The Electric Power System's Missing Intermediate Scale

Jeffrey P. Price
OnGrid Options, LLC
6830 Elm Street
McLean, Virginia 22101
www.gridoptions.com
(703) 448-3400

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Abstract

The North American electric power system now faces unprecedented challenges: it must simultaneously serve fast-growing loads, increase reliability and resilience, decarbonize, and deploy new and increasingly digital technologies. All this must be achieved while continuing to provide affordable electric service.

Meeting all these challenges will require major changes to the electric grid, which is currently composed of both large- and small-scale structures. These scales were originally created because they had significant advantages, but solutions to the current challenges at these scales are inadequate and unaffordable. Intermediate-scale grid structures are clearly needed but are missing. This missing intermediate scale can be affordably and rapidly created by adding community-scale structures to the existing grid.

The Electric Power System's Missing Intermediate Scale

Jeffrey P. Price
OnGrid Options, LLC
jeffprice@gridoptions.com

The electric power sector in North America faces the unprecedented challenge of rapidly and simultaneously achieving several difficult and intertwined goals:

1. Serving rapidly-growing loads,
2. Ensuring reliability and creating resilience,
3. Decarbonizing major sectors of the economy, and
4. Deploying new technologies throughout the sector.

All this will require massive investments in the electric grid. Critically, electric power is already the most capital-intensive economic sector. Improvements to the electric grid must be affordable to the public, to businesses, and to critical infrastructure. This will require making efficient investments. That will be a challenge.

This paper describes how the current electric grid system is composed of either very large or very small entities, and how a system with entities only at these scales makes simultaneously achieving all the goals extremely difficult and expensive. It then explains why adding an intermediate scale would make achieving all the goals more affordable and likely and how that scale can be created.

Challenges of Achieving the Goals

Each goal is ambitious, will create challenges, and will require significantly increased investments.

Rapid Load Growth. Electrification of every electricity consuming sector—transportation, buildings, and industry—is planned.[1] Data center electricity use is expected to vastly expand. The Edison Electric Institute, for example, projects that the 4 million EVs on the road in 2023 will reach 26.4 million by 2030, more than a sixfold increase.[2] All this will require vastly more resources and extensive grid enhancements.

Reliability and Resilience. Reliability has long been a central focus of the electric power sector. Extended outages with severe, large-scale impacts have occurred, spurring growing concerns about resilience.[3] Outages have been caused by extreme natural conditions and by man-made disruptions. Current methods of improving resilience—hardening the electric power grid, recovery plans, collaboration among utilities, and microgrids—all help, but have limitations. These methods are often expensive, cover only limited infrastructure and some threats, and each typically addresses a single threat. Yet, protecting everything from every threat is infeasible and unaffordable.

Decarbonization. Distributed Energy Resources (DERs), renewables, and other clean energy resources are planned to achieve decarbonization and other goals. At the same time, many, if not

[1] For example, John D. Wilson and Zach Zimmerman, "The Era of Flat Power Demand is Over," Grid Strategies LLC, December 2023, forecasts 4.7% annual increase in loads to 2028 compared to 0.5% annually over the previous decade.

[2] Edison Electric Institute, "Electric Vehicle Sales and Charging Infrastructure Required Through 2030," June 2022.

[3] There is no universally-accepted definition of electric system resilience. Most definitions, however, include concepts related to withstanding and recovering from power outages.

most, dispatchable fossil resources may retire, potentially creating resource adequacy problems.[4] Vast numbers of new resources will be needed.

Deploying New Technologies. The electric grid is undergoing its most profound technological transition in over a century. Renewable and DER technologies are increasingly being deployed; electric grid technologies are changing and becoming digital; dependence on data and digital communications is increasing and moving to the consumer sites on the distribution grid; and new approaches such as artificial intelligence are being used to address diverse issues. Vast numbers of small entities will challenge large, top-down controls.

Growing Investment Needs

Achieving all four goals will entail large investments in new clean energy sources, transmission and distribution, and other grid-related technologies. Investments are needed for electricity generation and storage, electric transmission and distribution, control and protection systems, end-use technologies, and electrification. Only a fraction of this investment can be expected to be covered by government funding. The power industry and consumers must also make large and unprecedented investments to achieve the goals.

