Testimony of Dr. Jeffrey Taft
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I would like to thank the Chair, Senator Murkowski, and the ranking member, Senator Cantwell, for inviting me here today.

My name is Jeffrey Taft, and I am the Chief Architect for Electric Grid Transformation at the Pacific Northwest National Laboratory. In my statement here today, I will offer three main points:

1. We are re-engineering the grid with advanced technology to support many new capabilities.
2. These changes are challenging our existing grid structure and grid management tools.
3. Certain key technologies could help resolve the widening gap in our ability to manage and operate the 21st Century grid reliably.

In the US, we are modernizing the grid with advanced technologies to support many new goals and emerging trends that were not envisioned in the original 20th Century grid.

The 20th Century model for the grid was a one-way electricity delivery channel from large centralized generation to passive users who have no choice of electric energy sources and with surprisingly little in the way of sensing and measurement to guide operation.

Present grid modernization efforts are driving new technologies into the grid at an unprecedented pace to serve a variety of new goals and emerging trends not contemplated for the 20th Century grid, including:

- expanded diversity and consumer choice in electricity sources, including distributed and/or clean generation such as distributed solar photovoltaics, wind, and energy storage,
- emergence of “prosumers” (customers who are both energy producers and consumers)
- ability of non-utility assets such as ordinary buildings to provide services to the grid and cooperate in managing grid operations
- convergence of fuel, transportation, and social networks with the grid
- desire for greatly improved reliability, resilience, and security for the grid

These changes, some of which are occurring virally rather than being planned, are actually modifying the characteristics, behavior, and even the very structure of the grid, and are vastly increasing the complexity of the already complex US power system.

The forgoing is causing a widening gap between the real grid and the one for which existing grid management methods and tools were designed.

New technologies and new goals are reducing the effectiveness of standard methods for operating and protecting the grid. As the gap widens between the emerging grid and traditional grid control tools, the ability of utilities to manage the grid reliability is increasingly challenged. Further, uneven penetration of new technologies, mixed with legacy systems increases the challenge. New methods and tools for grid control are needed, as well as new kinds of grid components and an architectural framework to coordinate overall integration and operation.

Among all the very valuable technologies being applied to the grid, a few stand out as key to resolving the widening gap between existing grid management tools/methods, and the needs of the 21st Century grid.

Certain technologies will be crucial to the future of the grid, regardless of how modernization proceeds. They are:

- Sensing and data analysis – electronic sensing and automated information extraction that will require new data collection and analysis tools
- High voltage power electronics – adjustable electronics for controlling grid power flows to replace today's on/off electromechanical switches
- Fast flexible bulk electric energy storage – can act as the buffer that evens out various power fluctuations and mismatches that can occur with diverse energy sources
- Advanced planning and control methods and tools – new approaches using advanced control methods suitable for the modern grid that will require next generation high performance computing coupled with new control mathematics

The last three have so much potential for positive impact that we view the combination of storage, power electronics, and advanced control to be a new grid component, as fundamental as a power transformer or circuit breaker.

The Grid Modernization cross-cut initiative launched last November by Secretary Moniz at DOE is an important effort to systematically address these emerging challenges. The initiative is designed to leverage the broad assets of the national laboratory system and deliver an integrated plan that connects all grid efforts at the Department of Energy. It also recognizes the importance of partnering with industry, the states and regional stakeholders in addressing these challenges going forward.

Thank you. I would be happy to address any questions that you may have.

Additional Written Testimony

Key Emerging Trends in the US Electric Utility Industry

A number of inter-related trends in the US utility industry are beginning to reach scales at which they may impact grid operations or interact with one another.

