The Bottom-Up (R)Evolution of the Electric Power System

The Pathway to the Integrated-Decentralized System

By Lorenzo Kristov

THE POWER SYSTEM OF THE FUTURE IS A WORK IN PROGRESS. How it eventually looks and works, its architecture, and its key participants' roles and business models will be the outcomes of trends, forces, and policies at play today and the decisions and actions of many diverse actors in the energy transition.

The author envisions a major role in the future power system for distribution-connected energy resources (DERs) of all types, on both sides of the customer meter, participating in local distribution-level markets, with each defined electrically by a single interface between distribution and the

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bulk power system. The term to describe this system is *integrated decentralized*—thousands of local distribution areas operated by distribution system operators (DSOs), all connected to the bulk power system to trade and move wholesale energy and provide reliability services.

The integrated-decentralized system is decentralized in a layered fashion (see Figure 1): an individual smart building within a microgrid, within a DSO's local distribution area, that is connected to transmission in its balancing area, which is connected to its peers to make up the regional interconnection. The entity at each layer performs an appropriate optimization to fulfill its role and manage interchange between it and the next layer above and next layer below. The system is fully integrated because the end users within the DSO service areas, and the DSOs in performing their own roles, all benefit from participating in the bulk power system's markets and services.

At first glance, this may appear not too different from how the power system works today and in many ways it isn't that different. A crucial exception is that power flows are no longer just one way from the bulk system to the end-use customer, some implications of which this article explores. Most points of interconnection (POIs) and end-use meters, on the distribution system or the bulk grid, may both inject and consume power and can switch smoothly between these modes. These features, along with the arrival of cost-effective energy storage at various scales, change everything. At a minimum, they require updating distribution systems and their operation. From the perspective of the bulk system and wholesale market operator, they suggest that each transmission and distribution (T&D) interface on the bulk system could switch storage-like between acting like a load node and acting like a supply node.

This article explains why the integrated-decentralized grid is a compelling vision of the future power system, a plausible and desirable convergence of the trends, forces, and policies in play. This end state is not yet worked out in detail, however, and its evolution is not proceeding at the same rate everywhere. Depending on decisions and actions of key actors—especially in the legislative and regulatory realms—the energy transition could be more or less chaotic, the power system could be more or less resilient for a more volatile future, and society could be more or less successful in achieving clean, sustainable energy practices.

The Dynamics of Power System Evolution

A complex system, whether created by human effort or arising organically in nature, evolves in response to multiple forces affecting various levels of the system. A whole-system perspective on the power system views all levels from the regional interconnection down to the individual end-use customer meters as a single integrated system, a system whose architecture should foster and deliver a set of desirable system attributes and performance characteristics that enable the system to achieve the societal objectives set out by policy makers to address a set of identified needs.

The identified needs that the system must serve will change over time. For most of the 20th century, societal needs emphasized industrial growth, universal access to electric service, growth of cities and suburban areas, and expansion of the consumer economy. Policy makers and industry participants addressed those needs through the vertically integrated electric utility structure and the one-way-power-flow operating paradigm, where real power generated by large power plants flowed one way over distribution wires to serve the exogenous demands of end-use customers. The 20th-century power system was built to serve a reliability philosophy that said customers' lights should almost always come on when they flip their switches, which drove infrastructure investment to meet peak load conditions that occur only a few dozen hours per year. Even the major industry changes related to the formation of open-access wholesale markets in the 1990s did not alter the one-way flow or the exogenous-demand-driven philosophy of reliability that shaped infrastructure investments and regulatory frameworks.

Now in the 21st century, new societal needs of the power system have become prominent: reduce greenhouse gas emissions, both from the power system itself and by electrifying other fossil-fuel uses in the society; build greater resilience to disruptive events; eliminate the adverse health impacts in communities where fossil plants are located; foster a diverse competitive arena of new energy technologies becoming ever more powerful and less costly; and allow end-use customers and communities to exercise greater choice and control of their energy sources and uses. Meeting these new needs is challenged, however, by legacy physical and institutional infrastructure—and embedded mind-sets—that are most compatible with 20th-century paradigms and can be very resistant to change.