International Energy Agency projections of investments needed in the United States by 2050 show $4.5 trillion of electric and end-use sector investments needed from 2024 through 2030.[5] Even more investment will be required afterward. End-use sector investments are also needed for electrification, DER, and energy efficiency. Reducing investment needs will decrease financial impacts on consumers and increase the probability of achieving all the goals.

One of the largest investment needs will be for transmission to bring renewable energy long distances from where it is abundant to where it is needed. Transmission investment must be for more than just carrying renewable energy, however. The transmission system is aging and needs to be modernized. In 2022, US transmission investment was $26.7 billion,[6] mostly to improve reliability. Investments needed both to carry renewable energy and for reliability are likely to greatly increase in coming years.

Inadequacy of Only Large and Small Scales

Over more than a century, the electric grid in the continental United States and Canada has grown from local utilities with independent grids to four major interconnections: Eastern, Western, ERCOT, and Quebec. Each interconnection is a unified alternating current system synchronized as a whole with various types of entities responsible for balancing loads and resources and maintaining frequency within the interconnections.

Large scale evolved because it enabled economies of scale, the reliability of interconnections and diverse resources, and efficient wholesale power markets. Increasingly, the disadvantages of very

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[4] For example, the North American Electric Reliability Corporation, "2023 Long-Term Reliability Assessment," December 2023, projects future electricity supply shortfalls in areas where generator retirements are expected before adequate replacement resources are in place.

[5] International Energy Agency, "World Energy Investment 2024," June 2024. https://www.iea.org/reports/world-energy-investment-2024/united-states.

[6] https://www.eei.org/-/media/Project/EEI/Documents/Resources-and-media/bar_actual_and_projected_trans_investment.pdf.

large scale are becoming apparent. Large scale requires vast investments, and it complicates efforts to address resilience by presenting multiple points of vulnerability and broadening the impacts of disruptions. It also poses challenges to the control of vast numbers of DERs.

RCGs are inherently part of the transmission network. This opens new possibilities for siting facilities, providing new services, and lowering costs. Large scale renewable energy generation—solar, wind, hydropower, and geothermal—is usually sited where those resources are abundant, have lower cost, and permits can be obtained, which may be distant from loads they can serve, requiring the electricity they generate to be sent over transmission lines to distant loads.

On a smaller scale, facility or campus microgrids are also being implemented and more are proposed. Backup generators are also used for many facilities and, increasingly, individual homes. Both microgrids and backup generators serve only that one facility and often have only one potentially interruptible energy source. DERs of various types are being implemented at many facilities, including many homes.

To deal with these concerns and provide a platform for load growth and DER, many enhancements of current grid structures are being implemented to improve capacity, visibility, and control. New grid architectures based on a distinction between transmission and distribution systems have also been proposed. Some involve creating new organizations such as Transmission Companies (Transcos) and Distribution Companies (Discos) each operating separately but in coordination, an approach similar to that in the European Union.[7] These may better enable use of DER, but top-down control may become more difficult, interdependent critical infrastructure are usually at different locations, and changes to transmission and distribution must be coordinated.

The usually unasked question is whether the large scale of the current grid coupled with the small scale of distributed systems is adequate to meet the needs of the communities in which most people live and work and to feasibly and affordably achieve the goals of the electric system. It is not. An intermediate scale at the community level would reduce investment requirements, best support new technologies, and assure reliability and resilience.

Creating an Intermediate Scale at the Community Level

The missing intermediate scale must be created and be financeable. It must enhance, not replace, the existing grid structure, thus preserving the advantages of both large and small scales. It must also incorporate evolving technologies and increasing consumer requirements and loads, cost-effectively support critical needs, enable rapid recovery during large-scale outages, and provide a better platform for renewables and DERs. This will be a very tall order.

Current Approaches to Intermediate Scale. Two intermediate scale solutions have previously been proposed, Virtual Power Plants (VPPs) and community microgrids. Neither addresses all of the challenges. VPPs address the challenge of incorporating DER into the marketplace and offer some controls. Still, VPPs don't address resilience because they don't deal with threats and interdependence of critical infrastructure. There is no commonly-accepted definition or implementation of community microgrids other than that they typically serve multiple relatively

[7] See https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en.

proximate electricity consumers. Except for remote communities, most do not serve the interdependent critical infrastructure needed to assure community resilience.