Increasing Data Volumes from the Grid

While much of the public discussion around increasing volumes of grid data has focused on meter data, the really large volumes are in fact coming --and will continue to grow--from newer instrumentation on both transmission and distribution grids. Already the more than 1,000 Phasor Measurement Units

(PMU's) on the US transmission grid produce vast volumes of data[1], and the number of PMU's is expected to grow significantly in coming years (PNNL expects that US transmission PMU data flow will eventually reach 50,000 PMU's and 1.5 Petabytes/year). Early adopters are the reliability coordinators and system operators (ISO/RTO), with transmission system operators following. Early work on applications of PMU's at the distribution level is being done, but no significant penetration exists to date.

PMU's are devices that measure voltage and current at different points across the grid as often as from 30 to 60 times per second. These measurements are also time-stamped, or synchronized, by GPS technology, which means that by comparing the measurements at any given moment operators can get an unprecedented picture of system conditions in near real-time. A handful of utilities and federal power marketing entities pioneered the early deployment of PMU networks, for purposes of wide-area situational awareness on the transmission system, particularly in response to cascading outage events in the West in 1996 and again in 1999. The Bonneville Power Administration became the first utility to deploy such a network in 2000[2]. Public/private partnerships were key to accelerating deployment of these networks after the Northeast/Midwest blackout of 2003—the largest in US history--and a number of investments pursuant to the American Recovery and Reinvestment Act (ARRA) of 2009 successfully leveraged additional industry investment[3].

The vast amounts of data now being generated from PMU's are due to that fact that these are streaming devices--much like video--in that, they produce streams of data that are used at multiple destinations. It's expected that similar technology is about to start penetrating distribution grids, which will have orders of magnitude more streaming sensors than the transmission system. As interest in asset monitoring continues to increase, vast new volumes of asset health and operational data will be generated, some to be used in real time, some to be stored and analyzed later. The newer protection and control systems needed for advanced grid functionality, such as integration of distributed generation and responsive loads at increasing scale will generate enormous volumes of sensor data that must be transported, processed, and consumed in real time, and potentially stored for offline analysis. All told, the utility industry will experience an expansion of data collection, transport, storage, and analysis needs of several orders of magnitude by 2030. Part of this growth is due to the next item in this list. New approaches for utility data acquisition, transport, storage, and analytics processing are needed, and new operational paradigms such as Cloud storage and computing will play roles as utility business models change.

Faster System Dynamics

The implementation of new grid capabilities has brought with it great increases in the speed with which grid events occur. This is especially true on distribution grids, although the trend exists for transmission as well. In the last century, aside from protection, distribution grid control processes operated on time scale stretching from about five minutes to much longer, and human-in-the-loop was (and still is) common. With the increasing presence of technologies such as solar PV and power electronics for inverters and flow controllers, active time scales are moving down to sub-seconds and even to

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[1] North American Synchrophasor Initiative, "PMUs and Synchrophasor Data Flow in North America as of March 19, 2014;" available at: https://www.smartgrid.gov/sites/default/files/doc/files/naspi_pmu_data_flows_map_20140325.pdf

[2] Virden et al, "Next Steps in Grid Modernization: Early Returns on U.S. Investment, and New Innovations in Electric Infrastructure Policy & Technology"; (April 2012).

[3] For example, see: Vanzandt and Nokes, "A Western Partnership Succeeds In Enhancing Grid Reliability"; (August 2014); available at: http://smartgrid.ieee.org/august-2014/1131-a-western-partnership-succeeds-in-enhancing-grid-reliability

milliseconds. The presence of significant levels or penetration of solar PV on a feeder (where prosumers may inject power into the feeder) has led to voltage stability problems, according to initial reports from Hawaiian Electric Company (HECO) and San Diego Gas & Electric (SDG&E). Conventional feeder control has been too slow to compensate, so each utility has applied fast power electronics in the form of DSTATCOM devices to stabilize voltages. As this fast automatic control has become necessary, the need to obtain data on the same times scales on which control must operate has arisen. Consequently, there is a sort of double impact: there are many more new devices to control on the system--and much faster dynamics for each device--leading to vast new data streams and increasing dependence on ICT for data acquisition and transport, analysis, and automated decision-making.