Nevertheless, change is happening and will accelerate, due in large part to the fact that DERs are well suited to meeting 21st-century policy goals and, in the process, are overturning the one-way-flow paradigm (see Figure 2) and challenging its constellation of industry institutions. Moreover, DERs are proliferating from the bottom up through the adoption decisions of millions of end-use customers, often for reasons that don't fully align with conventional investment logic, thus making a sharp break from traditional investment in massive assets decided in regulatory proceedings. Residential rooftop solar installations have already had major impacts in some states, and they are just the leading edge of the DER insurgence.

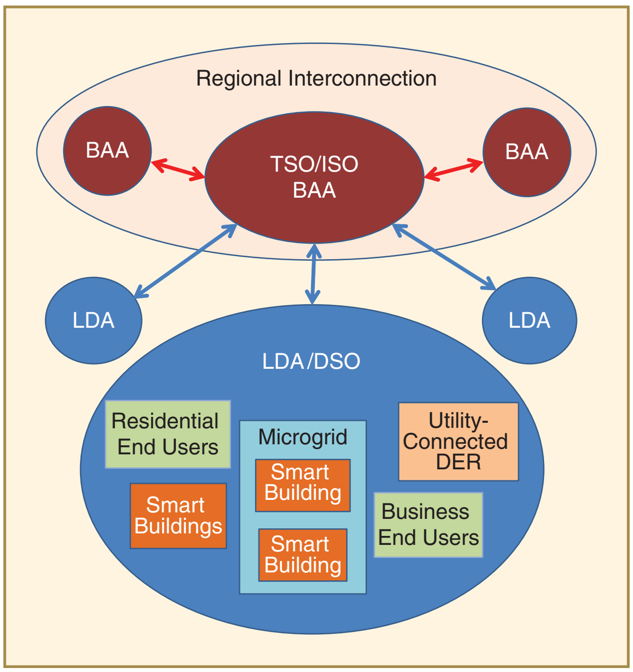

figure 1. The integrated-decentralized power system. BAA: balancing authority area; ISO: independent system operator; LDA: local distribution area.

Rise of the Behind-the-Meter Market

Powerful, cost-effective small-scale technologies are arriving just as end-use customers are seeking greater choice and control over their energy sources and uses, and communities and local governments are becoming more concerned about environmental impacts and climate adaptation. Where the market used to mean the market for grid-provided commodity kilowatthours, we can envision a not-too-distant future when the bigger market will be for behind-the-meter (BTM) energy resources and control systems, while the grid shifts into a complementary role as residual supplier and a network for economic transactions. This opens many beneficial possibilities for the bulk system: higher capacity factors with less congestion and easing of renewable integration challenges as net load profiles and DER variability are smoothed close to the source, largely BTM. It also triggers ideas about future distribution utility roles as DSOs, which could include operating transaction platforms and distribution-level markets; DSOs are discussed in following sections.

In the integrated-decentralized grid, the meters behind this new market are also the POIs and real-time interfaces between end users and the distribution grid. It is the point at which the regulatory frameworks must specify practical and reasonable interface requirements or good citizen principles that then translate into standards to enable a vibrant competitive BTM market that also supports reliable functioning of the electric distribution network. The BTM market includes control systems (e.g., building energy management and microgrid controllers), which manage internal energy uses and sources as well as the interface of

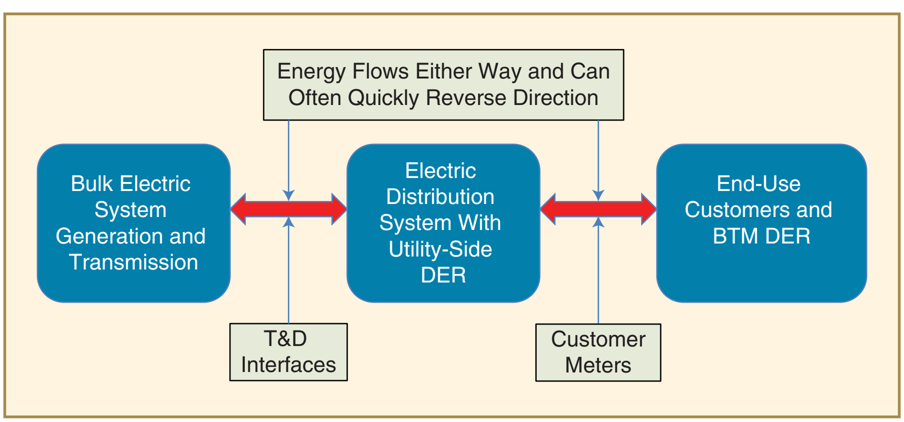

figure 2. The proliferation of DERs is overturning the one-way-flow paradigm.

