

The background is a complex, blue-toned digital landscape. It features a grid of data points or server racks that recede into the distance, creating a sense of depth. Several glowing, spherical objects with concentric rings are scattered throughout the scene. Bright, jagged lightning bolts in a lighter blue hue strike across the grid, adding a dynamic and energetic feel to the overall composition.

# Grid Futures

Evolutionary directions for  
electric system architecture.

By MERWIN BROWN, LLOYD CIBULKA AND ALEXANDRA VON MEIER



lectric transmission and distribution (T&D) systems today are going through substantial evolution. That evolution might proceed along any of several possible paths, each of which would affect the way utility companies operate in the United States.

To better understand how T&D systems are evolving, scenario analysis provides a method of disciplined speculation to help organize and articulate our thinking. The object isn't to evaluate the relative probability or merit of different future outcomes, but rather to consider how specific factors might influence and shape these outcomes in a way that's consistent with what we know today. Starting with explicit premises about cause-effect relationships, the exercise follows the logical implications of changes in specific variables in order to construct a set of distinct futures that are each plausible under different sets of conditions (see *Figure 1*).

### Yesterday, Today and Tomorrow

The analysis begins by observing the historical evolution of the T&D system<sup>1</sup> and identifying essential properties that have changed. A simplified view of this evolution is a transition from one era to another: "Yesterday," extending from the 1890s to roughly the 1960s, to "Today," from the 1970s to probably the 2020s. Crucial changes during this shift can be described in terms of three properties: function, operation, and form of the T&D system.

Yesterday's system had the essential function of providing a physical link between a utility's generators and customers' meters to deliver a product—electric energy. Its operation was deterministic and planned, and its form was mostly radial.<sup>2</sup> Today's system still has the function of providing a physical link, but among a more numerous and diverse set of nodes. Rather than facilitating the sale of energy by one party, the T&D system provides an infrastructure for multiple transactions among multiple parties. Its operation occurs increasingly in real-time and involves probabilistic estimation, as the number of variables and the strength of their interaction exceeds operators' ability to always understand the system's behavior deterministically. Its form is increasingly networked, allowing for greater connectivity among geographic regions.

The basic question of the scenario-analysis exercise can then be posed as follows: What would the function, operation and form of the T&D system evolve to be, under various sets of conditions?

A range of conditions or factors are likely to drive or influence the future evolution. These include societal factors, markets, policies, technological development, environmental factors and economic conditions. Of course, these broad categories

are interactive and necessarily overlap in multiple dimensions. For the present purpose, though, they're taken to be exogenous to the system under study, the T&D architecture. Graphically,

### The extent to which power systems will rely on transmission capacity is uncertain, but distribution plays a major role in each scenario.

Figures 1 and 2 represent the exogenous factors as clouds, symbolizing a lack of clear outline, morphing over time, and not being subject to any control from the vantage point of this analysis. The analysis simply posits that within each of these factors are key drivers of trends and discontinuities that, combined, create forces for change in T&D.

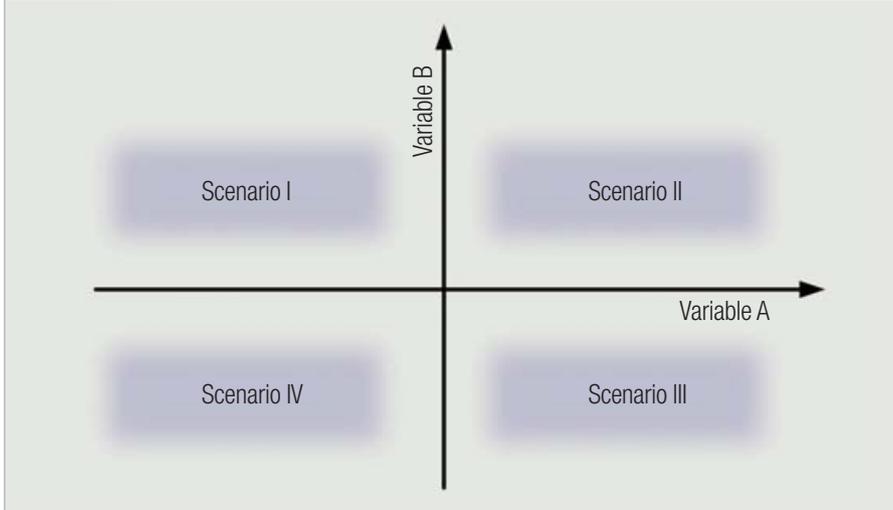
Having acknowledged the difficulty of defining exogenous factors and isolating them from each other, the analysis proceeds (boldly or naively) for the purpose of the exercise to choose two of these candidate forces to consider as the main drivers of the scenarios. But how to choose?

