Envisioning an S2 Grid

An Exercise in Understanding Grid Step Change

July 2023

Foreword

The Pacific Energy Institute (PEI) was founded to address the need for independent, informed, and balanced perspective on the complex issues related to a more distributed electric system. We seek to change the conversation by drawing upon leading insights from across the globe, to inform decision makers in the transformation of electric networks.

The Fellows and Advisors have held many excellent discussions over the 18 months (2022-23), following up on the two initial white papers *A Gambit for Grid 2035* and *Institutional Transformation.* These papers focus on the "why & what" of systemic changes to the grid, as well as "how" to manage the scope and scale of changes underway. Together, these papers provide insights to help the many industry constituents better understand and address the opportunities and mitigate the potential challenges inherent in the chaotic systemic shift happening to the electric sector. This paper attempts to extend that thinking by addressing what is meant by a "step change grid." While not a prescription, it shows how taking a different approach to the grid as a whole based on emerging 21st century needs and realities leads to significantly different grid structures, operations, and roles for electricity sector entities.

Acknowledgments

This paper was developed by Jeffrey Taft of the Pacific Energy Institute. The ideas in this paper were developed through publicly available work done at the Pacific Northwest National Laboratory and a series of collaborative discussions within the Pacific Energy Institute and with others across the globe regarding the future of the electricity systems in developed countries based on insights from Australia, United States and Europe.

This paper also benefited directly from thoughtful discussions with Paul De Martini and Mark Paterson.

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Disclaimer

The views and opinions of the author expressed herein do not necessarily state or reflect those of the Pacific Energy Institute's Fellows and Advisory Board, or their respective organizations.

Contents

Background

In 2021, the Pacific Energy Institute (PEI) released a significant white paper entitled *A Gambit for Grid 2035*.[1] The paper contains several advanced ideas about electric grid evolution but one in particular has struck a chord with some in the electric utility industry. That is the concept of the need for a step change in the structure and operation of 21st century electric grids. The paper argues that continuing the present-day approach to linear incremental change of the grid is not only ineffective, it will eventually become detrimental to the users of electricity. This step-change concept has been adopted by AEMO[2] in Australia, where penetration of rooftop solar PV (photovoltaics) is at far higher levels than in the United States (US). We view this as a leading indicator that the thinking outlined in the PEI paper does in fact constructively address a real emerging issue for the electric sector worldwide.

While the PEI paper provides the rationale for the necessity of step change, it does not address the nature of the step change, nor did it intend to either describe nor prescribe what we now refer to as an S2 grid. There is considerable discussion in the industry about future grids and any number of papers and presentations have offered visions of various kinds for “the grid of the future.” The vast majority of these visions are really small extensions of the present day S1 grid for the reason that it is hard to escape the bounds that regulatory constraint and over 100 years of grid design and operational history tend to impose on grid thinking. But as the PEI paper indicates, that is not the path from the grid we have to the grid we need.[3]

The purpose of this paper is neither to predict nor prescribe an S2 grid. Instead, it is an exercise in envisioning ways in which an S2 grid in the US could differ from the present-day US grid. It does not propose to show how to solve every problem or explain operational details. The purpose is to help expand the idea of a step change grid and to break out of some of the linear incremental thinking that dominates so much of the discussion on grids of the future. Keys to this approach are fundamental changes to core characteristics of the grid, and a recognition that the constraint-based volumetric charging model for utility business operation must change to an abundance-based multi-tiered services model.

This paper is not an architectural specification for an S2 grid, but employs much architectural thinking. This is because proper architectures provide the means to reason about complex systems without having to design them in detail or build them first. The methodology behind the discipline of Grid Architecture applied here is extensively documented online.[4] This paper also builds upon a number of blogs written for PEI that address specific issues related to the idea of an S2 grid, including how to use energy storage in the grid, fly-by-wire control, incremental vs. core grid transformation, centralization vs. distributed coordination, and the fallacies of Distributed Energy Resources (DER)-related grid optimization. What follows is an exploration of ideas derived from a body of grid architecture work that helped lead to the concepts in the PEI Gambit paper.

[1] https://pacificenergyinstitute.org/wp-content/uploads/2021/08/A-Gambit-for-Grid-2035-final-version.pdf
[2] Australian Energy Market Operator
[3] Statement originally articulated by Ken Fong, former Director of T&D Planning at Hawaiian Electric and Emeritus Fellow of PEI.
[4] https://gridarchitecture.pnnl.gov/ Sources for many of the diagrams in this paper can be found here.

Preliminaries

First, we review a few basic concepts to lay to groundwork for how the S2 grid exercise will be depicted.

We start with three basic architectural principles:

- An architecture is the highest-level depiction of a complex system – it enables one to reason about the system's characteristics and behavior.
- An architecture consists of three things: black box components, structure, and externally observable characteristics. Components are related via structure to yield systems having specific characteristics. Structure places bounds on what a system can and cannot do.
- Ultra-Large-Scale complex systems such as power grids are composed of a network of complex structures interconnected in complex ways. Consequences of this are that a grid architecture problem must be solved simultaneously for all of the structures, and no change to the grid exists in isolation.

In accordance with architectural principles, we will treat components as black boxes for the most part. This means that we will be concerned with function and externally observable characteristics to some degree but not much about how the component works internally. We shall only slightly be concerned with technology implementations and engineering design details, despite how important they are for real implementations.

The scope of the discussion will include six of the seven canonical grid structure classes: electrical infrastructure, industry structure, control, digital superstructure, coordination, and convergent networks (also known as sector coupling, meaning relationships of the grid to such networks as transportation, water and fuel distribution, and data transport). The seventh, regulatory structure, will not be addressed here, but see the discussion in the PEI Gambit paper about industry decision loops – this contains a strong implication for how electric sector regulation changes can benefit consumers.

The development of a plan to implement a new or changed complex system requires knowledge of two basic things in common with your GPS navigation system: where you are and where you want to go. In this paper we will not discuss transition plans, just some views on the "where you want to go" part of the problem. It is certainly the case that no developed nation can just shut down and rip out its grid to replace it with a new one. Aspects of transition and change in complex systems are discussed in the PEI paper *Survive, Thrive or Decline?* by Mark Paterson.[5]

The S2 grid ideas discussed here will be described in the present tense. Again, this is by no means a prediction or prescription, it is simply a convenient way to present the material.

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[5] https://pacificenergyinstitute.org/wp-content/uploads/2022/10/2022-09-PEI-Survive-Thrive-or-Decline-Organisational-Transformation-in-the-Power-Sector.pdf

Core Principles

The S2 grid depiction given below is based on a small set of core postulates:

1. Service to consumers, not control of them
2. Abundance thinking instead of constraint thinking
3. Ubiquitous use of buffering for volatility decoupling
4. Fast (sub-minute to sub-second) grid dynamics at all levels
5. Focus on reliability and resilience

The first postulate says that decision processes for the grid place the consumer at the reference input level, not buried at the bottom of a set of nested decision loops (i.e., driving the decision processes, not being the objects manipulated by them).[6] The second postulate means that electricity users should have the amount of energy they want, when they want it, and in the form they want. The third postulate changes the intrinsic characteristics of the grid. The fourth postulate addresses organic changes to grid behavior. The fifth postulate places a premium on grid planning and operation that serves the users, in line with the first postulate. In practical implementations, tradeoffs of objective derived from these postulates would be required.

Electrical Infrastructure

The S2 grid electrical infrastructure differs in many ways form the S1 grid, especially at the distribution level. The reason for so much change at the distribution level is the changed nature of interaction at the distribution edge and the consequent changed relationship between distribution and bulk power systems.