Hidden Feedbacks and Cross-coupling

As more advanced grid applications and systems are developed and deployed, more system interactions are emerging. These interactions are inevitable, although it seems that many applications have been developed to execute specific functions—without reference to broader system implications. These interactions occur and will continue to occur because the grid itself constitutes a hidden coupling layer for all grid systems. The coupling occurs due to the electrical physics of the grid, and in most cases this coupling propagates at nearly the speed of light. Such coupling can cause effects ranging from reduced effectiveness of smart grid functions, up to and including wide area blackout. Coupling exists because of electrical connectivity: for example, devices connected to the same feeder share voltages. In instances in which Demand Response (DR) is operated independently of voltage regulation, sudden changes in load change the conditions under which voltage regulation settings were created. This, in turn, leads to the settings becoming inappropriate on very short notice – too short for the relatively slow conventional voltage regulation methods to compensate effectively.

This applies to both commercial DR and aggregated residential DR, although most commercial DR has been operated so slowly that in the past this was not much of a problem, until more fully automated DR became available. The net impacts of this particular interaction can include[4]:

- Reduction of the effectiveness of DR by as much as 15 percent;
- Voltage violations on the affected feeder; and
- Feeder level circuit breaker trips.

This situation is further complicated by the fact DR applications may be developed outside the context of utilities' distribution management systems; and that, in some cases, third-parties are bypassing utility systems altogether, to aggregate DR through direct interaction with customers.

Other interactions have the potential to create wide area blackouts if they should occur during times of low stability margin operation. As smart grid functions become more complex, it is to be expected that more interactions will become manifest. Generally, effects of such interactions will not be important at the scale of pilot projects and demonstrations, but will become significant as penetrations pass tipping points that are becoming apparent from experience at several utilities.[5,6] In such cases, the correlation and

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[4] Medina, et al, "Demand Response and Distribution Grid Operations: Opportunities and Challenges," IEEE Trans. On Smart Grid, September, 2010, pp 193-198

[5] Thomas Bialek, "Renewable Impact on Electric Planning," available online: http://www1.eere.energy.gov/solar/pdfs/highpenforum2013_1_3_sdge.pdf

concentration of assets involved in these new grid applications—within and potentially outside utilities' control—will determine the operational consequences of such interactions.

RPS and VER Penetration

The trend of converting from traditional thermal generation to renewables such as solar and wind (known as Variable Energy Resources [VER]) has been driven by a combination of factors over the past decade, including Federal tax policy and state Renewable Portfolio Standards (RPS). Since VER is not dispatchable in the same way as traditional generation, operational challenges arise for a system originally designed around the concepts of power balance and load-following generation control. Solutions to these problems involve new types of grid components such as energy storage, but also greatly expanded measurement, data transport, analytics, and control.

Bifurcation of the Generation Model

Similarly, the VER/RPS trend is shifting the model of central station generation connected to transmission, to a mix of that and distributed generation connected to distribution grids. This split or bifurcation changes grid operations drastically, introducing multi-way real power flows and other effects not included in original grid design assumptions. In addition, distributed generation may be able to offer services ***back*** to the grid operator, such as reactive power regulation—a shift in paradigm that can provide operational benefits if the appropriate incentives are put in place.

Responsive Loads

Demand response has been used by the utilities for decades, mostly in conjunction with commercial and industrial customers, and mostly in a non-automated fashion. More recently, efforts have been made to create automatically responsive loads at the commercial building level, at the residential level, and even at the individual appliance level. With the rise of advanced commercial building controls, behind-the-meter storage, wide area communications, bulk power markets, and evolving approaches to "transactive" load coordination and control, the concept of building-to-grid integration is moving to a bidirectional multi-services model. This suggests it is possible that a grid/buildings convergence is forming[7]. Ultimately, this convergence would result in an extension of the grid--involving a class of assets *not* owned by the utilities. In this scenario, the observability and controllability issues resident in the operation of today's distribution grids will also extend to include grid-connected, responsive loads.