First, note that there's no right or wrong answer here: it's possible to perform a scenario analysis exercise with any pair of factors taken to be exogenous. The most instructive exercise, however, will likely result from choosing those drivers that entail the highest degree of uncertainty. A bit more specificity involves listing candidate forces for change in T&D. Again, these forces overlap and interrelate, but they're considered here as a spectrum of conditions that will in some way bear on how T&D systems are built.

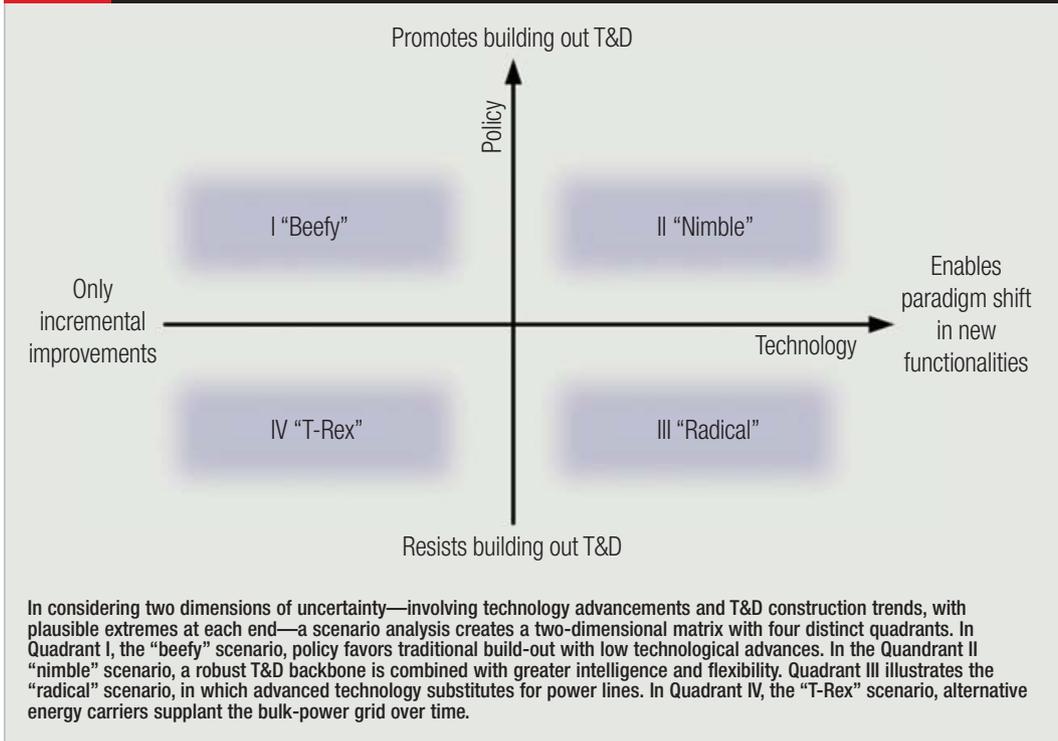
Though far from certain, the more confident predictions include suppositions that there will be economic pressures to keep costs down; that electric demand will grow and continue shifting from resistive or inductive to electronic loads; and that there will be less land available on which to build T&D facilities. Somewhat more uncertain are developments such as the future deployment of energy efficiency, demand response, renewable generation and distributed generation.<sup>3</sup> Within the category of technological change, the least well-known elements include

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**FIG. 1****SCENARIO ANALYSIS MATRIX**

generation projects are increasingly constrained to locations relatively far from load centers, whether for environmental health and safety reasons (coal and presumably nuclear) or due to resource availability (renewables). This condition exerts pressure to extend the high-voltage transmission system in order to provide access to these generation resources.<sup>4</sup> Another force acting on the build-out of T&D is the need to accommodate the behaviors of various generators with respect to inertia: this includes intermittency (*e.g.*, wind, solar: low-inertia), must-run conditions (*e.g.*, nuclear: high-inertia), and ramp rates for different units. Again, this factor pushes toward increasing transmission links between distant locations so as to facilitate complementing different types of generation with one another.