Buffering

A major change in grid structure is the introduction of buffering. Nearly all other complex systems have some form of flow buffering. In piping systems, they are called storage tanks. In logistics systems, they are called warehouses. In communication systems, they are called jitter buffers. They all have the same purpose – to decouple flow variations in on part of the system from another part. In other words, to smooth out fluctuations in sources and uses of whatever flow is involved, be it physical or informational. The introduction of significant power flow buffering to the grid profoundly changes core grid characteristics.

Bulk energy storage is embedded ubiquitously throughout the S2 grid, but primarily at the Transmission/Distribution (T/D) interface substations. These storage units are not treated as generation resources, nor as suppliers of ancillary services. Bulk storage is still used that way, but that is independent of the new Embedded Storage Networks (ESNs). The purpose of embedded storage is to provide the grid with buffering capacity that decouples power flow volatilities. Doing so reduces the effects of variations in both generation and load. This decoupling influences every aspect of grid operation, from interface of edge-based resources to management of bulk Variable Energy Resources (VER), and reduces the need for tight frequency regulation and spinning or ready reserves. It also simplifies balancing, even to the point (with large amounts of storage) of decoupling load from generation. Figure 1 below illustrates three levels of buffering. The top diagram shows early 21st century

[6] Pacific Energy Institute, *A Gambit for Grid 2035*, Figure 4, p. 18.

structure, with minimal or no buffering. It has a complex balancing problem, exacerbated by the presence of variable energy resources, and uses DR[7] as a means to aid grid operation. The middle diagram illustrates the use of sufficient buffering to partially decouple source and loads, thus relaxing but not eliminating the balance problem. The bottom diagram illustrates complete decoupling, achievable only with very large amounts of storage capacity. In this arrangement, the bulk power systems focus on maintaining storage charge state, while the Distribution System Operators (DSOs) draw upon storage for energy to meet load requirements.

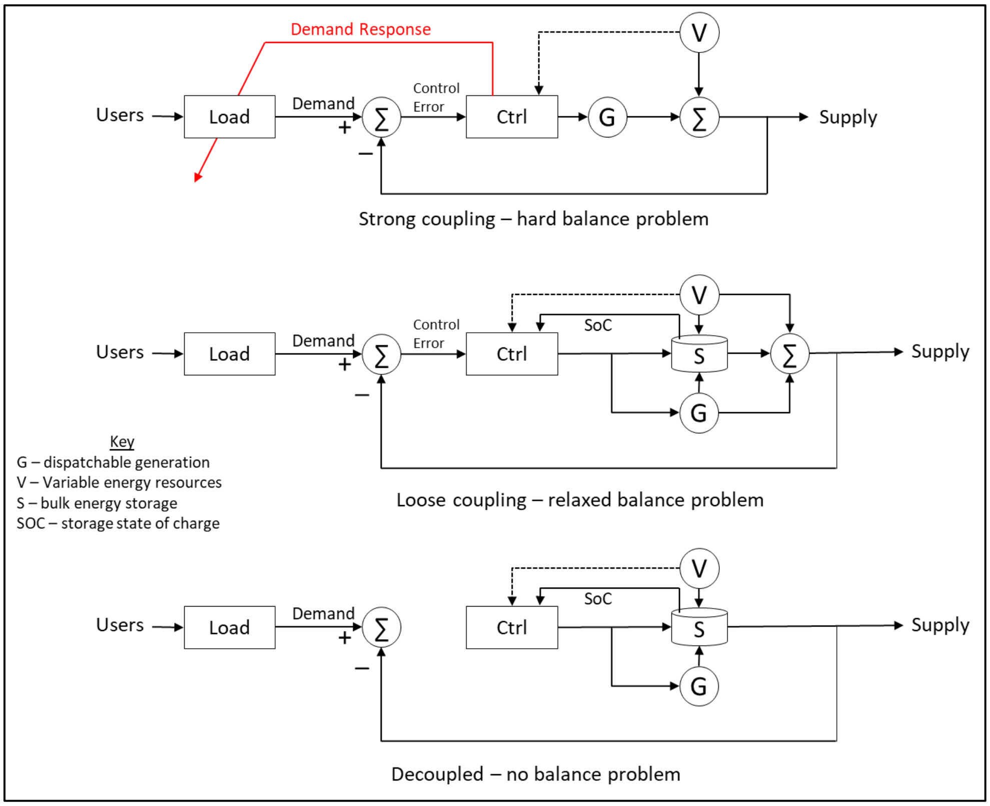

Figure 1 Grid Decoupling Models for Bulk Energy Storage

Bulk storage is also used as a means to improve resilience by providing outage ride-through. Storage devices are located on a per-case basis, as indicated by structural resilience analysis.[8] For example, bulk storage is located at or near Electric Vehicle (EV) charging stations to assure charging during large scale grid outages. Also, substation-embedded bulk storage eliminates the need for use of DR to aid in managing the grid, hence there are no DR programs and customers are not asked to change their behavior to suit the grid operator. This is in line with the abundance thinking postulate.

ESN bulk storage devices are located at substations and are interfaced to the grid via power electronics. The connection point or points depend on the bus structure at the substation and may be connected on the high (transmission) side or the low (distribution side). Figure 2 shows the basic substation storage unit package. These are located at **all** T/D interface substations. Storage power flow ratings are set by

[7] Demand Response – basically load turndown

[8] https://gridarchitecture.pnnl.gov/media/advanced/Resilence_Algebra_Foundation_final.pdf

local substation load peaks and energy storage capacity is selected as a tradeoff involving operation time scale, load profiles, available footprint space, and cost.

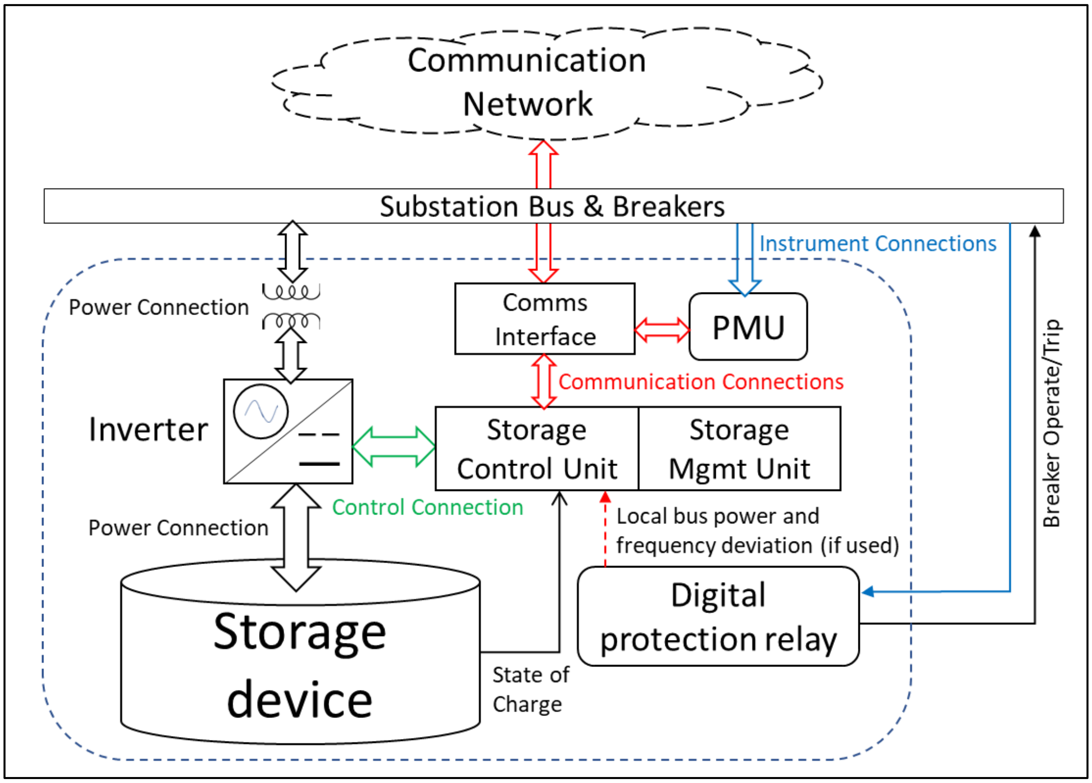

Figure 2 Basic Substation Bulk Storage Unit

Control of embedded storage has no relationship to the previous practice of treating storage as bulk power generation assets with negative output capacity, or as attached ancillary services devices. Embedded storage is directly controlled on a real time basis at the system level by the electric utilities, using grid state feedback telemetry and advanced grid state regulator methods. No market mechanisms are involved in the control of embedded storage (these storage devices do not participate in electricity markets) and embedded storage units are treated as grid assets, much like power transformers or circuit breakers. Battery energy losses are treated as technical losses.