Creating a Viable Intermediate Scale. A control system for temporarily balancing the grid at intermediate scale under emergency conditions would enable targeted and flexible control of individual circuits, loads, and resources at both the transmission and distribution levels, and it could reduce investment needs. As circuit conditions, power needs, and resource availability change, the system could respond as required. Even in a severe regional outage, power could come from where it is available on selected protected circuits and flow to where needed for critical infrastructure on those circuits. Resources on those protected circuits would have higher value.

The Resilient Community Grid. A new intermediate-scale grid structure operating at the community level, the Resilient Community Grid (RCG) would be an overlay to the existing transmission and distribution grid at this intermediate scale to enable it to better meet all the challenges. An RCG consists of a local section of an electric transmission and distribution (T&D) network containing both power generation and interdependent critical infrastructure facilities that can, when necessary, be "islanded" to operate independently of the rest of the T&D network. Generation and storage assets within an intermediate-scale grid system will operate as part of the broader regional power grid system under normal conditions but will operate as a secure island under independent control when the overall regional power grid is down.

An RCG has an independent control, communications, and cybersecurity system that does not operate and is not visible under normal conditions. RCGs incorporate advanced technologies and operational procedures for greater control, deeper grid visibility, enhanced cybersecurity, and hardening against multiple physical threats, both natural and man-made. Multi-threat hardening could prioritize protection of the electric loads most critical to communities and the nation. RCGs can also be high-value platforms for renewable energy and DERs, by enabling them to contribute to community resilience. The RCG can further be a resource to black start the regional grid in the event of a widespread outage.

RCGs would include selected T&D assets and may include both central-station generation and DERs as well as other resources such as demand-response, energy storage, and microgrids. RCGs would use these nearby resources to provide electricity to critical infrastructure serving the community, first responder, and national interests during broad regional outages.

Building Relationships. RCGs will need to interact in various ways with other types of entities on the electric grid—balancing authorities, utilities, consumers, and microgrids. All must benefit.

Balancing Authorities (BAs) are responsible for meeting North American Electric Reliability Corporation (NERC) standards for operations planning, balancing demand and resources, and maintaining interconnection frequency in real time for the bulk power system within their areas. A total of 70 active BAs operate in North America, including 61 in the United States, 8 in Canada, and one in Mexico. BAs in the United States include eight ISOs and RTOs, federal organizations, utilities, and independent organizations.[8] In Canadian provinces, BAs are provincial-scale organizations (other than in Manitoba where the BA is an ISO that also serves parts of the US).

[8] In the US beyond the eight ISOs and RTOs, it's complicated. Six BAs are operated by federal organizations and 39 by utilities of various types and sizes. Eight small BAs are operated by power plant companies. See https://www.eia.gov/electricity/930-content/EIA930_Reference_Tables.xlsx.

RCGs need to coordinate with the BAs that operate the transmission grid within which the RCG operates. RCGs assume control from BAs when regional outages occur and return control when the outages are over. This requires communication between the RCG and the BA and protocols for transfer of control.

RCGs will often serve facilities on distribution systems which are typically much more local than BAs and have their own distribution management systems operated by the local utility. Increasingly, utility-operated Distributed Energy Resource Management Systems (DERMS) are also being implemented. RCGs must also coordinate with the utilities that operate these systems.

RCGs will generally be owned and operated by BAs or electric utilities. Utilities also own the transmission and distribution systems over which RCGs are implemented and have existing relationships with retail customers, including critical infrastructure. Utilities will require adequate and fair compensation for RCG-related costs. In the US, both Federal Energy Regulatory Commission (FERC) and state utility regulatory commissions may be involved in ratemaking for the RCG depending on location and type of utility.

The facilities served by the RCG will generally be owned by a subset of a utility's customers. Many will be critical infrastructure, often the utility's largest customers. RCGs can also create opportunities to enhance utility relationships with customers and communities by providing more resilient service at lower costs to the customers and communities, by increasing the usefulness and value of DER, and by promoting economic development.