**FIG. 2****GRID FUTURE SCENARIOS**

smart-grid enabling technologies such as power electronics along with a sensing, communications and control infrastructure, as well as new T&D material technologies. Finally, the greatest uncertainty probably lies in the area of policy: this includes energy markets and tariffs, siting of power plants and grid facilities, regulation or taxation of carbon emissions, and other societally determined constraints on what can and can't be done in the context of providing electricity.

**Evolutionary Forces**

How the above forces currently act on planning and operations of the T&D system bears brief examination. Sites for large new

opposition or NIMBY effects and cost-allocation deliberations. Some new lines are approved and built with considerable effort, while many more remain on the wish lists or drawing boards of utilities and system operators. As a result of this stand-off, there's an increasing scarcity of transmission capacity. This scarcity is acute for system operators in the context of technical control, where thermal limits and stability constraints leave a shrinking range of options for operating the system in a secure “N-1” state—*i.e.*, with reserves sufficient throughout the system to accommodate the loss of any one component at any time. In the context of electricity markets, the same scarcity is observed in the form of geographic price differentials or congestion charges.

If any growth in electric demand is to be sustained at a level of power quality and reliability comparable to that enjoyed at present, and if the present shift to carbon-free generation resources is to continue, some expansion of the T&D system seems inevitable. But arguably there are two fundamentally distinct options for how T&D architecture and operations can grow to accommodate electric customers' needs: either by traditional build solutions—that is, investment in wires, towers, poles and power plants—or by new and improved T&D functionalities which, through relatively small or novel material, control or software additions, extract new performance from existing hardware and real estate.

This brings the analysis to a critical pair of assertions: First, the ability to physically build out the T&D system by adding significant amounts of copper, steel and aluminum will be primarily affected by public policies and social acceptance. Second, T&D functionalities will be primarily affected by availability, costs, and adoption rates of new technologies. Not coincidentally, these two sets of drivers—in shorthand, policy and technology—are the most uncertain among the broader set of exogenous factors considered above.

Again, isolating technology and policy as mutually unrelated factors is a gross simplification. Nevertheless, the respective correlations expressed in the above assertions—traditional T&D build-out with policy, and new T&D functionality with technology—are both sufficiently strong and sufficiently separable from each other to permit the two pairs to be graphed in orthogonal directions for purposes of the scenario-analysis exercise. Thus two axes are constructed: In the horizontal direction, a continuum illustrates how much new technology is available. At the left end, a paucity of technological development—or adoption—means that T&D functionalities are improved only in small increments, if at all. At the right end, significant technological innovations enable a paradigm shift in new T&D functionalities. In the vertical direction, a continuum illustrates policy, which at the bottom resists and at the top promotes the construction of traditional T&D facilities. The intersection of these two continua, technology and policy, will form the basis for distinguishing future scenarios.

Characterizing the two extremes of each continuum in a bit more detail allows examining the plausibility of each. At the low end of technological development, T&D functionalities would barely improve. The lack of development could be due to intrinsic physical difficulties, excessive risk for T&D owners, operators, investors and regulators, or economic returns that favor incremental improvements over radical innovation or replacement. At the high end, devices and techniques become commercially available and affordable that qualitatively change the way power flows are accommodated by the T&D system. This might include techniques for increasing power flow capac-

ities along existing wires or existing rights-of-way, such as higher-density power flows and direct-current (DC) links, as well as techniques for more optimally controlling power flow along different links, such as active phase-angle shifting supported by detailed synchro-phasor measurements.

In addition, technological development might make T&D facilities less objectionable by allowing smaller profiles or economical underground siting. At the distribution level, technology could enable not only bi-directional power flow but also

## More transmission links might increase the potential for power instabilities, loop flows and cascading blackouts.

options for deliberately islanding portions of the system, *i.e.*, allowing microgrids of various scale whose power quality and reliability is negotiated locally rather than supported by distant resources. The overall result is that providing the same level of end-use service requires a smaller amount of visible metal between generation and load.

Along the policy continuum, traditional T&D build-out is either resisted or promoted. At the resisting end, permitting of transmission projects would take longer and projects would be delayed or denied by public opposition and environmental regulations. Cost and benefit allocations become more contested and prolonged, and there's pressure to minimize power transfer rates among states or control areas. Policies might also incentivize distributed generation that relieves some transmission loading.