The basic function of the embedded storage network is as a grid state feedback regulator, as Figure 3 illustrates. Real time measurements from the grid feed state regulator controls. This creates the basic “shock absorber” capability which is the essence of the power flow buffing that provides volatility decoupling.

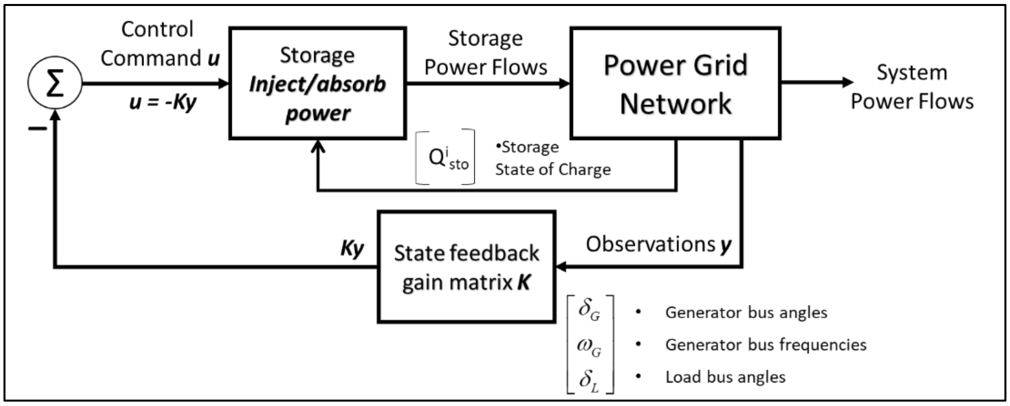

Figure 3 Basic Storage State Feedback Regulator

To accommodate substation load profiles, the control introduces a time-varying reference input to the regulator, as Figure 4 shows.

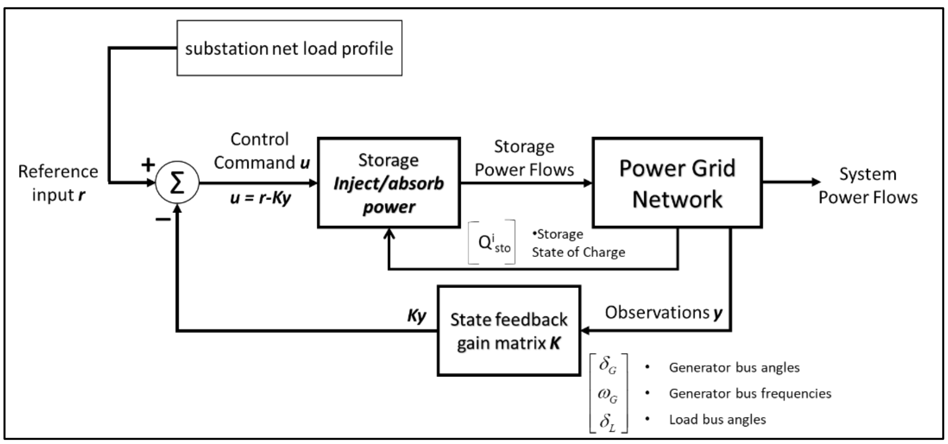

Figure 4 Storage State Regulator with Load Profile Reference Input

Local load balancing (which eliminates the need for DR) is accomplished by employing demand feedback in the same control structure. See Figure 5.

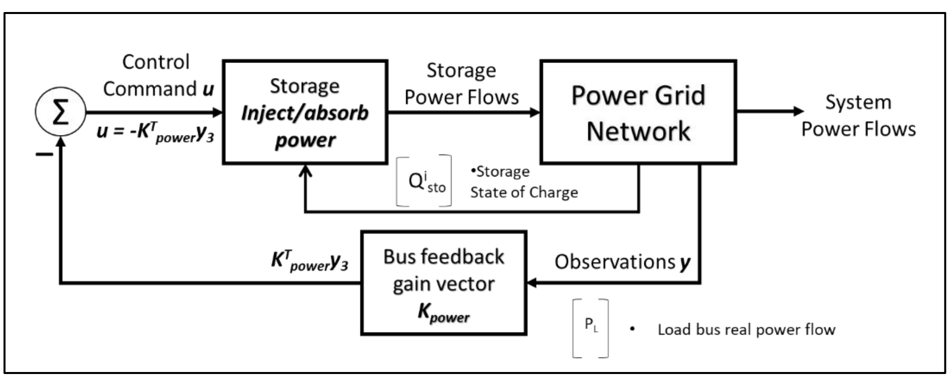

Figure 5 Load Balancing Storage Feedback Control

If augmentation of system inertia is needed, embedded storage networks supply power injections/withdrawals using the same basic control structure with additional telemetry, as indicated in Figure 6.

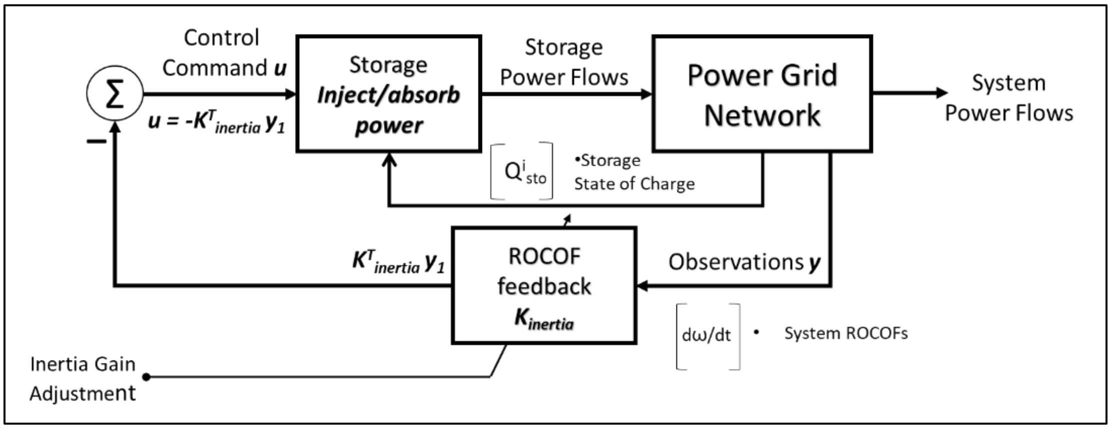

Figure 6 System Inertia Storage Feedback Control

Finally, preparation for planned events is accommodated by creating charge/discharge schedules that modify state of charge appropriately (see Figure 7).