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the POI with the grid. In this way, each POI can be both a grid user and a provider of grid services.

Electrification of All Major Fossil-Fuel Uses

Major reductions in greenhouse gas emissions require substituting renewable electricity for fossil fuels throughout the economy, not just greening the grid. In California, roughly 70% of greenhouse gas emissions come from uses of fossil fuels in transportation and buildings. Two crucial questions require practical strategies. First, how will this electrification occur? Where will the activities to achieve it be designed, prioritized, and set in motion? Second, what will growing electrification demand mean for power system operations, planning, markets, and regulatory frameworks?

On the first question, an overlooked fact is that the policies, initiatives, and projects that can achieve broad electrification are things local governments address in their general plans and climate action adaptation plans. Such plans deal with zoning and building codes, transportation policies and mobility alternatives, public space and land use, local business development, housing densification, resilience of municipal services to disruption, and other essential quality-of-life elements that make up the energy transition landscape. Thus a crucial, necessary component of a state's electrification strategy is to engage with local government planning, provide resource support to cities and regions that are at risk of being left behind, and foster partnerships between communities and distribution utilities to design and implement high-value local electrification and resilience projects.

On the question of power system impacts, one could imagine a spectrum of solutions and associated system impacts along an axis between two extremes.

- ✔ *Unstructured demand and DER growth*: View demand growth as mostly exogenous and, following the traditional reliability philosophy, centrally plan T&D infrastructure and procure supply resources to meet the demand with high reliability. This approach continues the conventional views of demand and reliability, which lead to infrastructure investment sufficient to meet all demand during peak periods that occur infrequently, resulting in excess capacity most of the time.
- ✔ *Shaping demand growth*: Create incentives and requirements to shape new demand growth locally and manage extreme net load profiles and volatility close to the source. The idea is to create incentives (including interconnection codes as well as financial incentives) for each POI on the grid to maintain its real-time interface with the grid within specified parameter ranges so as to minimize grid impacts. In addition, DSOs must have regulatory structures that incentivize them to obtain services from qualified flexible DERs, so they can reliably integrate growth in demand and diverse autonomous DERs without driving costly distribution infrastructure investments or exporting variability and uncertainty up to the bulk system.

There are good reasons why demand shaping with incentives and DERs will be preferable (see Figure 3). It uses the full value of flexible DERs, many of which are still struggling for commercial viability waiting for well-defined distribution-level services and markets. Local smoothing of net load and DER profiles and variability can yield substantial cost savings in the rapidly changing industry by minimizing commitments to 40–50-year infrastructure investments. Financial incentives for a POI to manage its grid interface reliably will better align a POI's cost for network services with its impacts on the grid. Demand shaping can increase capacity factors on transmission, without increasing congestion, by smoothing T&D interface flow profiles. A demand-shaping approach creates a more level playing field for DERs to compete based on cost and performance against the often-touted economies of scale of utility-scale resources and grid assets. Finally, it creates a practical basis for partnerships and planning collaboration between local governments and distribution utilities, which will lead to higher-quality and more cost-effective electrification and resilience initiatives.

The integrated-decentralized grid views the growth in electrification demand and the local shaping of that demand as composing a virtuous cycle, a positive feedback system that drives—and finances—community energy supply and storage projects, building electrification and efficiency retrofit programs, new construction specifications (e.g., all-electric and microgrid-ready codes), new local mobility services and strategies to reduce mobility demand, local economic stimuli, environmental footprint reduction, and greater local resilience to disruptive events. Thus the integrated-decentralized architecture, by incorporating bottom-up projects driven by local priorities, will be a central strategy for achieving broader societal goals.

Redefining Electric Distribution Service

The North American Electric Reliability Corporation (NERC) functional model defines *distribution provider* as

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"The functional entity that provides facilities that interconnect an End-use Customer load and the electric system for the transfer of electrical energy to the End-use Customer." This definition makes explicit the 20th-century service of the distribution provider and its value to end users, whereas the one-way paradigm behind it justifies a volumetric revenue model. But with BTM generation and two-way flows at the POIs, the NERC definition no longer fully describes and recovers the distribution system's value. The drop-in kilowatthour sales with rooftop solar portended greater changes to come in use of the distribution system. Modernization strategies for distribution operations and planning are currently under way or being initiated in many jurisdictions.