On the other hand, increases in power outages, congestion costs, and concerns about national security or economic health could plausibly lead to more public tolerance of T&D facilities, or increased use of eminent domain to force their permitting. At the same time, policies such as tariffs and incentive regulations for demand response or distributed generation, aiming toward relieving T&D congestion, might fail to achieve timely results. Consequently, at the other extreme, legislative and executive branches might support an interstate highway-style build-out of a national transmission network, and traditional T&D facilities could be sited relatively freely.

In considering these two dimensions of uncertainty, with plausible extremes at each end, the analysis in effect creates a two-dimensional matrix with four distinct quadrants, representing the four possible combinations along the two axes. The next step involves imaging what the evolving T&D system might look like in each of these four quadrants.

### Function and Form

Figure 2 labels the scenarios I through IV in the clockwise direc-

tion, starting from the upper left.<sup>5</sup>

Quadrant I presents what might be called the “beefy” scenario, with policy that favors traditional build-out while featuring low technological advances. It’s characterized by many more wires, towers and poles. Quadrant II represents the “nimble” scenario, which combines a robust T&D backbone with more intelligence and flexibility. Quadrant III is the “radical” scenario, in which advanced technical capabilities substitute for traditional power lines. The scenario in Quadrant IV, finally, might be called the “T-Rex”; with neither bulk nor smarts being added to the grid, its functionality might be expected to decline over time, with alternative energy carriers (for example, hydrogen) deploying new technologies and taking the place of large-scale electric power delivery.

Consider the three properties of function, operation and form for each scenario. The “beefy” T&D system continues to fulfill the same function as the legacy grid, providing the capacity to transact increasing volumes of power over long distances. It readily accommodates central-station generation wherever it is desired or economical to build the power plant, so that generation—and not transmission—siting constraints dominate planning decisions. In the absence of transmission constraints, economics would typically favor bulk generation projects, connected in the traditional manner at the transmission voltage level. The penetration level of distributed generation would also be limited by the technical capability to allow safe back-feeding of power.

Operationally, the beefy system works much like before. Especially at the distribution level, very little would change in architecture, since power continues to be fed hierarchically out from substations. Distribution feeders might be added locally to accommodate load growth, but without changing the fundamental radial structure of the system. At the transmission level, incremental changes can be summarized as reducing the impedance between nodes in the grid, by upgrading links or adding lines along new rights-of-way. At the extreme, this scenario might be called the “metallic skies.”

One caveat of this growth in transmission capacity is the potential instability in alternating-current (AC) transmission systems resulting from very large power transfers over long distances. Voltage magnitude and angle oscillations have been increasingly observed in synchronous AC systems spanning large geographic regions, and aren’t very well understood at present. With thermal limits generally increasing due to transmission system build-out, stability constraints can be expected to play an increasingly important role. Without significantly better knowledge of system stability behavior and implementation of phase-angle measurement and control, or the strategic introduction of DC links, brute-force addition of transmission capacity can be expected to run up against this fundamental limitation. Another

way to say this is that while more transmission capacity on the one hand adds to security, when fully utilized it also introduces new vulnerabilities. Besides oscillations, a well-known example of this is relay tripping and system separation in response to distant events (such as the proverbial tree limb in Oregon taking down California). A related caveat of reducing impedances between nodes is the associated increase of fault currents. Because of this, interconnectivity of transmission networks might be limited by the capacity of devices to safely interrupt large fault currents. Finally, more transmission links might also increase the potential for other power instabilities, loop flows and larger wide-spread cascading blackouts.

In sum, while the overall T&D operating philosophy wouldn’t change much in the “beefy” scenario, and while the system would be built out incrementally in response to operational needs, operational limits ultimately would arise that can no longer be addressed with just the addition of traditional capacity.

Note that because grid technology plays a small role in this scenario, this discussion of T&D operation assumes that smart grid technology is minimally implemented at the load level (such as meter reading and billing, signal-controlled demand response,

**Increases in power outages, congestion costs, and security concerns could lead to more public tolerance of T&D facilities—or increased use of eminent domain to force their permitting.**

or charge scheduling for electric vehicles) and for generation (such as wind resource forecasting). Also it doesn’t assume a particular regulatory or market model for transactions of energy and ancillary services. Where information technology does become crucial for T&D operation is in supporting operators’ situational awareness, equipping them to maintain system reliability. Wide-area situational awareness would likely be the most acutely felt need for intelligence in the beefy grid.