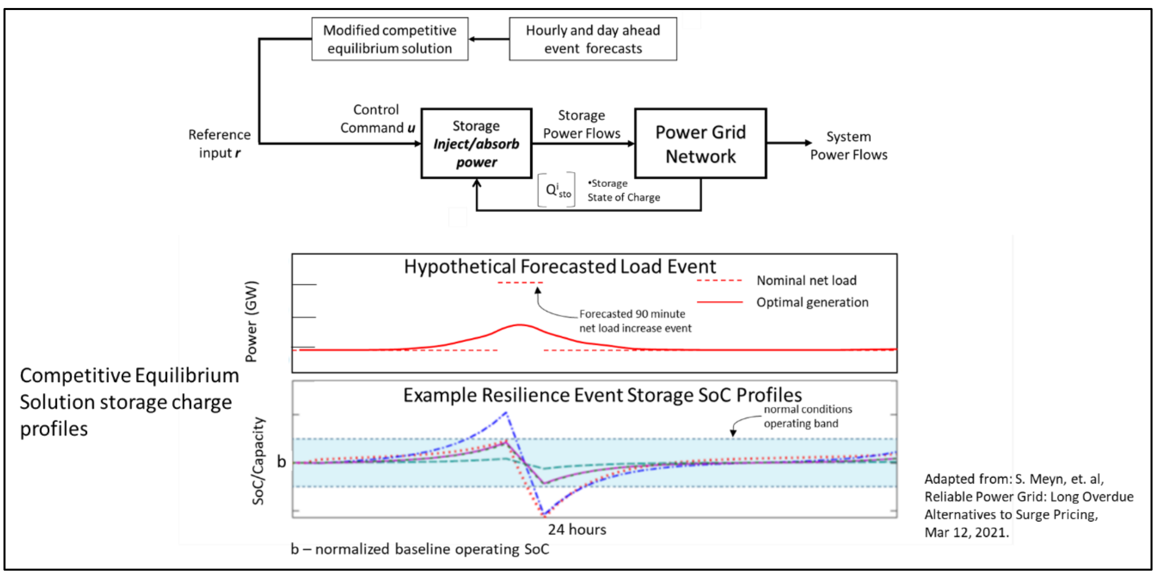

Figure 7 Planned Event Feedforward Storage Control

Note that the same control structure is used in all cases, with differing state variable feedbacks and control laws. These are combined into a multi-modal control that simultaneously handles multiple objectives, as shown in Figure 8.

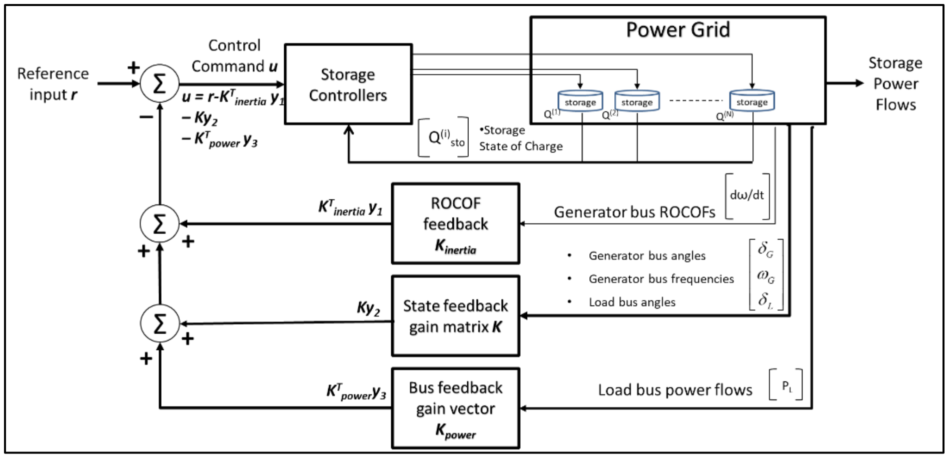

Figure 8 Multi-Modal Storage Control

This control consists of two primary functions: calculating control law coefficients (which must be continually updated to reflect actual grid conditions) and execution of the control laws to operate the storage units. Note that the control signals for the storage units are not identical, but they are all solved for and operated simultaneously. They operate as a coordinated network, not as a set of independent autonomous devices. Figure 9 illustrates the basic control processes.

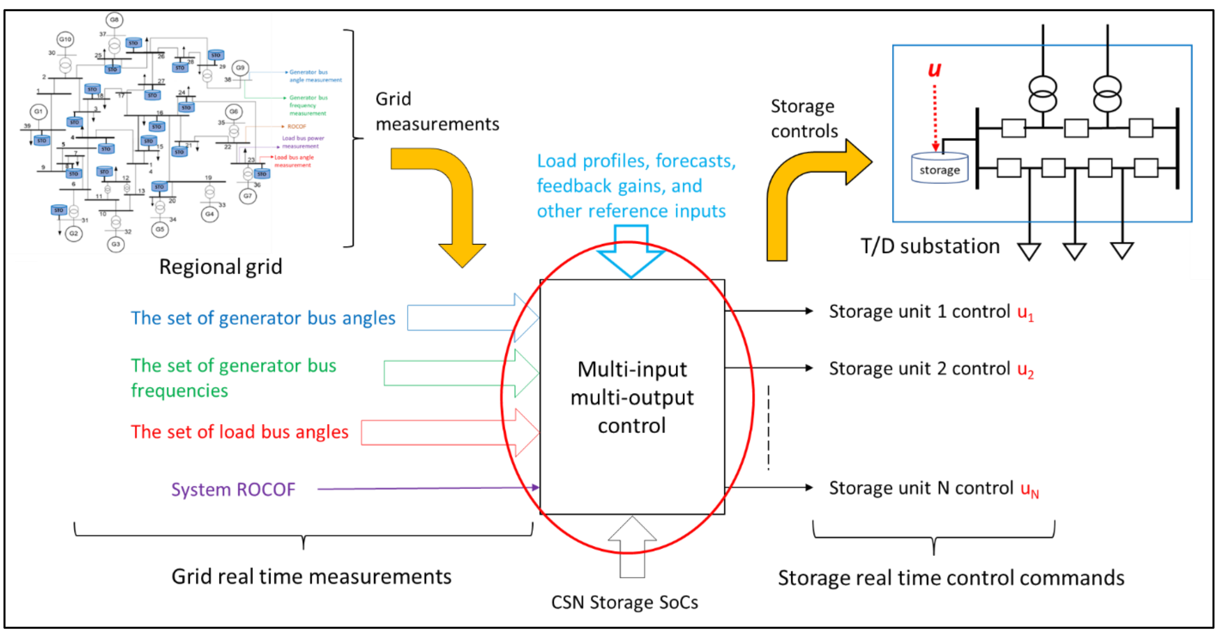

Figure 9 Embedded Storage Control Architecture

This control systems entails multiple roles and responsibilities. The physical location of the control is actually distributed throughout the network for resilience reasons. Multiple entities have roles in the operation of the control system. Figure 10 maps out ESN control roles in the S2 grid.