Changing Fuel Mix

The change from traditional thermal generation to renewable sources is one shift that's been underway for some time; but it is also the case that retirements of coal and potentially nuclear plants will manifest in new grid operating characteristics. In addition, this trend is surfacing in its effect on utility planning – for example, in some regions, gas pipeline planning and build-out has to a significant degree displaced transmission line planning and build-out. At present, the industry lacks the tools required for ***joint*** electric and gas system planning. Moreover, Information and Communication Technology platforms do not yet commonly exist within utilities to support interactions with both electric and natural gas markets.

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[6] Martin Lamonica, "Why is Hawaii Scaling Back on Solar?" Greenbiz.com, Jan 28, 2014, available online: http://www.greenbiz.com/blog/2014/01/28/solar-hawaii-utilities-scaling-back

[7] See Hagerman et al, "Buildings to Grid Technical Opportunities"; available at: http://energy.gov/sites/prod/files/2014/03/f14/B2G_Tech_Opps--Intro_and_Vision.pdf

Evolving Industry/Business Models and Structure

A number of key stakeholders believe that the penetration of new functions at the distribution level, along with responsive loads and distributed generation, is causing the original mode of distribution operations to become inadequate. Proceedings in Hawaii, New York and California are all aimed at reconsidering the roles and responsibilities of distribution grid operators as is much thought leadership in the industry at large[8,9,10].

Evolving Control System Needs

Utility controls systems have traditionally been centralized, with hub and spoke communication to remote subsystems and equipment, as needed. As the various trends cited above have emerged, the need for changes in control system structure has become apparent. Specifically, control systems must change from being centralized, to a hybrid of central and distributed control. Distributed control is distinguished from *decentralized* control in the following important way: decentralized control involves moving some control to remote locations; but the remote elements perform controls tasks in isolation, with perhaps some coordination from a centralized supervisory element. Distributed control includes those aspects, but also is distinguished by the following: the decentralized elements cooperate on solving a common problem. This aspect creates new requirements for communication, methods for coordinating the elements and converging on a common solution.

Interdependence on Information and Communication Technology

Interdependence of electric and ICT infrastructure has increased in recent decades, and recent trends in the utility industry suggest an even tighter coupling of these networks in coming years. While cyber vulnerability must remain a focus of federal research, development and information-sharing efforts with industry, the convergence of these networks also holds substantial promise as a platform for energy innovation, leading to potential new value streams and enhanced system resilience. The pace at which this convergence occurs and new services and operational methods emerge will turn on a number of factors, including regulatory structures that set the framework within which utilities and grid operators prioritize infrastructure investment decisions.

In assessing the challenges and opportunities presented by the enhanced interdependence of grid and ICT infrastructure, it is key to understand the ways in which utilities might use different classes of data, the characteristics (such as latency) that determine the operational and business value of that data, the implications for communications network investments, and required evolution in analytics, visualization and software tools that will help unlock new services and bolster desired system attributes such as resilience. Grounded in this understanding, a handful of key priorities emerge as potentially appropriate initiatives designed to convene relevant stakeholders, provide tools and methods that help inform industry investment strategies, and accelerate the pace at which innovations are brought to market. In particular:

- Leadership in convening industry stakeholders for purposes of developing a ***reference architecture for control systems***-- extensible across electric and ICT networks--is a key first step in enabling the

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[8] Lorenzo Kristov and Paul De Martini, "21st Century Electric Distribution System Operations," available online: http://smart.caltech.edu/papers/21stCElectricSystemOperations050714.pdf

[9] Hawaii PUC, "Exhibit A: Commission's Inclinations on the Future of Hawaii's Electric Utilities," available online: http://puc.hawaii.gov/wp-content/uploads/2014/04/Commissions-Inclinations.pdf