An RCG can include microgrids, but it is not the same thing. Microgrids typically operate independently of the regional power grid under both normal and outage conditions. The grid system within an RCG is BA-controlled under normal conditions but shifts to RCG control during an outage.[9] Microgrids can be nested within an RCG, thus creating an even-stronger layered defense against threats. Also, a microgrid can serve as a resource for the RCG. Microgrids typically serve only one facility. By contrast, an RCG can serve the entire community.

Microgrids typically connect with the utility distribution system through points of common coupling and switch between connected and independent operation at those points of common coupling. RCGs, by contrast, are an integral part of the T&D system and can have switching capabilities for islanding at multiple transmission substations.

Reducing Investment Needs and Financing Costs

An RCG can reduce investment needs by using existing facilities and allowing the sharing of costs among multiple protected critical infrastructure and electric consumers. This lowers investment needs while dealing with interdependence vulnerabilities within the electric sector and with other sectors. It has the important advantage of being a higher-value platform for DER. It would not replace or eliminate either larger BAs or microgrids but would complement them. Since RCGs serve entire communities, they leave no one behind or unfairly impacted. RCGs are feasible in

[9] BAs are responsible for meeting NERC standards for resource planning and maintaining demand and resource balance as well as interconnection frequency in real time.

many—but not all—geographic locations. Part of what makes them feasible is that generation and storage assets as well as critical loads often cluster around the community load centers they serve.

Most of the investments to achieve the four electric system goals would likely be made by utilities using their usual methods, which would vary with the type of utility: investor owned, public power, or cooperative. Appropriate use of new technologies coupled with prioritization RCGs provide can reduce total investment needs. Some investments may also be made by critical infrastructure owners served by the RCG. Critical infrastructure investments might include, depending on the financial structuring of the RCG and specific needs, demand response equipment, self-generation or storage, and its own internal communications and controls.

The likely participation of diverse entities in the RCG also creates opportunities to lower the cost of capital for investments in the RCG. For example, one potential form for the RCG is a Public Private Partnership (PPP). These have been widely used to reduce the costs of public infrastructure developed privately because they can enable the use of tax-exempt bonds. PPPs can be structured in diverse ways. It may also be possible for an RCG to facilitate lease financing where off-the-balance-sheet financing of equipment is most desirable or where leasing lowers the cost of capital.

A further method for reducing the financing costs of RCGs for investor-owned utilities and ratepayers could be securitization. Securitization requires the state legislature to enact a law authorizing the state utility regulatory commission to issue a non-revocable "financing order" enabling a utility to create a Special Purpose Entity (SPE) to issue bonds that are more secure than other utility debt. The SPE is given an "intangible property right" to collect payment from the utility through a rate surcharge regardless of whether the utility defaults on other debt. Neither the state nor the utility regulatory commission may rescind or change this intangible property right. Due to higher security, these bonds are typically rated AAA enabling lower interest rates, which provide savings for both the utility and ratepayers. Utility debt securitization has been used in many states for purposes such as storm damage recovery, environmental compliance, and the recovery of stranded costs.

Yet another possible means of financing RCGs that may be particularly appropriate for public power utilities is the use of "resilience bonds." These bonds are a type of financial instrument offered mostly by reinsurance companies as a means of financing claims after a disaster. Resilience bonds link insurance coverage to investments in infrastructure that reduces risk, providing a "resilience rebate" for reducing risk, for example, building a seawall or flood barrier.[10]

Using the Transmission System to Reduce Investment Needs

Although intermediate in scale and sometimes involving distribution circuits, RCGs are inherently part of the transmission network. This opens new possibilities for siting facilities, providing new services, and lowering costs. Large scale renewable energy generation—solar, wind, hydropower, and geothermal—is usually sited where those resources are abundant, have lower cost, and permits can be obtained, which may be distant from loads they can serve. The electricity generated by these renewable resources can be sent over transmission lines to distant loads. More transmission capacity will also be needed to serve rapidly-growing electric loads. Many proposals have been