One big question is to define the new value of the distribution grid. Its original value as one-way delivery service is shrinking, but there are benefits for end users to remain on the network even without complete dependence on grid kilowatthours and with grid defection becoming cheaper. What are those benefits? Who receives them, and what should the beneficiaries pay for them? Who drives the costs of the system, and how should they pay for their impact? How do DSOs recover their costs, and how are they incentivized?

In the integrated-decentralized grid, each POI pays for the services it receives, such as the opportunity to participate in a market as either buyer or seller. The POI also pays for grid costs it drives. For example, to pay for the impacts of an extreme net production profile and the storage services of the grid, a nonparticipating POI with BTM solar and no storage would pay more in distribution charges than a similar POI with BTM solar plus storage. POIs with suitable performance characteristics will earn revenues by providing services to the DSO. All of the rates, charges, and payments for the above would be structured to create incentives, for both users of DSO systems and DSOs themselves, that align with public policy objectives and support optimal use of the grid.

Redefining Roles and Responsibilities at the T&D Interfaces

As today's interconnected power system realizes higher DER volumes, what happens in the distribution system does not stay in the distribution system. Electrical behavior in the high-DER distribution system will propagate up to transmission. With high DER penetration, two essential functions become much more complex: forecasting net demand at each

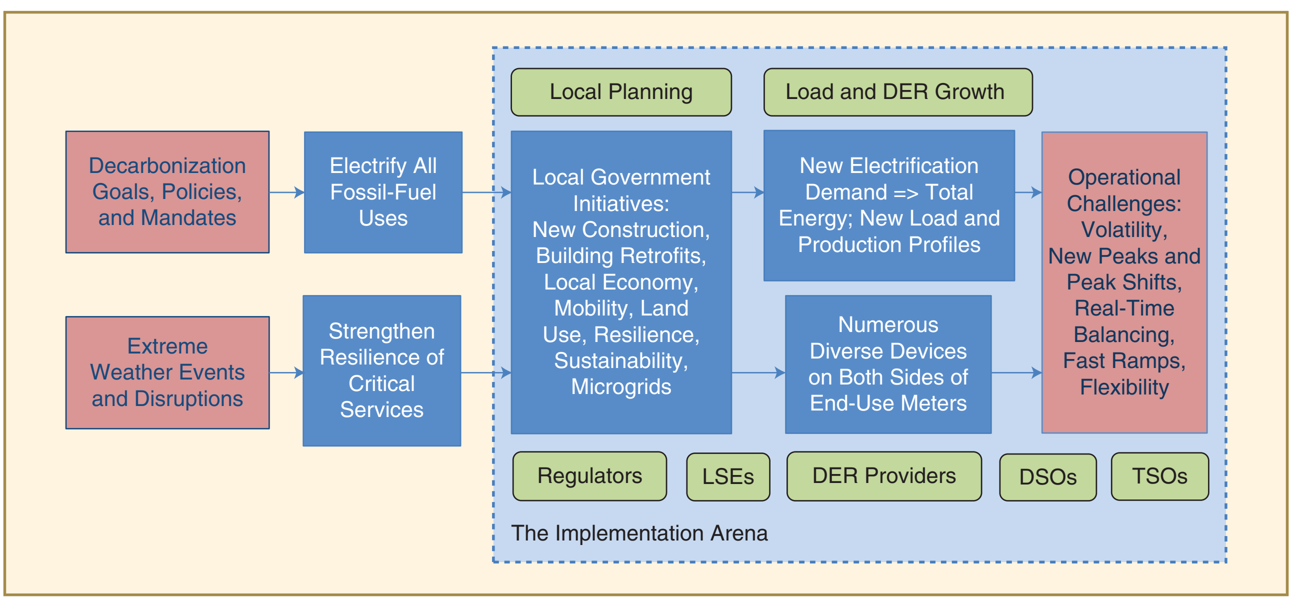

figure 3. The decarbonization and resilience goals drive new electrification demand and growth of DERs and could add to operational challenges and costly infrastructure needs unless shaped through incentives and grid services opportunities. LSEs: load-serving entities.

