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Perspective

DC Communities: Transformative Building Blocks of the Emerging Energy Infrastructure

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Abstract: Serious environmental concerns call for revolutionary solutions to cope with the harmful effects of the conventional energy landscape. Therefore, residential and commercial customers require cleaner and more reliable energy sources as they become more dependent on energy for daily and critical needs. In this case, transitioning to a cleaner energy economy is of paramount importance for both the environment and the utilities as well as the end-users. The desired transformation will require the deployment of massive amounts of clean energy sources. Many of these resources, such as solar photovoltaic (PV), provide electricity in the form of direct current (DC) that enables the return of DC grids to the electric power arena. The electric system has slowly transitioned to DC, mainly on the demand side. In recent years, modern electronic devices, lighting systems, and an increased number of appliances (≈22% of the residential and commercial loads) have adopted DC systems. Studies suggest that DC loads would account for more than 50% of the available loads in the next few years. Furthermore, the growing proliferation of electric vehicles influx is another example of a successful DC application. From this perspective, the viability of returning to the DC distribution system in the form of DC community grids is explored. We start by defining the DC community grid, which is followed by introducing the benefits of adopting DC at the distribution level. Finally, a summarizing outlook of successful pilot cases, projections of DC community deployment, barriers and concerns, strategies to address barriers and concerns, and suggestions for future research directions are presented. This perspective could shed new light on the building blocks of the transformed energy landscape for various stakeholders.

Keywords: DC power system; DC microgrid; DC community; distribution grid; energy infrastructure

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1. Introduction

Global efforts to address the U.N. Sustainable Development Goals are calling for fundamental transformation of the current energy infrastructure [1]. The world is facing challenges to disrupt a century-old utility business model while undergoing a profound transition toward a green energy economy [2]. The opportunity for policy makers to encourage a structural and accelerating decline of power sector emissions is still available [3]. Modernizing and upgrading electricity infrastructure is critical for the power grid to become more inclusive, intelligent, resilient, reliable, sustainable, digital, and secure [4]. Previous studies suggest that achieving a 100% renewable energy generation in the next three decades is possible [5,6], which will require substantial installation of renewable energy systems (RESs) and large-scale deployment of energy storage systems (ESSs) [7–9]. One of the most promising RES technologies is solar photovoltaics (PV); it is projected that solar PVs will be the primary source of energy in the future, reaching penetrations at terawatt levels [10]. Solar PVs are also expected to be able to cover about 30–50% of the world's energy needs [11].

The aforementioned transformation of the energy landscape encounters significant challenges such as (i) maintaining the stability and reliability of the electric system under high penetration of renewables due to renewable resource variability and their intermittency nature, (ii) allocating enough resources that are able to cope with the dramatic ramp-up and ramp-down of renewable generation and dynamic load, (iii) increased ON and OFF cycles of fossil-fueled generators, and (iv) improving efficiency, resiliency, and affordability [12].

To address these challenges, many solutions have been proposed [13–15]. One of the solutions that is gaining momentum nowadays is the transition from AC to DC power systems. Studies have highlighted the advantages of DC over AC at different levels [16]. *At the generation level,* the grid requires centralized generation to be AC power, which, in the case of intrinsically DC generation such as solar PV [17], causes loss of efficiency during the conversion. *At the transmission level,* from the break-even overhead transmission distances of 300–800 km and offshore/underground transmission distances of 50–100 km, the DC power system is more advantageous in terms of lower losses, reduced costs, longer distances coverage, smaller cross-sectional area of conductors, and lower power line right-of-way [18]. *At the distribution level,* the literature provides a long list of benefits including reduced losses, improved voltage control, improved transfer capacity, and increased distributed generation hosting capacity [19–21]. *At the utilization level,* new DC distributed energy generation and DC microgrids can be easily integrated into the grid, which facilitates the participation from users, large (businesses) or small (residents), in demand–response programs. Other benefits of DC grids include a reduction in electricity costs, the exclusion of reactive power and frequency management, the freedom of DC systems from current surges, harmonics, skin, and proximity effects [22]. The elimination of AC/DC conversions for appliances can improve the efficiency significantly [23]. Therefore, modernized DC systems can achieve better coordination and allocation of resources compared to AC systems (these are required conditions for the energy transformation). Moreover, planning, operation, and control are also simpler for a DC grid.