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[10] Shalini Vajjhala, "Financing Infrastructure through Resilience Bonds," Brookings Institution Commentary, December 16, 2015 at https://www.brookings.edu/articles/financing-infrastructure-through-resilience-bonds/.

made for new transmission lines, but they need to be justified economically, permitted, and built, an extremely long, very arduous, and often uncertain process.[11]

Transmission lines that carry the output of large-scale renewable resources may pass through or near communities with an RCG and may be part of the RCG. Transmission lines that serve other purposes such as balancing loads and generation, improving reliability, or facilitating electricity markets may also pass through or near communities with an RCG. Transmission lines often serve multiple purposes and may need to be built or increased in capacity for more than one purpose.

Future transmission investments will likely grow very rapidly to meet the needs to carry renewable energy from areas of abundance to areas of load, potentially over vast distances including over High-Voltage Direct Current (HVDC) lines and across interchange borders, creating an even larger electric grid, sometimes called a "macrogrid." Electric transmission permitting and siting can pose challenges, especially with its regulation still evolving and controversial.[12] Investments in distribution, clean energy resources, energy storage, electrification, communications and control systems, grid hardening, and resilience will also need to grow rapidly.

Various methods have been proposed to reduce investment needs for transmission. These include grid enhancing technologies and advanced conductors and cables, as well as greater deployment of local resources such as local power plants, energy storage, DER, and microgrids. As a Department of Energy report notes, many forecasts of transmission needs have been made and results vary, but all show substantial needs for new transmission, even with transmission alternatives deployed.[13] Further methods to reduce transmission investments by better enabling community needs to be met by local resources would be very helpful.

RCGs could reduce investments required for transmission by providing resources closer to the loads, either within the RCG's community or further down the transmission line. Moreover, by providing resources within the communities they serve, costs could be better allocated to those who benefit, and benefits from sales to others could be realized by communities that invest in an RCG. This is particularly important for transmission when generation resources are in one state and the consumers who benefit are in another.

Transmission lines and communities with RCGs could potentially benefit each other, regardless of whether their purpose is to carry renewable energy or serve other purposes. The transmission lines could bring some of the low-cost output of renewable resources into the RCG's community, and resources within the RCG could potentially add to those available to the transmission lines. If needed, the RCG could also provide black start capabilities to the broader grid. Moreover, some of the RCG's threat protections could potentially be extended along transmission lines outside the RCG, creating economies of scale and making the broader regional grid more secure. Co-financing may also be possible. The benefits of such arrangements could potentially help with permitting transmission lines through the communities they would benefit. Agreements for this would need to be negotiated between RCGs and transmission line owners.

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[11] See US Department of Energy, "National Transmission Needs Study," Washington, DC, October 2023.
[12] For example, FERC Order 1920 (http://ferc.gov/media/e1-rm21-17-000) issued May 13, 2024, has been opposed by the National Association of Regulatory Utility Commissioners (NARUC) and is likely to face further legal challenges.
[13] US Department of Energy, *op. cit.*

Improving Resilience with Lower Investments

Large scale has long provided reliability advantages to the electric system. Scale brings redundancy, operational flexibility, and diversity of resources. Those advantages led to the creation of four synchronized electric interconnections in North America and to large ISOs and RTOs. Today's resilience concerns, however, are about very different and more extreme risks including black sky events.[14] New and evolving risks, rapid load growth, increasing interdependence, and changing technology create resilience challenges that differ from traditional reliability problems. A large scale may not be the solution and, indeed, it may be a vulnerability.

Cost-Effectiveness. Resilience at an intermediate scale is much more cost effective than each facility making independent investments. Indeed, many facility owners would likely not want or be able to make substantial investments to improve the electricity resilience of their own facilities. RCGs have the potential to provide greater resilience to more critical infrastructure facilities at a lower cost to each. This makes it more likely that corporate boards, public-sector decision makers, and regulators can be convinced that participation in an RCG is justified. Community-wide resilience also gives communities served by RCGs an economic development edge in attracting businesses such as data centers and process industries requiring very high electricity reliability.