T&D interface (both for real-time operation and planning) and controlling or dispatching resources that provide flexibility services to maintain real-time system balance.

Taking a whole-system perspective, the grid architecture question is how to specify roles and responsibilities of the key actors—especially the transmission system operators (TSOs) and DSOs—to best achieve the 21st-century objectives of the power system. Here again it is useful to explore a continuum between two extremes.

- ✔ *The grand central optimization*: Based on the success of wholesale spot markets integrated with transmission system operations in the United States, it may seem like the most natural adaptation to DER proliferation would be to fully integrate DER dispatch and distribution system operation into the TSO's central optimization. This trajectory seems to have generated considerable interest in Europe as well, where the TSO just provides transmission service and real-time balancing while a separate entity operates the energy markets. Taking the grand central approach to the extreme, the TSO's network model would include distribution circuits, with near-real-time configuration updates for running the optimizations and real-time visibility and control of vast numbers of DERs. This model is often referred to as the *total TSO* from the TSO perspective or the *minimal DSO* from the distribution system perspective.
- ✔ *The layered system architecture*: As shown in Figure 1, the layered approach specifies roles and responsibilities for each of the key actors with regard to managing what's internal to their respective layers and the interfaces between their own layer and the layers immediately above and below. For the TSO, which is the balancing authority, this means optimizing only what's directly connected to the transmission grid, including its interfaces with DSOs at the T&D substations and its interties with adjacent balancing authority areas. Taking this model to the extreme, we have what is called the *total DSO* model, in which the TSO does not have or need visibility to anything on the distribution system, because the DSO's responsibility encompasses aggregation of all electrical components within a local distribution area and presenting the TSO with a single virtual resource at each T&D interface.

The integrated-decentralized power system adopts the layered structure, including the total DSO model, recognizing that there must be significant DER penetration in the local area to participate in the total DSO's procurement of grid services and aggregation functions. For this reason, if a DSO with a large service area adopts the total DSO model, it will likely do so first at T&D interfaces where DER growth is high enough to provide flexibility services to the DSO and be aggregated for the DSO to bid as a virtual resource to the TSO or energy market. The total DSO model will also require major new functional capabilities compared to today's distribution utilities, e.g., to coordinate with the TSO for reliable operation at the T&D interfaces. For the TSO, this means that it will probably have more than one DSO model operating at different T&D interfaces in its system, with total DSOs at interfaces where load and DER density are high and the value of the total DSO model is greatest.

Admittedly, the total DSO approach seems at odds with current initiatives to enable DERs and DER aggregations to participate directly in wholesale markets. The author suggests, however, that direct DER participation in wholesale markets is likely to be far less remunerative and more costly to implement than its proponents anticipate. And with a properly designed and regulated DSO, with transparent open-access DSO markets for DER services, DER developers and operators would not be commercially disadvantaged by the total DSO structure. For the TSO there will be vast simplification and greater predictability in dispatching a single virtual resource at each T&D interface because the DSO would deliver the optimal response based on real-time distribution system conditions. Moreover, this structure is readily scalable in the sense that the relationship between TSO and DSO can be replicated in the relationship between the DSO and a microgrid connected to its system and between a microgrid and a smart building inside the microgrid. Finally, there are mathematical methods for optimizing a layered system without loss of efficiency relative to a centralized optimization (see Pacific Northwest National Laboratory's Grid Architecture site for extensive literature on this subject).

Rethinking Benefit-Cost Analysis for the 21st Century

The economic case for many otherwise desirable DER-based projects, including microgrids, is hampered today by the limitations of benefit-cost analysis. A fundamental defect of the entire approach is that its outcomes depend on which benefits and costs are included and how they are measured, things that can be highly subjective and arbitrary. Historically, benefits and costs that are too hard to measure or would lead to an inconvenient answer are left out of the analysis. Today we're struggling with the environmental and societal impacts of having assumed we can leave out these costs and still get good answers. When it comes to valuing DERs and microgrids, there are crucial potential benefits that will grow in importance but are not yet well quantified.

