. pages 1–1, 2020. ISSN 1949-3061. doi: 10.1109/TSG.2020.2969657.

United Nations. Paris Agreeement. Technical report, United Nations, Paris, France, January 2016.

Urstrom eG Bürgerenergiegenossenschaft. Homepage. https://www.urstrom.de/index.php, February 2019.

Tineke van der Schoor and Bert Scholtens. The power of friends and neighbors: A review of community energy research. *Current Opinion in Environmental Sustainability*, 39:71–80, August 2019. ISSN 18773435. doi: 10.1016/j.cosust.2019.08.004.

Gordon Walker. What are the barriers and incentives for community-owned means of energy production and use? *Energy Policy*, 36(12):4401–4405, December 2008. ISSN 03014215. doi: 10.1016/j.enpol.2008.09.032.

Gordon Walker and Patrick Devine-Wright. Community renewable energy: What should it mean? *Energy Policy*, 36(2):497–500, February 2008. ISSN 0301-4215. doi: 10.1016/j.enpol.2007.10.019.

Gordon Walker, Sue Hunter, Patrick Devine-Wright, Bob Evans, and Helen Fay. Harnessing Community Energies: Explaining and Evaluating Community-Based Localism in Renewable Energy Policy in the UK. *Global Environmental Politics*, 7(2):64–82, May 2007. ISSN 15263800. doi: 10.1162/glep.2007.7.2.64.

Asher Wolinsky. Information Revelation in a Market with Pairwise Meetings. *Econometrica*, 58(1):1, January 1990. ISSN 00129682. doi: 10.2307/2938332.

JongRoul Woo, Sungsam Chung, Chul-Yong Lee, and Sung-Yoon Huh. Willingness to participate in community-based renewable energy projects: A contingent valuation study in South Korea. *Renewable and Sustainable Energy Reviews*, 112:643–652, September 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2019.06.010.

World Wind Energy Association (WWEA). Headwind and Tailwind for Community Power. Technical report, Germany, February 2016.

Xiandong Xu, Xiaolong Jin, Hongjie Jia, Xiaodan Yu, and Kang Li. Hierarchical management for integrated community energy systems. *Applied Energy*, 160:231–243, December 2015. ISSN 0306-2619. doi: 10.1016/j.apenergy.2015.08.134.

Özgür Yildiz, Boris Gotchev, Lars Holstenkamp, Jakob R. Müller, Jörg Radtke, and Laura Welle. Consumer (Co-)Ownership in Renewables in Germany. In Jens Lowitzsch, editor, *Energy Transition: Financing Consumer Co-Ownership in Renewables*, pages 271–293. Springer International Publishing, Cham, 2019. ISBN 978-3-319-93518-8. doi: 10.1007/978-3-319-93518-8_13.

C. Yuan, K. Lai, M. S. Illindala, M. A. Haj-ahmed, and A. S. Khalsa. Multilayered Protection Strategy for Developing Community Microgrids in Village Distribution Systems. *IEEE Transactions on Power Delivery*, 32(1):495–503, February 2017. ISSN 0885-8977, 1937-4208. doi: 10.1109/TPWRD.2016.2544923.