[10] NYS Department of Public Service staff, "Reforming the Energy Vision," available online: http://www3.dps.ny.gov/W/PSCWeb.nsf/96f0fec0b45a3c6485257688006a701a/26be8a93967e604785257cc40066b91a/$FILE/ATTK0J3L.pdf/Reforming%20The%20Energy%20Vision%20(REV)%20REPORT%204.25.%2014.pdf

kinds of innovations that will enhance grid observability and controllability in coming decades. A reference architecture is a technology neutral framework applicable to complex systems such as the grid, which takes a disciplined approach to characterizing system components, structures and attributes. Such an architecture helps identify potential gaps in technology and operations, assists in defining key system and component interfaces and provides context for interoperability and standards-setting activities.

- Exploration of mechanisms and tools relevant to ***ensuring ICT network investments are sufficient*** to enable enhanced grid management functions at the distribution level. For example, while wireless mesh networks built to support AMI deployments are more affordable than optical fiber or other advanced wireless technologies, certain characteristics may render them insufficient for system restoration and resilience functions in an outage or emergency scenario. In addition, early indications suggest meter communication networks have often been designed only to support consumers' usage reporting and thus lack the bandwidth and latency capabilities needed to support operation as a grid sensor network. Networks are increasingly integral to modern power grid operations, yet most power grid simulation and design tools today lack means to include communications-related elements. Measures to accelerate integration efforts and move them into use by utility planners and design engineers may help better inform grid operators' investment decisions. Moreover, certain regulatory reforms and/or tax incentives to encourage appropriately scaled investments may warrant consideration.
- And finally, ***acceleration of ongoing research and development efforts to develop new grid management tools***, linking capabilities in high-performance computing and advanced power systems engineering with software developers and utility/grid operators. While it's reasonable to expect the commercial marketplace to ***eventually*** solve issues associated with emerging software needs of the utility industry, it is unclear this will take place in time to keep pace with the changing operational landscape of the grid, particularly at the distribution level. That's because software developers face a classic "chicken and egg" scenario. The market for these solutions is relatively thin (confined to the number of utilities in North America), which leads to conservatism in investing in new products for control systems that, in essence, might also replace existing product lines. Utilities, in turn, may agree with an assessment of their changing needs—but don't commit to buying new solutions until they have been well tested and demonstrated. Within this context, DOE can play a key, ongoing role in bringing together the ecosystem of stakeholders required to accelerate the path for new products from the laboratory to control rooms, in a way that unlocks new value streams and bolsters system attributes such as enhanced reliability and resilience.

Architectural View of the Grid

The grid may be viewed as a complex network of structures that has evolved over the past century, driven by a patchwork of regional economic prerogatives, diverse business models and variable regulatory structures. A number of current trends including the convergence of electricity and natural gas infrastructures, and the bifurcation of generation—the emerging split of generation between bulk transmission-connected generation and smaller distribution-connected resources—are adding additional complexity, as well as providing potential opportunity to create new value streams and enhance system resilience.

Below, selected views of selected present grid structures provide a number of key insights relevant to emerging trends, specifically with respect to industry structure, business/value streams, electric/power system structure, and control/coordination frameworks.

Industry Structure

Geographic-based structures have shaped the evolution of the electric power industry over the past century. However, the deployment of more non-utility assets interacting with the grid and emergence of merchant and prosumer-controlled distributed energy resources operating as a set or group despite wide geographic dispersal can erode the concept of a geographically bounded customer.

A review of industry structures shows that distribution operations are disconnected from the rest of the system in a control and coordination sense. In certain contexts, however, system operators at the wholesale level had already begun bypassing distribution utilities to directly engage distributed energy resources in the last few years. Recent court rulings and industry deliberations on the future of distribution have already opened up reconsideration of roles and responsibilities for ensuring system reliability, especially at the distribution level and have implications for grid control and coordination structure. However, many state and local laws and regulation would have to be changed.

Business/Value Stream Structure

Modeling the accrual of value streams within industry structures helps illustrate the kinds of business ecosystem partnerships required to realize such value. Regulatory variables figure prominently in determining which entities can realize such value, and what forms these values (products or services) may take.