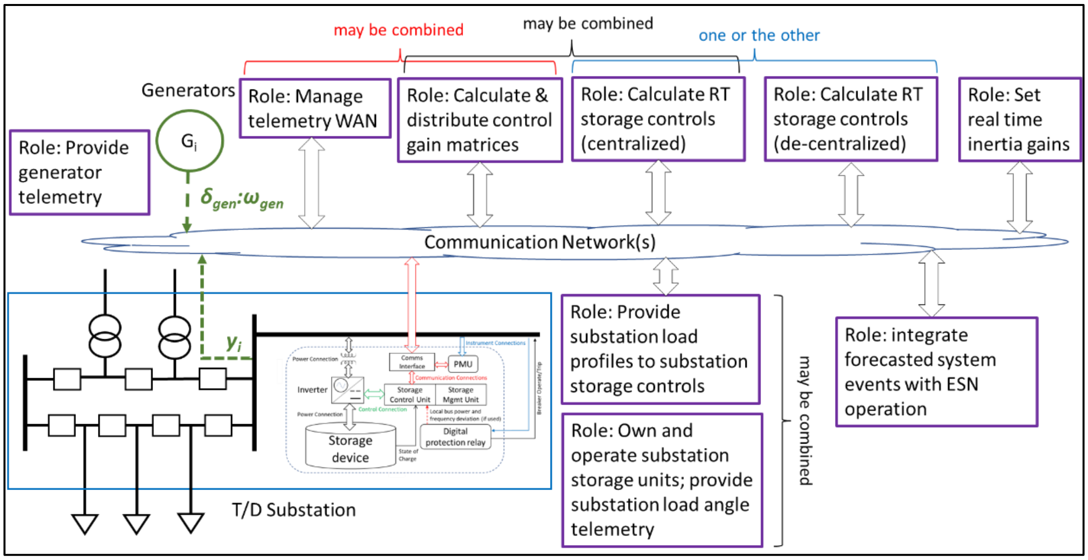

Figure 10 ESN Control Roles

Table 1 shows how roles are allocated. Some roles can be handled by more than one entity and so are assigned based on specifics of particular grids and the relevant entities.

Table 1 ESN Role Assignments

Role	Entity	Comments
Own and operate T/D substation storage units; provide substation load angle telemetry; measure local instantaneous RoCoF	Substation owner/operators (this means that each unit may be owned/operated by a TO, for example, or a wires company). Not all storage units in a regional grid must be owned by the same entity.	This is utility-type equipment, placed on utility property. Role involves providing telemetry from inside the substation ands implementing control directly affecting the substation and so is not suitable for a non-utility entity for cyber security and other reasons.
Provide generator telemetry	Generator operators	This is a connection agreement requirement.
Manage telemetry WAN	TSO/ISO/RTO or Regional Reliability Coordinator	This is essentially the same as for transmission level PMU networks; can be same network and responsible entity
Calculate & distribute control gain matrices	TSO/ISO/RTO, Regional reliability coordinator, or BA	Must have access to system models, grid state, and generator specifications and/or grid telemetry, depending on method used. May be combined with WAN management.
Provide substation load profiles to substation storage controls	Substation operator, such as TO or wires company. Can be done by BA or TSO.	Five-minute to hourly forecasted load profiles needed by storage control.
Calculate RT storage controls (centralized)	TSO/ISO/RTO, or BA (weaker resilience)	Must receive grid telemetry, calculate controls, and distribute to storage devices in a manner like ACE/UCE, but much faster.
Calculate RT storage controls (de-centralized)	TO, or substation owner/operator, depending on how decentralization is structured (stronger resilience)	For fully decentralized mode, control resides in the substations, so by default, the role falls to the substation owner/operator. A TO might do this for its subset of substations (partial decentralization).
Set and distribute real time inertia gains	TSO/ISO/RTO, or BA	Must have full real time system state/contingency view
Integrate forecasted system events with ESN operations	TSO/ISO/RTO, or BA	Must have knowledge of forecasted events and means to combine ESN profiles with BPM operations (via competitive equilibrium)

ESN control extends to all grid-embedded storage devices, but does **not** include any behind-the-meter storage. Customers are free to make use of energy storage for their own internal purposes without submitting to utility control. Because there are no time-of-use rates, no Net Energy Metering, and no use of customer assets for Non-Wires Alternatives, customer interfaces and billing are simplified[9] and there are no issues of energy arbitrage based on time varying rates.

Embedded bulk energy storage also provides:

- Congestion management
- DER hosting expansion
- N-way flow facilitation
- Outage ride-through and Zero CMO[10] support
- Accommodation of fast and slow EV charging, and both stochastic and dispatchable generation
- Grid flexibility and agility via inertia modulation
- Support for microgrids and community microgrids
- Support for peer energy transactions via energy “parking lots”

By specifying bulk storage at the T/D substations, the optimal storage location problem is eliminated.

Embedded Power Electronics

The S2 grid makes extensive use of embedded power electronics at all levels. These devices are used for a number of purposes, including:

- Adjustable flow control
- Voltage/reactive power regulation
- Stabilization
- Synchronization
- Interconnection

Flow control is used at the bulk power system level to manage transmission line loading and to control power interchange among neighboring utilities. It is also used at the Eastern/Western/ERCOT /Quebec Interconnection Intertie level, where the old 200-Megawatt (MW) AC-DC-AC converters have been replaced with 5000-MW power electronic ties. The major interconnections are not unified into a single national synchronous grid. Power electronics is also used for endpoint power conversion for HVDC transmission lines where they exist but no national HVDC backbone has been created.

Similar functionality exists at the distribution level, with power electronics deployed on primary feeders and at service transformers. Connection of non-utility-owned such as rooftop PV is via power electronics in the form of controllable inverters. These inverters provide for controllable power injection into the grid, and in some areas also provide voltage/reactive power regulation. The inverters are operated in any of several modes (not just grid-following and grid-forming), as Figure 11 shows.

[9] Unlike in the 2020’s, when even experienced utility economists could not decipher their own home electric bills.
[10] Customer Minutes of Outage

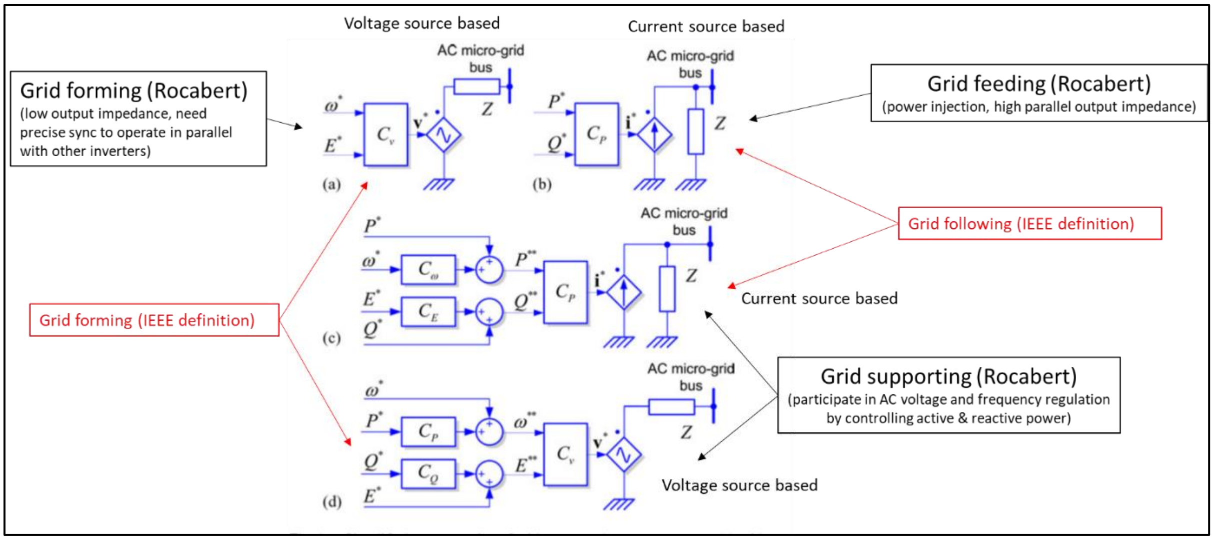

Figure 11 Inverter Control Modes

Storage and power electronics form two parts of a triad that is key to the structure and design of the S2 grid. The third part, advanced control, is discussed later in this paper.