As in each scenario, the form of the beefy T&D system can be expected to follow function. Transmission towers and lines will be a major visible presence, with new links traversing the countryside to connect distant resources with metropolitan areas. Numerous wind farms likely would crop up in the central United States and solar arrays in the Southwest, sited and scaled so as to make optimal use of resources. Because of the need to complement the short-term intermittency as well as the seasonal availability of different renewable generation resources, a high-voltage interstate highway would span the continent, with a capacity that represents a significant percentage of total demand in the eastern and west-

ern U.S., respectively. Probably the key aspect of the beefy system's overall look, therefore, is that T&D facilities increasingly cover sparsely populated land areas not previously associated with much electricity infrastructure.

In the "nimble" scenario, the T&D system's function can be more broadly described as connecting supply and demand of electricity, probably accommodating a broader spectrum of generation. Specifically, if technology implemented at the distribution level affords more refined voltage control and sophisticated protection coordination algorithms at reasonable cost, higher penetration levels of small- and medium-scale distributed generation become a viable option to complement central-station plants. The need for adding transmission hardware would be less pronounced, partly due to more distributed generation, and partly due to technical options such as routing intelligence (*i.e.*, power flow control) and increased utilization of existing lines. Because building out T&D capacity in the traditional way and improving asset utilization through technology are both feasible, the nimble scenario could be called "have-your-cake-and-eat-it-too," with the motto "Deliver a kWh from anywhere to anyone, anytime." The extent to which new technologies are integrated would depend on the details of local constraints and cost-benefit optimization.

Indeed, optimization would become the name of the game, as more than one viable solution would exist for relieving any given set of operational pressures. Rather than playing defense against encroaching constraints, T&D operators and planners could be proactive in comparing and choosing among solutions that afford desired gains. Overall, therefore, the "nimble" scenario would offer flexibility, adaptability and resilience. Operationally, the biggest challenge of the nimble scenario could become processing a large volume of information from different levels and sources into effective operating actions, spanning many orders of magnitude on both time and distance scales.<sup>6</sup> Some important questions would include how information is aggregated and which processes can and should be operated in closed-loop automation mode. The benefit of an extended menu of hardware and intelligence would also entail challenges at the planning and design level, since the analytic tools (not to mention criteria) for optimizing system function with so many diverse variables have yet to be developed.

It seems safe to say, nevertheless, that the T&D system's relative trend from Quadrant I toward Quadrant II would depend heavily on comparative economics. Because local variables might play an important role in this case, the grid might not retain a unified look in the "nimble" scenario. An interstate highway-scale system would still be built to access the most desirable energy resources, but to a lesser extent than in the "metallic skies" scenario. This backbone would be complemented by a diverse set of smaller-scale resources including dis-

tributed generation, storage, and demand response suited to different geographic areas.

### The Obsolete Grid

In the "radical" scenario of Quadrant III, rather than augmenting the transmission backbone, distributed capacity itself becomes the key structural element of grid architecture. Most

## Microgrids could operate as power islands, introducing a more proactive approach to variable topology for T&D systems.

if not any large-scale transmission to be added would have to be underground, or otherwise unobtrusive to the public eye—say, by consolidating circuits into superconducting links—as a socially acceptable alternative to overhead transmission capacity. While the cost of transmission is highly project-specific, and while technological improvements might reduce these costs, it seems a safe bet that buried transmission systems will tend to remain more costly than standard overhead lines. For this reason, the "radical" scenario would include a competition between

advanced transmission on the one hand and a narrowed geographic focus on the other, where the system's function becomes defined as facilitating the exchange of electricity locally or intra-regionally. In other words, the economic incentive could shift in the direction of finding local alternatives to long-distance connectivity.

To the extent that expensive, invisible transmission isn't built and access to significant amounts of distant generation reserves is therefore unavailable, siting enough distributed generation would be the first challenge, followed by matching this generation to load. An extremely high premium on energy efficiency, combined heat and power, demand response and electrical or thermal energy storage would be expected. Furthermore, the actual value of service reliability to different loads would likely receive much scrutiny. Enabled by intelligent switching technology, microgrids might provide variable power quality and reliability to specific loads as appropriate.