Protecting Critical Infrastructure. While evolving technology has improved grid operations by providing greater control and visibility, it has also created new challenges and vulnerabilities. Simple solutions are more difficult and ineffective for larger, more complex, and interdependent systems. All these factors together can cause longer-term outages made worse by interdependence among critical infrastructure and electricity.

RCGs provide protection against threats for which neither large scale nor small size helps. Protection against multiple threats can be done most cost-effectively at an intermediate scale. Resilience concerns are about unprecedented events triggered by extreme, evolving, and unexpected threats or combinations of threats. Scale does not necessarily help and may even exacerbate those events. By contrast, RCGs can prioritize what is most important, thus simplifying the problem and reducing the cost of the solution.

Against threats to multiple and interdependent criterial infrastructure and communities, the best defense is neither large nor small scale. Rather, critical infrastructure and communities are best protected through reduced interdependence, redundancy and diversity of supply, hardening of both the critical infrastructure and the elements of the grid that connect them, layers of defense, independent operability of sections of the grid, and prioritization. Everything cannot be defended from every threat. A targeted focus would produce the greatest benefits. RCGs create or enhance defenses for what is critical—and, importantly, without losing the advantages of scale.

Addressing Critical Infrastructure Interdependence. The intermediate scale of an RCG—larger than a microgrid but smaller than an ISO/RTO or utility service territory—also makes protection of the electricity supply to interdependent critical infrastructure easier and less costly. One of the greatest vulnerabilities of crucial infrastructure is their interdependence. Complex webs of

[14] A "black sky" event is a catastrophic event that severely disrupts the normal functioning of critical infrastructure in a wide area for long durations. Examples may include extreme storms, multi-site coordinated physical and/or cyber-attacks, major earthquakes, extreme geomagnetic storms, and combinations. See President's National Infrastructure Advisory Council, "Surviving a Catastrophic Power Outage," December 2018.

interdependence can create multiple modes of common failure.[15] Electricity is the most widely needed input to the 16 critical infrastructure sectors.[16] Much, but not all, interdependence is within communities. Neither regional grids nor microgrids address this interdependence. By protecting multiple local critical infrastructure and the local grid serving them, RCGs cost-effectively reduce interdependence vulnerabilities. In addition, and importantly, RCGs could also assist in the restoration of the broader grid during a regional outage.

Adding Layers of Cybersecurity. Different control, communications, and cybersecurity systems would also be a major cybersecurity enhancement. While the RCG's operation will need to be coordinated with the operation of the entire grid, both the RCG's control system and its cybersecurity would be different and separate from those of the local utility and ISO/RTO control and cybersecurity systems**.** RCG control and cybersecurity systems would not be used except during outages, making them invisible and unreachable to potential hackers at all other times. Separate control and cybersecurity systems significantly reduce the vulnerability of single systems creating widespread interruptions such as those caused by the July 2024 CrowdStrike update.

Creating Local Resource Diversity. Intermediate scale broadens the scope and creates cost-effective diversity of power supply to individual communities. Virtually no individual microgrid alone can provide this resource diversity; it would simply be too expensive. Renewables plus energy storage may be used in microgrids but can be expensive to serve the critical round-the-clock loads of a single facility. Since the RCG serves a number of critical infrastructure facilities significant to a community, central station power plants, emergency generators, energy storage, local renewable resources, and DER can cost-effectively create the needed diversity.

More Cost-Effectively Deploying New Technologies

Affordably serving rapidly-growing loads will require the electric sector to meet higher expectations than before, and it will need to do so with new and evolving technologies. Renewable resources, DER, energy storage, and new control and communication systems all support both load growth and decarbonization. They each have higher value at the intermediate scale and can be more broadly and affordably deployed where they can be used to improve the resilience of both critical infrastructure and host utilities and can help black start the grid. RCGs thus create ideal platforms for the grid interconnection and operation of both centralized and distributed resources.

RCGs create new financially-viable aggregation opportunities, thus broadening the base of potential investors. Electric vehicles are usually charged at the distribution level and can also be used as storage resources at that level. An intermediate scale grid would also maximize DER value by enabling DER to provide new, valuable, and compensated services to their communities.