First is the ability to use DER services to shape the additional net demand and renewable energy profiles that result from broad electrification of the economy. This requires defining the distribution grid services that DERs can provide and estimating the avoided costs of upgrading infrastructure to meet unstructured electrification demand. The lack of well-defined DER services and benefits at present is one of the main factors driving DER developers to pursue wholesale market participation, which this author suspects may not yield big enough returns.

Second is the option value of avoiding 30–40-year asset investments on the T&D systems by substituting smaller-scale, shorter-lived DERs to enable infrastructure to evolve in alignment with ongoing technological changes in the industry. A significant barrier to more rapid change today is the unquestioned need to fully compensate the book value of assets that really ought to retire to achieve carbon reduction targets. At the very least, let's avoid building new stranded assets wherever possible.

Third is the value of resilience. Although current industry discussions of resilience focus on the bulk power system, resilience is first of all a local capability. When a major disruptive event occurs, people have to deal with immediate, life-threatening local impacts no matter how widespread the event may be. Resilience entails maintaining essential services like water supply, wastewater pumping and treatment, emergency rescue, shelter, and medical and food services, all of which require power. Quantifying the value of resilience is complicated by the tendency to equate it to a kind of insurance against rare events. This equation is too limiting, however, as the local benefits of strengthening essential services and incorporating resilience thinking into city and regional planning will be much more extensive (see Figure 4).

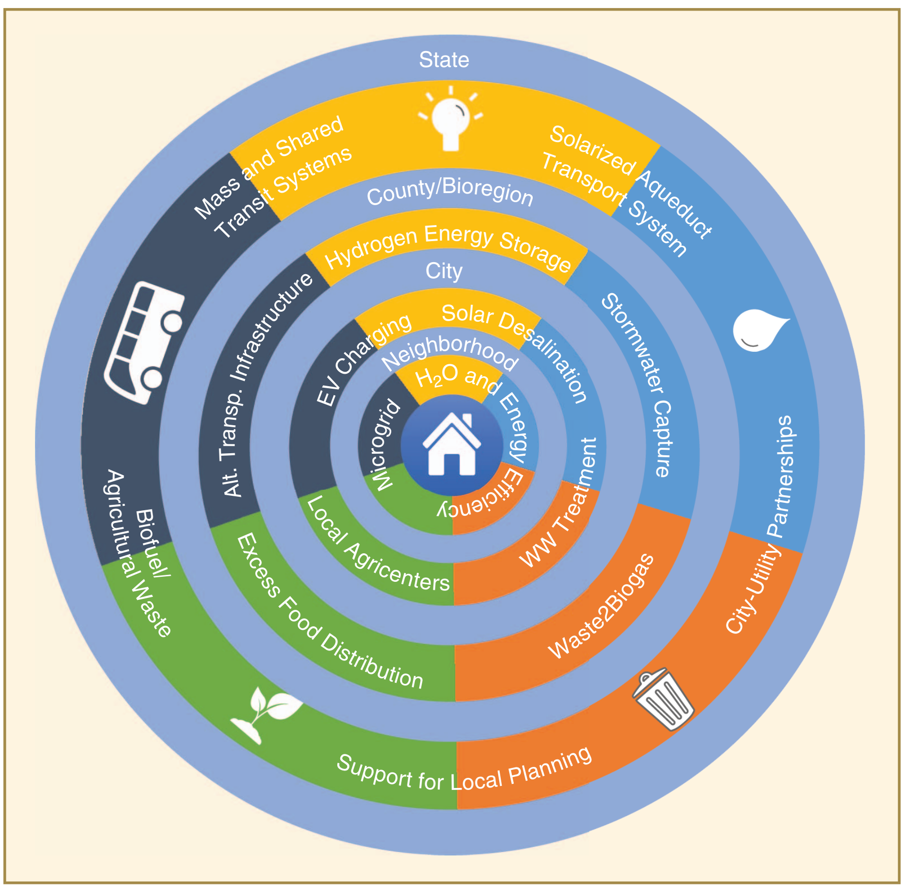

figure 4. The multilevel architecture of resilience will incorporate DERs at all levels. EV: electric vehicle; WW: wastewater. (Image used with permission from World Business Academy.)

Policy and decision makers will need to consider all of the previously mentioned values and benefits in shaping the trajectory of the future power system. The integrated-decentralized vision described here fully recognizes the value of DERs and microgrids in the layered system architecture and expects their perceived values to grow in the coming years. If benefit-cost analysis is going to be a meaningful decision tool, then quantifying these values is an urgent need.