Generation

Generation consists of small modular (nuclear) reactors, gas turbine plants, bulk wind and solar, hydro (including low head hydro), and community-level and rooftop solar PV. Transmission-connected bulk generation facilities are operated as distributed networks interconnected by partial mesh transmission systems managed by transmission systems operators (either independent entities, or as roles supplied by vertically integrated utilities). Gas turbine generators provide firming and dispatchability, and combined with embedded storage (see above) enable best use of renewables. This arrangement allows for maximal use of renewable generation *when it is available*, without compromising system reliability or resource adequacy. Fusion-powered electric generation remains 30 years in the future, still slipping at the rate of one year per year.

Critical facilities are powered by sub-40 kW (kilowatt) nuclear micro-reactors of the type developed in the 2020s for space applications.[11] These sealed compact uranium or americium-based reactors generate heat via natural nuclear decay to generate electricity for 20 years before being replaced like cartridges. Smaller units are used to power critical infrastructure elements, such as core communications and control systems. In addition, some community microgrids, campuses and military bases are powered by 15 MW thermal/5 MW electrical high-temperature gas-cooled micro-modular nuclear reactors.[12,13]

Sub-20 MW gas turbine generators placed at fracked natural gas cryogenic separation plants feed electricity back to gas fields and mid-stream compressor stations (as well as local customers) to improve

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[11] https://www.techspot.com/news/97435-rolls-royce-teases-small-nuclear-reactor-space-travel.html
[12] https://www.usnc.com/mmr/#:~:text=The%20Micro%20Modular%20Reactor%20(MMR,%22fission%20battery%22%20in%20commercialization.
[13] https://www.world-nuclear-news.org/Articles/US-university-announces-plans-to-build-microreacto

resilience of the gas/electric systems. Figure 12 shows a schematic version of a combined gas/electric system.

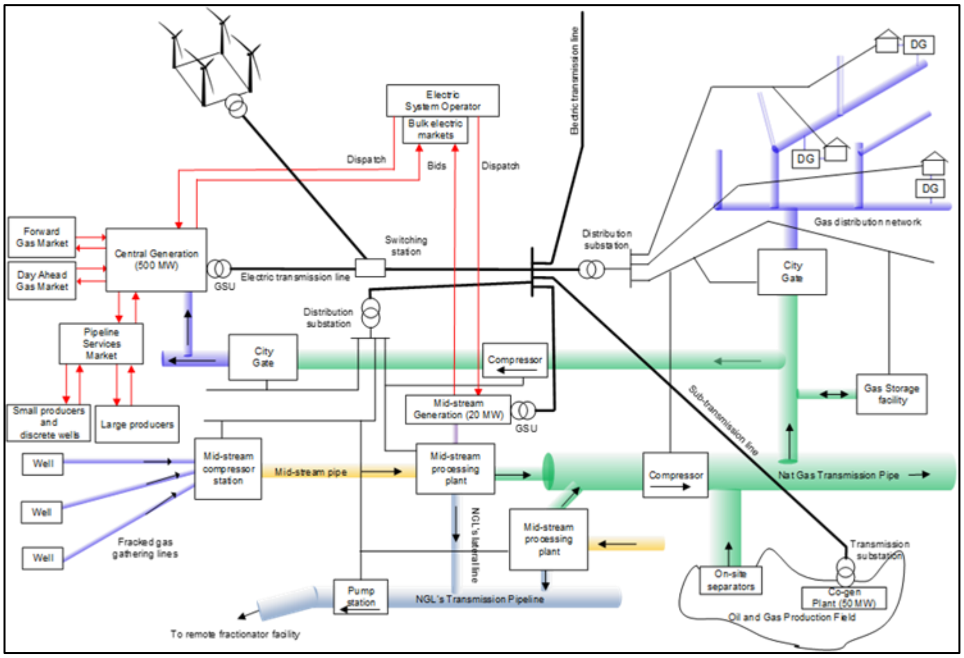

Figure 12 Converged Gas/Electric Infrastructures

The use of mid-stream generation to power gas fields and equipment forms a “resilience loop” to strengthen gas delivery in the event of electric grid failures. Figure 13 shows the basic elements and structure of a gas/electric resilience loop.

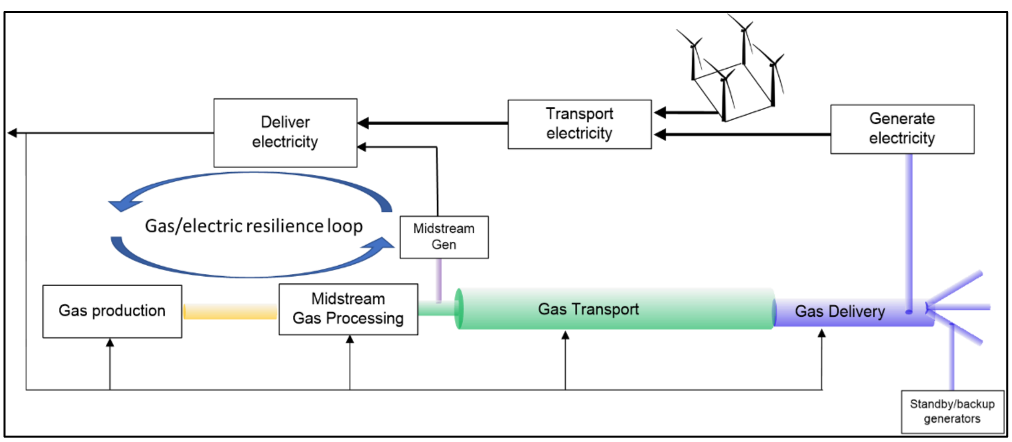

Figure 13 Gas/Electric Resilience Loop

It is important to note that while solar and wind generation are used, they *are not counted* when determining necessary reserves for grid operation when ambient temperature is above 105 deg F or below 25 deg F,[14] or in the case of extreme weather conditions such as hurricanes or ice storms. Renewables are proven unreliable in such circumstances.

Distribution Topology, Variable Structure, and Virtualization

Distribution grids vary in topology, primarily as a function of load connection point density. Rural feeders are still mostly radial, although primary feeders are constant wire gage throughout, as the large wire-small wire issue has been eliminated to facilitate stronger grids. Urban and suburban primary feeders are either partially or fully meshed to facilitate network functionality. Flow control and interconnection are automated via power electronics (see below) and communications infrastructure. In high density areas, feeders are parallel redundant, meaning that typically three feeders run in parallel, with cross connections about every kilometer or so. Each feeder is broken into segments with interties to the two other feeders so that power flows can be re-routed across feeders at each segment boundary. Automatic control balances power flows across feeders in each segment, with flows being shifted from feeder to feeder along the length of the triple feeder. This segmentation also facilitates virtual microgrids.

Variable feeder topology facilitates N-way logical power flows, which are automatically mapped onto real physical flows at the circuit level every several seconds. Virtual flow structure is mapped on the feeders as a part of the real time grid management process. Figure 14 illustrates the grid topology control process. The parallel feeder flow switching process (not shown) works "underneath" this process to maintain reliable flow and feeder balance.