The DC community concept outlined in this perspective holds the potential to address the specific needs of a community in terms of resiliency, robustness, and power quality at distribution to utilization levels. The key enabling technologies of DC grids have seen continuous advances. For instance, DC-DC converters have been widely used in high-voltage DC (HVDC), medium-voltage DC (MVDC), the automotive industry, renewable energy, telecommunications, and consumer electronics [24]. Research on the transition from the present AC infrastructure to DC concludes that it is not only viable but beneficial [21,25]. Surprisingly, even though the main source of power in the future is foreseen to be DC, there have been inadequate efforts toward transforming the predominantly AC network into DC. Over the recent years, DC power systems have slowly reclaimed their share of energy generation level (e.g., PV) [26], transmission level [18] (i.e., HVDC), and applications (electronics, appliances, electric vehicles (EVs) etc.) [27]. The only sector that DC has not yet gained a serious role in is at the distribution level [23], although it is an actively researched area [28]. This perspective aims to lay out the roadmap for a future vision of the DC community.

After exploring the viability of returning to the DC distribution system in the form of the DC community grids in Section 1, the rest of this perspective's structure includes defining the DC community grid in Section 2, which is followed by introducing the benefits of adopting DC at the distribution level in Sections 3 and 4. Finally, Section 5 summarizes an outlook of successful pilot cases, projections of DC community deployment, barriers and concerns, strategies to address barriers and concerns, and suggestions for future research direction are presented.

2. What Is a DC Community?

In Table 1, the relevant terms of DC electric power technologies are described. This provides a context of DC communities (DC-COMs). There are similarities between DC microgrids (DC-MGs) and DC-COMs. Both operate at the MVDC to LVDC level and are part of the distribution grid. Both involve RES, ESS, and other components. Conceptually, a DC-COM differs from a DC-MG. DC-MGs are largely self-sufficient electric systems that manage their generation and storage resources locally. A DC-COM may host one or more DC-MGs and can benefit from the coordination of the embedded microgrids. However, DC-COMs are not necessarily self-sufficient, and there may be no microgrids within a DC-COM. Therefore, DC-COMs are not equivalent to networks of DC-MGs.

Table 1. Relevant terms of DC power systems.

Relative Terms	Explanation and Features
HVDC	• High-voltage direct current (HVDC) is a technology used to transmit electricity over long distances using overhead transmission lines or submarine cables. Projects in operation range from 100 to 1100 kV.
MVDC	• Medium-voltage direct current (MVDC) is a technology used to transmit electricity. It is suitable for network reinforcement, integration of renewables, connection of islands and medium-voltage grids, etc. Suppliers offer voltages ranging from 24 to 50 kV, which can deliver powers from 30 to 150 MW [28].
LVDC	• Low-voltage direct current (LVDC) is a technology intended to feed the "last mile" of the distribution network with voltages ranging from 100 to 1500 V [29].
DC Distribution Grid	• Can be defined as a DC bus connected to various sources (AC grid, renewable sources, energy storage systems) and loads (electronics, lighting systems, variable frequency drives, etc.) [30].
MG	• A microgrid consists of a group of loads, distributed generations, and energy storage systems that can be (1) connected to the utility grid (UG), (2) interconnected with other MGs, (3) connected to the UG and other MGs, and (4) in island mode. • MGs can be formed in multiple formats: AC (ACMG), DC (DCMG), and hybrid AC/DC [31]. • Voltage levels within an MG are typically in the ranges of LVDC and MVDC.
DC load	• A DC load is an electric unit that receives DC current from a power source in order to operate (computers, speakers, electronics, EVs etc.).
AC load	• An AC load is an electric unit that receives AC current from a power source in order to operate (household appliances, motors etc.).
Prosumer	• A prosumer is an individual or business that can produce electricity that can be sold or provided to another entity as well as consuming it.
Consumer	• A consumer is an individual or business that consumes electricity in different ways based on the demand.
DG	• A distributed generation (DG) is a group of electrical distributed energy resources (DER) and energy storage activities operated by a range of small, grid-connected, or distribution system-connected devices [32,33].
ESS	• An energy storage system (ESS) is a system in which the process of capturing energy produced at one time for use at a later time. The device that stores energy is commonly known as a battery.