Operationally, the major implication of the "radical" scenario would be a redefinition of the role of electricity distribution. With all stops pulled to reconcile electric supply and demand locally, the distribution system is no longer a one-way delivery infrastructure: instead, it collects, coordinates, stores, and delivers. As in the nimble scenario, the problem of managing large volumes of information will arise. Because of the reduced connectivity, however, at least the geographic scope of high-priority information would be more limited. More

importantly, owing to increased generation and power quality control capability at the local level, more local intelligence could be depended upon. The key question for distribution operations might become where to draw the line on information management and control relative to the customer meter, and placement of this line could change over time. Indeed, microgrids at various scales could intentionally operate as power islands under specific conditions, introducing a much more proactive approach to variable topology for T&D systems than is currently used by any utility.

While potentially radical in its departure from traditional operating philosophy, the T&D system of Quadrant III might not look too different to the casual observer than what we have today. Existing transmission facilities aren't likely to be torn down; they will just supply a smaller fraction of energy and capacity resources and ancillary services as electric demand grows. Similarly, legacy distribution hardware would stay in place, with new electronic gadgetry added that isn't easily visible from the street. Underground T&D facilities, too, would be added out of sight. The most noticeable change in form would be the increasing presence of electric generation and support facilities amidst densely populated areas and on private property. From solar panels and inverters to fuel cells, microturbines, transformers, batteries and switchgear, small fences and base-ment doors with "Caution: High Voltage" signs would become the norm rather than the exception.<sup>7</sup>

Another observation is that the radical T&D scenario would less readily accommodate large baseload generation with high inertia, such as coal-fired and especially nuclear plants. With decreased or even intermittent connectivity of the transmission system, must-run units become a heavy liability, and economic incentive to build them would rapidly diminish.

Quadrant IV, finally, would be an archipelago of electric islands; it could be called the "T-less" T&D system—or, suggesting the possibility that large-scale electric power transmission goes extinct, the "T-Rex." With neither build-out nor intelligence to enhance the grid, its function would be essentially to sustain electric power delivery during a large-scale societal transition to other energy carriers. Bulk energy storage and delivery could eventually come in the form of hydrogen, produced wherever cheap energy resources are available, shipped by pipeline or high-pressure Dewar, and converted at the end-use location into heat or power. Some alternative visions involve decreasing energy consumption, which might be seen (optimistically or pessimistically) as a return to a less wasteful, less affluent or less materialistic society; the possibilities are too broad to speculate here.

It does seem safe to assume that owing to the unique physical characteristics of electric energy, most fundamentally in the context of electronics and information technology, electricity itself

can't become obsolete. The island scenario simply represents the extreme case of minimizing the geographic scale of electrical interdependence. According to the initial assumptions for this exercise, local electricity provision by microgrids would be constrained by today's technological capabilities, which aren't negligible. Power quality and reliability might be less effectively managed than in Quadrant III, with the result of further migration (especially of critical loads) away from the interconnected T&D system. Operational challenges and workforce demand could be shifted from T&D grid operators to local design and maintenance expertise.<sup>8</sup> A high premium would exist for pre-packaged, self-contained energy supply systems such as building-integrated photovoltaics or fuel cells with heat recovery.

The appearance of the "T-Rex" system would be similar to the radical one in that local, small-scale power equipment becomes a common sight. The migration of revenue base away from the interconnected system could result in a critical lack of incentive to maintain the existing infrastructure, preventing aging and unsightly equipment from being replaced—eventually becoming more eyesores than

critical functioning parts of our economy. The role of the electric grid in the 20th century as a public good and symbol of societal connectedness would fade into history like public telephones or canal barges, perhaps giving way to new, as yet unimagined infrastructures.

## Information technology becomes crucial for T&D operation—supporting operators' situational awareness, equipping them to maintain reliability.

### Scenario Signposts

What can we learn from this exercise? In general terms, the scenario analysis provides a framework for observations about current trends, as well as for discussions of relative merit, preferences, and policy implications. First of all, which scenario do we appear to be in, today? It might be possible to identify

signposts that indicate which scenario is presently unfolding, or about to unfold, potentially preventing some surprise down the road. Second, does any one scenario appear most or least desirable? For professionals in the field of electric power transmission, it might be tempting to jump to the conclusion that the "T-Rex" scenario of Quadrant IV represents a tragic loss. Nevertheless, it isn't obvious *prima facie* which scenario might offer the greatest social benefit, or benefit-cost ratio. An important continuation of the exercise would be to ask what each scenario might imply for society, and under what assumptions and conditions. Other questions would involve what

planning or investment strategies might be most advantageous to implement in any given scenario, and by whom, along with what technologies and policies would be most desirable.