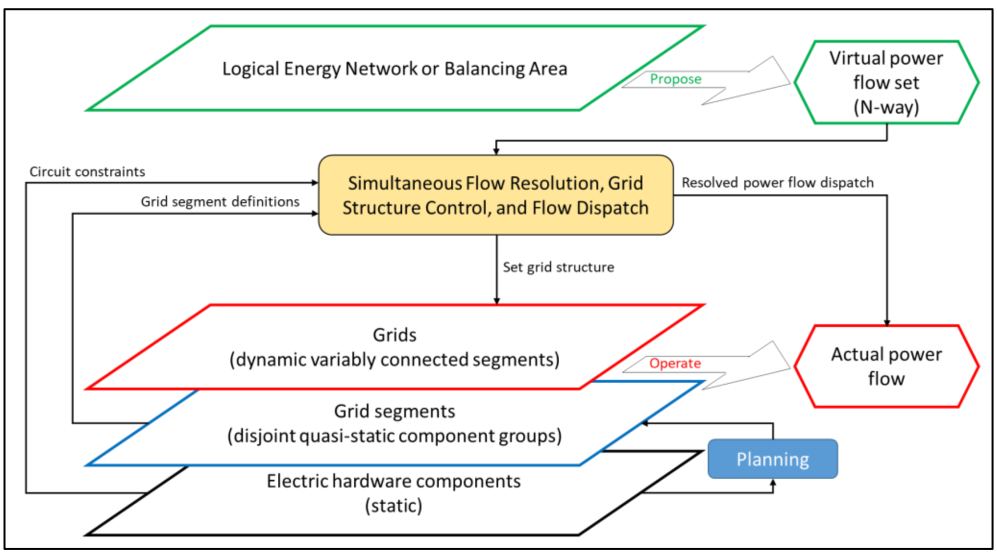

Figure 14 Variable Structure Grid Mapping

Feeders are broken into virtual zones that can be treated as microgrids by using the feeder topology and flow control capabilities. Groups of loads are organized at the software level and grid hardware is managed via software applications that operate on Logical Energy Network (LEN) abstractions, independent of underlying circuit hardware details, much like the way that applications are insulated from the details of hardware in a personal computer. The distribution system is operated as a multi-

[14] This view of the frailty of the S1 grid was communicated to me by P. De Martini.

services network, analogous to how a digital communication network transports multiple data flows from various sources to destinations. Such services include power transport, LEN-to-LEN power wheeling, energy warehousing, and outage ride through. Figure 15 shows an example of a primary feeder decomposed into a series of LENs. LEN domains are specified by distribution engineers with the following constraints:

- Can be fed from at least two substations
- Disjoint (no overlap)
- Contiguous – cover whole distribution system with no gaps
- Operate in a cellular fashion, like a microgrid network
- Can function as microgrid-like "resilience cells" if there are local electricity resources
- Autonomous when needed; globally coordinated normally via Laminar Coordination network (see below)

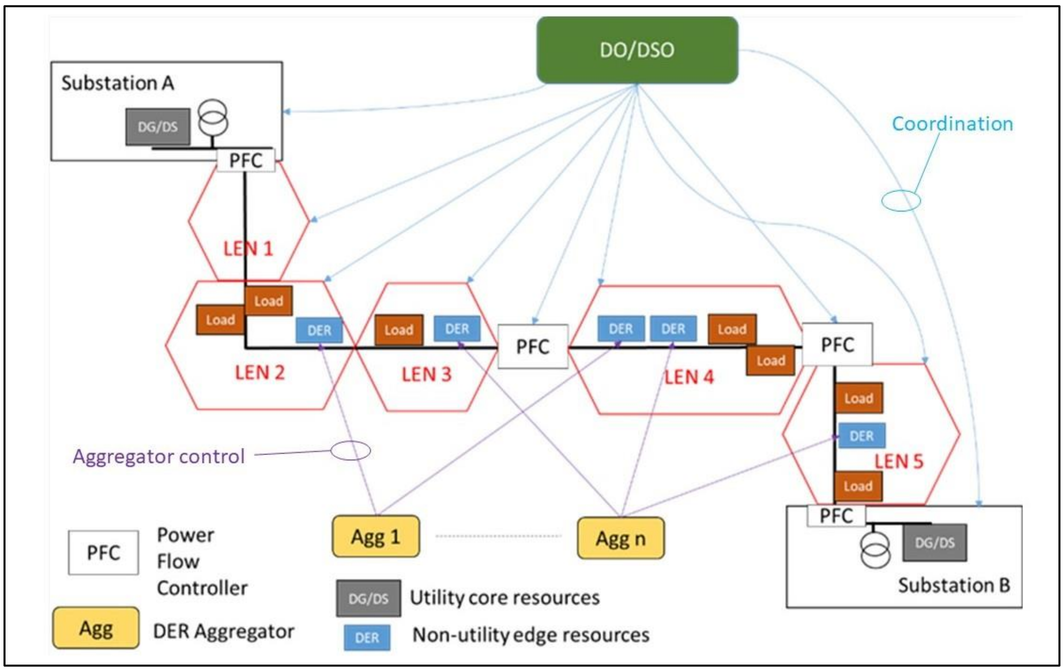

Figure 15 LEN Mapping to a Distribution Feeder

The overall structure of the grid with this arrangement consists of a physical portion and a logical or cyber portion. Figure 16 shows this in Entity-Relationship form.

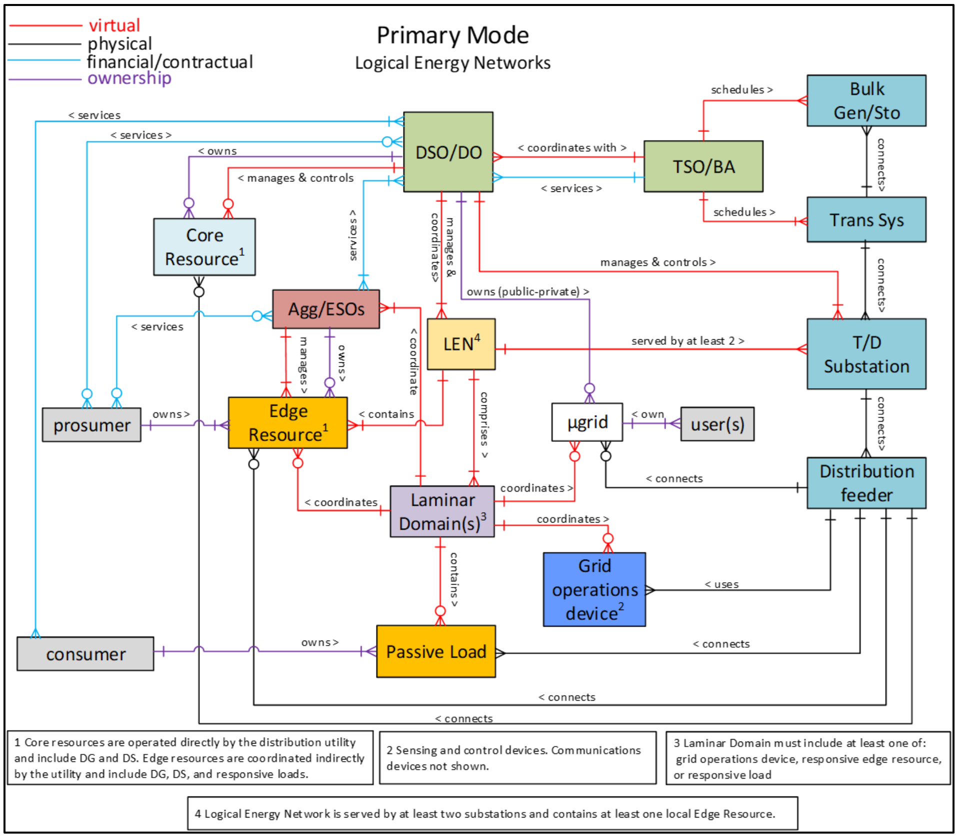

Figure 16 Virtualized Grid E-R Diagram

The combination of variable structure, embedded power electronics, and virtualization (LENs) provides considerable operational flexibility and the abilities associated with most of the early 21st century proposals for grid restructuring, including agile/fractal grids, networked microgrids, and autonomous cellular grids.