Low-growth value streams are those most directly connected to provision of electricity as a regulated commodity; whereas potential high-growth streams are tethered to customer/prosumer products, devices, and services. Once again, what value streams are regulated, by whom, and under what terms, will bear on the distribution of these opportunities in what is essentially a zero-sum situation, and what entities are positioned to capture shares of the sum.

Electric System Structure

The structure of the grid determines important system properties and basic limits. For example, in major cities, the structure of dense underground urban mesh underlying the distribution system limits any services that buildings might supply to grids to the local feeder secondary, except for those that reduce net load. In these contexts, distributed generation and storage cannot push power back into the distribution feeders, and thus cannot push power to the grid. Furthermore, tripping of multiple network protectors will cause a portion of the secondary mesh to island. Since the network protectors are not coordinated, the extent of the island is unpredictable. Where fuses are used in the secondary, some of these may blow, requiring truck rolls to replace before normal operation can be restored.

The enablement of two-way flows within distribution systems in the face of such structural limitations can have costs that go beyond those related to new premises equipment and software. Some amount of change at the utility level may be needed just to unblock the potential for certain building-to-grid energy/power services.

While basic coupling occurs electrically at multiple levels in the grid, coupling can and does occur in other ways, some of which can be quite subtle. Coupling can occur through controls, markets, communications networks, fuel systems, loads, and social interactions of customers/prosumers. Unsuspected coupling is a hazard of increasing grid complexity.

The list of interactions between system elements is growing as the penetration of new devices and functionality increases. Responsibilities for reliability management have historically been established hierarchically, starting with wholesale generation/transmission treated in a semi-integrated fashion, but then separately at a lower level within distribution—where reliability requirements have historically been assigned to single regulated entities. Two-way power flows within distribution systems will require greater focus on making more explicit shared responsibilities for reliability management (and supporting investments) between distribution system operators and loads/producers within that distribution system.

Another structural consideration relates to system inertia and coupling of generators with droop control through the transmission system, which is crucial to proper grid operation. The implications for system inertia associated with replacing traditional forms of central station generation with DG and variable resources are not thoroughly understood. This is particularly the case in the loosely coupled Western Interconnection. Exploring methods for measuring—and potentially predicting—system inertia associated with existing operations as well as in context of a changing generation mix may provide key insights for policymakers and regulators concerned with system reliability. At present, this may require additional R&D efforts. In addition, such methods would be useful in the development of joint planning tools, which likewise do not yet exist for purposes of enhancing industry and policymakers' understanding of emerging infrastructure interdependencies (such as electricity and natural gas). Meanwhile, efforts underway in ERCOT to consider inertia-related grid services merit careful attention. Novel configurations of assets at the distribution level (including storage) may ultimately be leveraged to help provide such services—but once again, regulatory friction associated with determining which entities are eligible to provide such services, and allocation of costs and benefits, may once arise under current law.

Control/Coordination Framework

The inclusion of markets inside closed loop grid controls means that markets could contribute to control instability. The problem will worsen with additional entities in the loop and the presence of faster dynamics and diverse sources of net load volatility.

Consider the isolation of distribution control and coordination from the rest of the grid in the light of regulatory structure, namely the Federal regulation of the bulk power system, versus State and local regulation of distribution grids. Note that regulatory structure, industry structure and control/coordination structure are currently aligned—but this alignment is with a control structure that is increasingly problematic as the grid changes due to emerging trends.

In particular, the changing nature of system dynamics, implications of DER deployment at increasing scale, new technologies and models of consumer engagement are putting pressure on regulatory boundaries drawn over the past century. Current academic and industry literature suggests a consideration of a new, Distribution System Operator (DSO) model, though this thinking is very new and includes a highly varied set of topics.