Geographically, a DC-COM could be a small town/city, an industrial park in rural area, or a functional district in urban area. Electrically, a DC-COM can be abstracted as a node in the sub-transmission or distribution grid, i.e., consisting of the portion of the electric grid downward from a distribution substation. As illustrated in Figure 1, the interface between a DC-COM and the AC power grid is a bi-directional AC/DC converter. Within the boundary of a DC-COM, there are multiple residential and commercial end-users. Some of the end-users may form DC-MGs that are relatively independent. Some may have RES or ESS installed. However, the majority rely on the DC-COM grid, which is supplied by community-level ESSs and the utility grid.

A DC-COM can be easily embedded in the existing AC distribution network to serve a cluster of residential and commercial consumers and prosumers, as well as critical facilities such as emergency shelters, electric vehicle charging stations, hospitals, etc. The rationales of DC-COM development are two-fold. First, the end-users within a community are heterogeneous, and it is not realistic to require all households to upgrade to prosumers or all businesses to be equipped with MG technologies. Community planners need to make a long-term, comprehensive deployment plan. This plan needs a framework that has taken the heterogeneity into consideration. DC-COM has a fit there. Second, new communities to be built in the future can also adopt DC-COM prototypes.

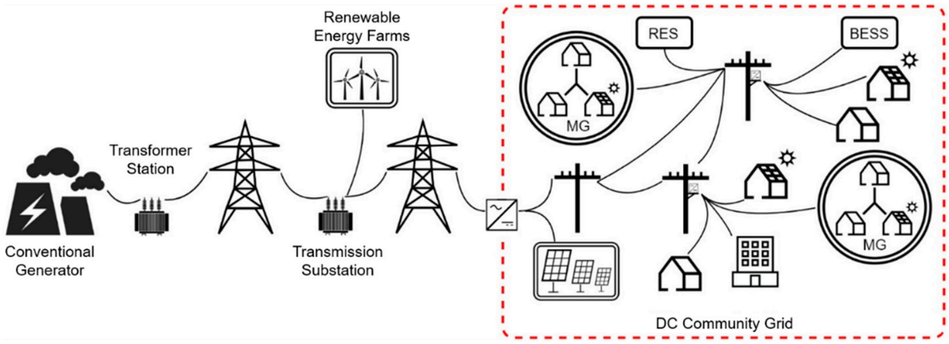

Figure 1. Schematic of DC community perspective. The DC-COM can autonomously operate from the AC grid or interconnect with the AC grid seamlessly.

The potential benefits of DC-COMs are summarized in Figure 2. DC-COMs will typically allow a high penetration of RES (not necessarily within the community). It serves as a "buffer" to reduce the impacts of RES variability and load fluctuations on the power system, therefore maintaining the overall system stability while minimizing the curtailment of renewable generation. Some RES generation and the end-users of a DC-COM will have a higher efficiency thanks to the elimination of conversions. For prosumers, the DC-COM can provide a local marketplace that may be designed to be more profitable than directly transacting with the utility grid. Finally and probably most importantly, the DC-COM architecture enhances the robustness and resiliency of the power supply within the community. Similar to MGs, the attainment of a certain level of independence through distributed generation and energy storage [34] can be crucial when the main grid fails. Inside a DC-COM, with the increase in DC-MGs, the DC-MGs can also be coordinated and dispatched to improve community grid reliability and resilience. In this sense, DC-COMs, DC-MGs, and the AC utility grid can coexist in a symbiotic relationship where all entities can benefit from each other and operate independently when circumstances arise.