This exercise has also provided the opportunity to make more specific observations related to the different scenarios. One observation is that while the extent to which power systems will rely on transmission capacity is uncertain, distribution plays a major role in each scenario. Furthermore, technological innovation in distribution systems might proceed somewhat independently of innovation in transmission. Investment in distribution technologies and systems should therefore be a no-regrets strategy, as returns on such investment might be largely independent of which scenario becomes reality.

Perhaps the most striking observation is that the “beefy” scenario of Quadrant I is the one that in effect imposes the most definite limit on the amount of central station generation that can be utilized. This is due to the intrinsic stability limitations of synchronous AC systems, which would be overcome by solid-state switching technology in Quadrants II and III and by substitution of other energy carriers in Quadrant IV. Therefore, one take-away lesson is that “building ourselves out of” the constraints that presently appear to limit the growth of central-station generation, by simply adding more conventional transmission capacity, might not ultimately be the way to accommodate the most of such resources.

Yet there appears to be a focus in the industry today on overcoming the considerable hurdles to getting transmission projects built, and a national Interstate-highway type of grid (establishing rights of way by eminent domain) is under discussion in policy circles. These efforts can be seen as signposts that our industry currently finds itself in Quadrant I, pushing in the upward direction toward building out the capacity (rather than to the right, toward substituting technology). The scenario analysis exercise suggests it may behoove the industry to focus more attention and efforts on technological innovation, especially given the likely limitations of large-scale AC networks, which would be awkward to discover subsequent to a major public funding effort.

Following up on this initial analysis, future research and discussion might flesh out the scenarios in more detail and examine discontinuities in any one independent variable. For example, analysis might focus on the impacts of common-mode failures (what if the advanced metering infrastructure didn't work?) or killer apps (what if electric vehicles swamp the market?) in each quadrant.

Finally, economic pressure by itself is insufficient to determine which scenario might come to pass. Pressure to minimize the cost of electric energy delivery seems likely to exist regardless of quadrant, while at the same time each scenario would require some significant expenditures. Thus, cost-benefit calculations and contests among technologies would occur within any quadrant and guide tactical investment decisions. But the strategic question of which direction public policy ought to steer the evolution of T&D systems is ultimately not one of minimizing costs, but of maximizing social benefit. To this end, the scenario analysis exercise is intended to provide some useful framing and vocabulary. ■

### Endnotes:

1. These scenarios focus specifically on the United States, but some of this discussion may be internationally applicable. The analysis refers to “the system,” singular, as either collective or representative of what can also be seen as multiple AC systems across the continent, assuming the main drivers of evolution to occur at the national level and therefore lead to unified or at least similar development.
2. Although certain portions of T&D systems have always been networked, the overall character of the architecture is best described as a radial, hierarchical structure extending from a central transmission backbone out toward customers along links of successively lower capacity, somewhat like major arteries branching out into capillaries.
3. Arguably, these factors aren't exogenous to, but are mutually interactive with the development of T&D architecture. That argument may be conveniently avoided because these factors weren't chosen as drivers for the exercise.
4. There's also a growing interest in distributed generation sited on customer property (*e.g.*, rooftop PV) and interconnected at the primary or secondary distribution level. At sufficiently high penetration levels, this distributed generation will impose a different set of pressures on the T&D system, particularly the accommodation of bi-directional power flow with associated requirements for voltage control and protection coordination. The jury is still out on what the critical penetration levels are that would necessitate architectural changes in distribution systems, but they have not yet been reached in the United States; therefore, the dominant pressure at present is to extend transmission.
5. With apologies to mathematical convention.
6. The temporal scale of interest ranges from high-frequency switching at the sub-cycle level, 10-6 seconds, to planning on the order of decades, 10<sup>9</sup> s—fifteen orders of magnitude! Geographically, the range might be considered from distribution at 101 meters to transmission over 106 m.
7. Ironically, public aversion to siting transmission lines could thereby result in much greater population exposure to 60-Hz electromagnetic fields.
8. The auto mechanics of Cuba come to mind, who are renowned for their ability to keep an aging vehicle stock operational in the absence of new cars or parts being imported.