Summary and Policy Needs

Grid architecture principles urge us to start from the societal objectives and then describe the attributes, features, and performance the system must have to achieve those objectives. On this basis, we then define roles and responsibilities of the key actors in the system and how they must interrelate to produce the desired performance.

The shift from 20th- to 21st-century objectives focuses us on reducing environment impacts, which means broad electrification with clean energy, greater resilience of power-dependent essential services to disruptive events, increased capability for end users of all types to choose and control their energy sources and uses, and quality-of-life improvements for disadvantaged and vulnerable communities. These new objectives point to a process of change that is as much from the bottom up as from the top down. Statewide and national policies matter in that they provide direction and often define roles and responsibilities and create incentives. But the crucial and less-well-recognized arena of change is at the level of local governments, communities, and energy users. Add in the rapidly improving and proliferating small-scale technologies, and the bottom-up (r)evolution of the electric power system becomes eminently practical and desirable, if not inevitable. Those who oppose DERs and local energy initiatives to maintain the status quo may slow the process of change for a while, but as more local plans and initiatives arise to reduce the carbon footprint and build resilience, it will become apparent that success in achieving ambitious environmental policy goals is most promising with bottom-up-meets-top-down strategies.

The challenge for policy makers and regulators, then, at both state and national levels, is to enable local energy initiatives and decisions to flourish while continuously raising renewable generation's share of power supply, modernizing the grid, and maintaining reliability at the level required for each energy-using function. The value of the integrated-decentralized power system described here is that it offers a flexible grid architecture—a grid architecture based on layered operating and market responsibilities with well-defined performance criteria at the interfaces between the layers—that will support the most urgent high-level societal objectives and elicit the power system performance needed to achieve them.

The policy makers now need to enact a few key measures that will pave the way for the integrated-decentralized future. Policy makers must clarify the future role of the distribution utility as a DSO that provides transparent open-access distribution service. This will require a new regulatory framework, including DSO incentives tied to performance of services rather than investment in assets, and a retail tariff that charges users of the distribution network based on the specific services they receive and the extent of system costs their behavior incurs. In local areas with sufficient density of DER adoption, the DSO will procure grid services from DERs, perhaps through local markets regulated by municipal or regional regulatory authorities. A necessary early step is to define distribution grid services DERs can provide, with enough specificity of performance criteria, measurement, procurement, and compensation to allow DER developers to estimate realistic revenue streams to finance projects.

Regional policy makers will also need to invest in local government capabilities to develop general plans and climate action adaptation plans with implementable electrification, local energy, and resilience projects and ensure that the more fiscally challenged cities and counties are not left behind in the transition to clean energy. For the DSOs to become partners to communities and local governments in these projects, new regulations will need to spell out performance-based DSO incentives, cost recovery, project decision making, and oversight.

Finally, policy makers need to develop regulatory and reliability frameworks that align with the layered architecture of grid operations and markets. The architecture of the total DSO model focuses on the interfaces between layers, potentially obviating the need for the operator of each layer to have visibility or control into adjacent layers. This implies that the DSO could balance supply and demand within each local distribution area, incorporating imports and exports with the bulk system and real-time services from DERs. With effective rules and procedures for T&D interface scheduling and real-time operation, the TSO's responsibilities could, to a large extent, end at those interfaces, much as they do today with adjacent balancing authority area. Although such a system would be a major departure from today's industry structure, it could yield great benefits by reducing the complexity of coordinating large numbers of DERs, increasing grid capacity utilization, and simplifying jurisdictional boundaries. In the United States, e.g., layering at the T&D interfaces could simplify federal and state jurisdictional roles for the high-DER power system.

Policy makers now have the opportunity to facilitate changes in power industry structure that will guide the industry to a truly 21st-century architecture. The bottom-up DER-based (r)evolution is driven by much greater needs and goals than simply producing clean kilowatthours of electricity at the lowest cost. DER proliferation will continue in any case as local electrification projects become more central to city and regional planning, as disruptive climate-based events raise the urgency of local resilience, and as technologies continue to become ever more effective enablers of power system decentralization.

For Further Reading

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Biography

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