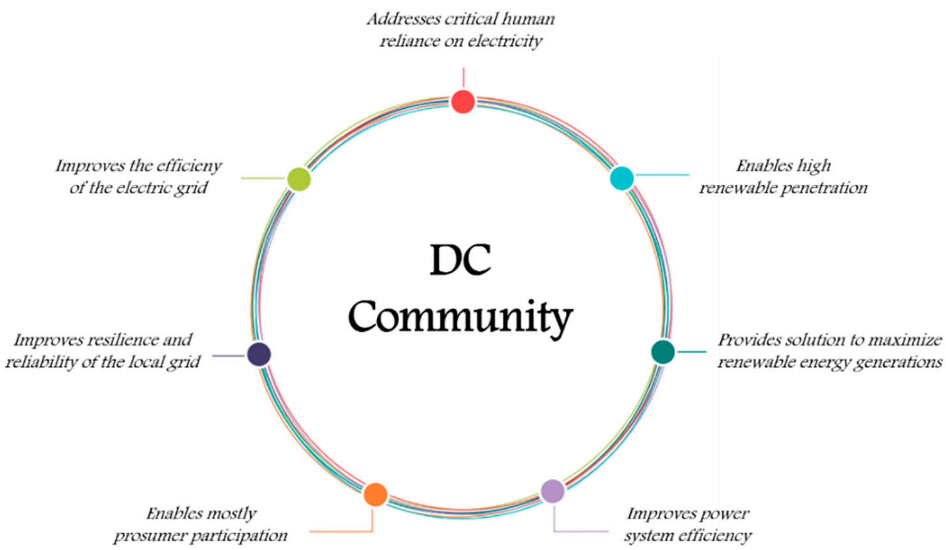

Figure 2. Characteristics of the DC community. DC-COM provides better coordination and allocation of resources. DC-COM has many design advantages at the community level that include the phases of planning, operation, and control.

3. Technological Viability

DC-COM is not only beneficial, it is also applicable and feasible. This section provides a brief overview of the recent advancement as well as the envisioned research and development on DC grids with the objective of identification and discussion of the viability of DC-COM. DC grids at various voltage levels are discussed. For more details, please refer to [22]. The battle of the currents began in the late 19th century: the DC-Team represented by Thomas Edison and the AC-Team represented by Nikola Tesla and George Westinghouse [35]. The first DC community grids were introduced by Edison in New York City in 1882. Eleven years later, Westinghouse won a bidding contract to supply the World's Fair in Chicago City, IL, USA with the then-new type of current, the AC. Since then and for over a hundred years, the AC system has proven to be the preferred solution, which has expanded to every corner of the world. However, it seems that the battle of currents is not over yet! Recent technological advances have demonstrated that DC systems can still bounce back. HVDC power lines have been built for long-distance, large-capacity transmission. Several DC-MGs have been developed and tested around the globe. One of the most prominent efforts is being done by Emera Technologies and Sandia National Laboratories in Albuquerque, NM, USA. These projects tend to be small in scale compared to the proposed concept of DC-COM. Nevertheless, the increased population of DC-MGs in the future is likely to become a bottom–up approach to reaffirm the viability of DC-COM from the supply side.

On the other hand, although it is not very evident to the observers, DC systems recently have been adopted widely, mainly in the form of the final loads. Studies suggest that about 22% of loads in the residential and commercial U.S. sectors use the DC form of electricity, especially in modern electronics and lighting systems. With the adoption of variable speed drives in motors, which are now mostly used in refrigeration systems, projection analyses suggest that DC loads could grow up to 52.1%. The recent advances in power electronics and the significant reduction in renewable energy and battery costs are enablers for DC systems deployment. These indicate that the DC-COM is not only compatible but also desired from the demand side.

4. Challenges and Potential Solutions

Barriers for the large-scale implementation of DC-COMs are mostly beyond the technological issues. Most technologies needed for the implementation of DC-COMs are commercially available. However, the main challenges that nowadays face the DC-COM deployment originate from (1) a lack of clear definition of the strategies for the large-scale deployment of DC solutions at the community level; (2) a lack of guidelines to ensure that systems are optimally designed and operated considering the community-specific conditions and (3) a lack of incentives and demonstration project results for the community members to voluntarily support DC-COM transition that can provide stable, reliable, and affordable power supply.