The RCG control system balances supply and demand at a more granular level than most BAs. It can be more responsive to the variability of renewables, facilitate aggregation at a level and locations that best serve communities, and effectively manage unexpected behaviors of numerous independent agents. Similarly, smaller amounts of energy storage can have a greater benefit balancing renewable variability in an intermediate scale system.

[15] Shannon Prier et. al., "Interdependence Across the National Critical Functions," Rand Corporation Homeland Security Research Division, Report WR-A210-1, January 2023.
[16] See https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors.

RCGs significantly broaden the locations where solar energy and energy storage can be developed for a community. These locations do not have to be at or even near the consumer's site. This can create economies of scale and locational advantages such as proximity to substations. It lowers costs, optimizes benefits, eases grid integration, and allows a broader range of ownership and financing options, but could involve a local permitting process.

Many solar installations have inverters that do not operate during outages. By powering distribution lines and feeders with solar during an outage, RCGs can use those solar installations to benefit the community, the resource owner, and the regional grid. Balancing supply and demand at a more granular level would be more responsive to the variability of solar.

Multiple new technologies with which the electric power sector does not have much experience will be used, and the operations of those technologies will often need to be coordinated with each other and the grid. Some of the new technologies, such as artificial intelligence (AI), can have unexpected behaviors. The impact of such unexpected behaviors can be compounded if the coordination results from interactions among the participating entities independent of the grid. This can best be addressed at an intermediate scale, thus limiting cascading effects.

Both the grid and electricity markets are changing in ways that may alter their behavior and how they influence each other. Historically, the grid has behaved in a manner that system scientists call "coherent behavior." That means that it acts in such a well-understood and predictable manner that it can be managed using large-scale, unified, top-down methods. A different set of system behaviors is what system scientists call "complex system behavior."[17] Complex system behavior consists of different behaviors at different scales that could make top-down control extremely difficult. Complex system behavior could materialize as large numbers of very small independent participating entities enter the grid and power markets, especially if guided by AI and capable of communicating directly with each other. Complex system grid behaviors could require different control systems and incentives best implemented at an intermediate scale to ensure reliable, resilient, and cost-effective operation throughout the entire grid.

Conclusion

The electric power sector faces multiple unprecedented challenges in achieving the goals society has set for it: rapid load growth, high reliability and resilience, decarbonization, and deploying new technologies. Achieving the goals is especially vital as society becomes even more dependent on electricity. All this will require massive investments from both the electric sector and consumers.

While both large and small scales offer advantages, lack of an intermediate scale makes simultaneously achieving all the goals more difficult and expensive. Intermediate scale can be created by using local transmission and distribution circuits as well as existing and new resources to serve, at a minimum, the community's critical infrastructure and to better host its DER.

Financing requirements to achieve all the goals will be extensive. Intermediate scale creates opportunities to reduce financing requirements by effectively using existing facilities and the transmission system, enabling cost sharing, prioritizing investments, and using targeted financing

[17] A non-technical description of complex system behavior can be found in Yaneer Bar-Yam, Making Things Work: Solving Complex Problems in a Complex World, New England Complex Systems Institute, Cambridge, MA, 2004.

methods such as PPPs and resilience bonds. Importantly, RCGs use the local transmission system to reduce total investment needs.

Reliably serving rapidly-growing loads while incentivizing, integrating, and controlling vast numbers of new small-scale technologies such as DERs poses a particularly difficult challenge to the large scale of the existing electric grid. The value of those technologies would be much greater within an intermediate scale grid structure. Improved reliability, resilience, and integration of new technologies could, in many locations, be most effectively and affordably delivered at the intermediate scale. RCGs uniquely provide the needed intermediate scale grid structure.

Only the intermediate scale of RCGs enables resilience by cost-effectively protecting interdependent critical infrastructure within a community. The vulnerabilities of interdependent critical infrastructure within large scale grid structures can only be addressed by protecting the entire grid, which is clearly infeasible. Small scale does not address interdependence. Microgrids and other distributed generation resources benefit only the facilities they serve, leaving those facilities vulnerable to interruptions of other facilities and not providing needed resilience.

Both large-scale and small-scale have advantages and will continue to benefit electric systems, but an intermediate scale must be added to affordably and effectively meet all the challenges.