Grid Architecture 2030

Looking forward using grid architecture principles and methods, it is possible to derive a number of preliminary insights:

Buildings: Buildings are significant users of electricity. Today, they exist primarily as passive loads, but hold promise for potentially providing services back to the grid in a transactive mode. The key grid-side factors limiting the expansion of building-to-grid services are not interoperability or interface standards (important though these are) or quantification of value streams. Instead, they are structural limitations to the distribution grid (such as those previously discussed in context of dense urban mesh), and current lack of a coordination mechanism on the grid side that extends across the grid/building boundary.

Storage: Storage is unique in that it can be capable of taking energy or power from the grid, adding energy or power to the grid, and supplying a wide range of grid services on short (sub-second) and long (hours) time scales. It can supply a variety of services simultaneously. There is an emerging sense that the combination of fast bilateral storage, flexible grid interface mechanisms, and advanced optimizing control is *a general purpose grid element as fundamental as power transformers and circuit breakers*. One of the most significant impacts of storage will be the ability to *decouple generation and load volatilities*. Since it is known that the impact of storage can be location-dependent, there is a need for new planning tools and procedures to make use of storage as a standard grid component, and to optimize storage location and size.

Whole Grid Coordination (Laminar Coordination Framework): Coordination is the means by which distributed elements are made to cooperate to solve a common problem—in this case, grid control. It is clear that existing grid coordination has gaps and lacks a rigorous basis—and that the gap is widening, with respect to grid behavior and desired capabilities. Where the grid is concerned, a structure that accommodates multiple simultaneous approaches to control is likely required. ***Local optimization inside global coordination*** is a principle for a mix of centralized and distributed control that provides properties such as boundary deference, control federation, disaggregation and scalability.

ISO's/RTO's and DER Dispatch: In certain (but not all) markets today, DER is being dispatched by Independent System Operators or Regional Transmission Operators, which retain system balancing and reliability responsibilities at the transmission level, and also operate wholesale markets. The ISO/RTO approach has led to several problems that have caused the industry to seek alternative arrangements. For example, letting an ISO/RTO handle DER causes a bypassing of distribution operators, which introduces ambiguity in the responsibility for distribution reliability, compromising the ability of the distribution operator to manage its assets and operations. A recent 3rd Circuit Court of Appeals ruling, a position statement by PJM, and proceedings in California and New York are addressing these issues. Second, as the number of devices that can participate in the markets and grid operations grows, a scaling problem arises in terms of communications, as well as in the complexity and computational requirements associated with control mechanisms (and associated latency requirements).

DSO Structure: While motivated by the need to clarify and simplify responsibility for distributed reliability, the emerging thinking around a Distribution System Operator (DSO) model appears entirely consonant with a laminar coordination structure. Since the laminar structure was motivated by the need for whole grid coordination with a rigorous basis for predicting properties such as scalability, it is reasonable to expect that the DSO model can share those properties that derive from such structure. If the DSO were to be implemented as an independent DSO (IDSO), then the IDSO may have issues of economy of scale sufficient to be viable and related cost problems.

Power Electronics/AC Power Flow: There are several means to adjust power flows in AC power systems, including phase shift transformers, variable frequency transformers, and various forms of power electronics. Power electronics get attention as edge connection tools, in the form of inverters for solar PV and storage, but can be used internally in the grid for power flow control.

Flexible Electric Circuit Operation: Adjustable flow control can be used to provide flexibility in electric circuit operation. It can also be used to cut or limit the effect of some kinds of constraints that exist in present circuits, such as unwanted cross feeder flows or unscheduled flows to the transmission system. Meshing provides more paths for power flow (with flow controllers directing the "traffic"), such that it becomes possible to make more effective use of storage and distribution level DG. That means the cost effectiveness of such assets is enhanced two ways: better sharing of the assets, and enablement of new value streams and innovations. At present, distribution grids suffer from poor observability given their lack of sensing capability. Additional efforts to develop observability strategies and tools for design of distribution sensor networks would further enhance flexible circuit operations.