To address these challenges, we propose a hierarchical design methodology for the planning and operation of DC microgrids and DC communities. In our proposed approach, each newly added system to the grid/community (i.e., a new DC-MG) must be optimally planned and not only reflected as a stand-alone element but taking into consideration the community context. Applying the DC-COM concept by starting with the most effective initial market which is in regions where solar energy has high potential (i.e., sunbelt) would be beneficial, especially when no changes are required by the customer or new home constructions. Furthermore, it would offer a valuable solution to the metering issue. For instance, adopting this format in the United States could have a significant impact by increasing solar power technologies deployment by 5 GWs annually (≈50% increase). The DC-COM may include other microgrids, renewable resources, consumers, and prosumers and may be subject to variable energy rates, current infrastructure constraints, vulnerability to weather conditions, local weather conditions, etc. The planning and operation phases should be hierarchical, i.e., Level 1: microgrid level, Level 2: interconnected microgrid level, and Level 3: community level.

On the planning side, the pursued goals would be set clearly in order to allocate the resources deployed within the DC-COM. The most critical target at this stage is to maintain a community with the maximum reliability and resilience. *On the operation side*, multiple system configurations could be applied within DC-COM; microgrids, as a part of the community, could operate separately, covering the users' (consumers and prosumers) energy needs. A cluster of MGs could interconnect with each other (the same concept as teamwork); whenever a requirement in one MG is not met, another MG can be called for support. *On the control side*, since both planning and operation phases are tiered, the DC-COM response to real-time changes with no delay is mandated. With the advancement in DC power systems [36], DC-COM components are reliable to deal with sudden and emergent changes as the new technologies facilitate the transformational opportunities in the energy landscape. DC communities would be optimized, combining the hierarchical phases of planning and operation of a fully distributed control design. Such configuration would allow the DC-COM system to be very simple, modular, and scalable to any size using new trending technologies (machine learning, artificial intelligence, and game theory) where every module is an active agent.

5. Outlook and Conclusions

In this perspective, the future of electricity infrastructure is reimagined with a new concept of DC-COM based on the simple, modular, efficient, and reliable DC technology. The DC-COM would leverage the development of (i) material improvements in power electronics and decreases in their costs, (ii) substantial reductions in ESS costs, (iii) more costs decline in solar energy-harvesting technologies, and (iv) DC form of electricity growing to be the dominant format in communities. The focus of the DC-COM notion is on the long-standing challenges and requirements such as (1) rising costs of electricity, (2) critical reliance of the society on electrical energy, (3) strong demand for cleaner energy sources, and (4) problems that face the optimum integration of RES into the existing electric grid.

For newly developed DC buildings at both residential and commercial levels, many prior works have embedded DC loads within MGs, appliances, lightings, motors, and other electronics [37–41]. Moreover, an expandable, reconfigurable, and renewable DC-MG for grid-independent communities was modeled in [42]. With these enriched research efforts, there are many challenges at the present situation that include the following major gaps: (1) the demand for more resources at both planning and operation stages for the interconnected DC microgrids with the constraints of the existing infrastructure, (2) the need for more demonstration sites and testbed projects to validate current solutions, and (3) the necessity of a framework that sets the roadmap for DC microgrid planning and operation in medium-sized communities.

The proposal of the framework of DC-COM with multiple consumers, prosumers, and DC-MGs is only the beginning. These concepts can be further expanded when considering multi-energy and poly-generation foundations. Here, electricity is not the sole concern; there are many other issues that require investigation such as heating, refrigeration, local production of biofuels, heat and cold storage, and local water desalination. All of these and probably many others should be added to the mix. These additions can help make communities be more self-sufficient while improving the efficiency and operational cost aspects.

The main objective of this perspective is to set a starting point for researchers, utilities, industry, and other stakeholders to build up solutions that will help steer the energy systems to be more secure, resilient, clean, and affordable in the near future. In addition, there are few more aspects that cannot be ignored while planning for a better future of electricity such as (i) the security of communities against cyber-attacks, since everything is now connected in the modern IT world, (ii) architecting the standards and policies set to legislate the actions within the DC-COMs, and (iii) the entities' responsibilities toward the attractive incentives provided to the participants as encouragements.

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