The connective tissue that relates LENs to physical infrastructure is comprised of Laminar domains employing Laminar coordination. Laminar coordination derives from the concept of network utility maximization via layered decomposition, a technique for solving optimization problems with coupled constraints. The mathematics induces a structure for coordination that has the following properties:[15]

- Multi-scale structure.
- Modularity: core repeating building blocks (coordination domains).
- Allows mixed coordination signal models:
    - Allocations (control-like signals),
    - Prices (market-like signals).
- Extensibility – the composable nature of laminar coordination domains means that a framework can be made to fit an existing grid structure, can be built out incrementally, and can be extended incrementally when grid structure changes.

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15 https://gridarchitecture.pnnl.gov/media/advanced/Architectural%20Basis%20for%20Highly%20Distributed%20Transactive%20Power%20Grids_final.pdf

- Boundary deference – the decomposition method and composability of coordination domains enables the creation of an interface wherever one is needed to accommodate a device, system, or organizational boundary.
- Local objective support (selfish optimization) – by introducing additional objective terms at any particular coordinator node, local objectives can be integrated into the overall solution. This is a form of goal decomposition.
- Constraint fusion – by adding in constraints as needed at any coordinator node, local constraints can be accommodated in a distributed fashion.
- Scalability – since coordination signals do not need to aggregate up or down the coordination chain, no communication scalability issues arise from depth of the coordination chain. Layered decomposition can be used to create new layers as needed if the southbound fan-out for any particular node becomes too large, thus providing structural scalability.
- Securability – the inherent form of the coordination framework and consequent coordination signal flows provides a degree of regularity that supports signature and traffic analytic security measures much more so than arbitrary networking.

Figure 17 shows how the layered decomposition mathematics induces the modular decomposition structure that can be mapped to a multi-scale grid coordination framework.

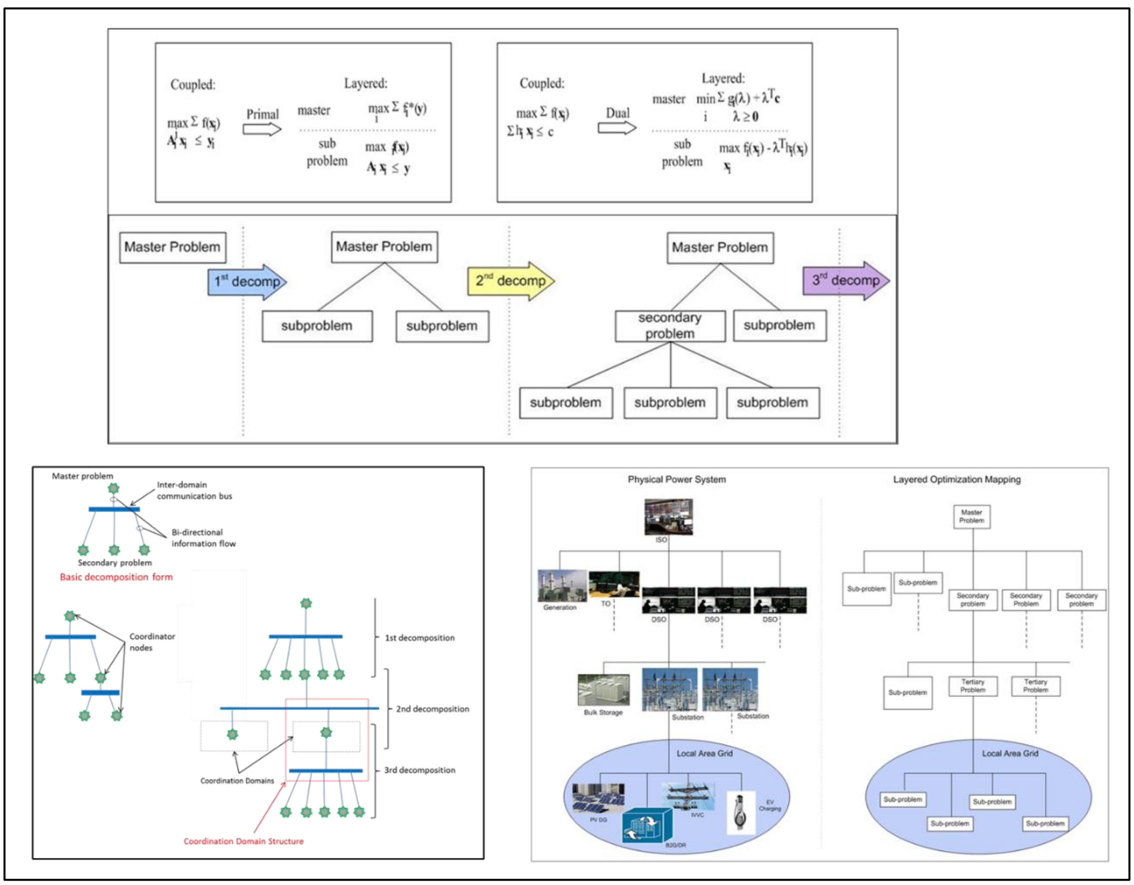

Figure 17 Layered Decomposition Structure Mapping to a Grid

The use of this framework prevents the creation of structural problems such as tier bypassing, coordination gapping, and hidden coupling, all of which occurred in the S1 grid. Figure 18 shows these structural problems. Use of Laminar coordination structurally eliminates the possibility of these occurring, important because these structural flaws result in improper system operation.

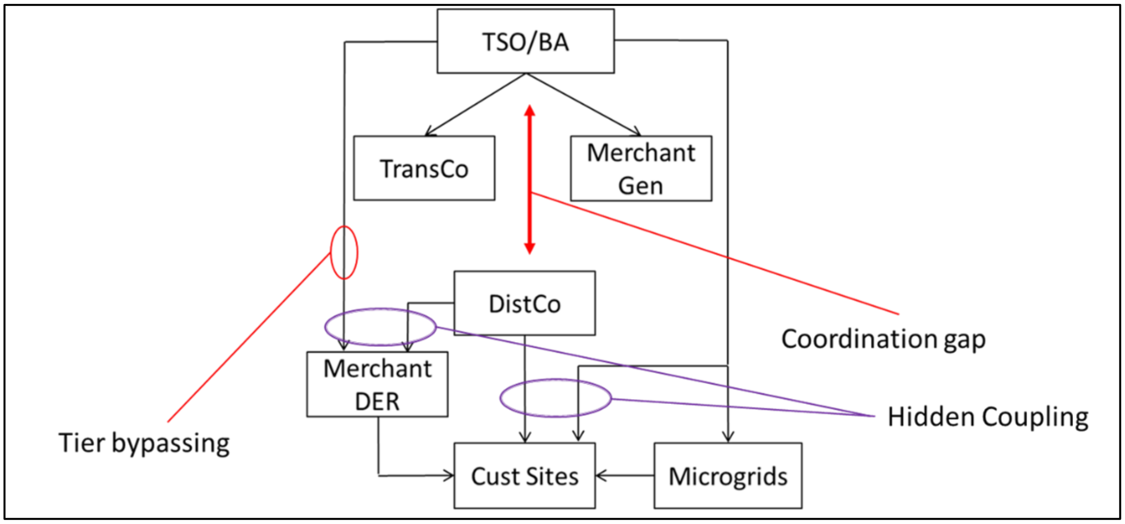

Figure 18 Common Grid Structure Problems

Figure 19 shows three ways hidden coupling occurred in the S1 grid, all of which are prevented in the S2 grid by the use of Laminar structure.

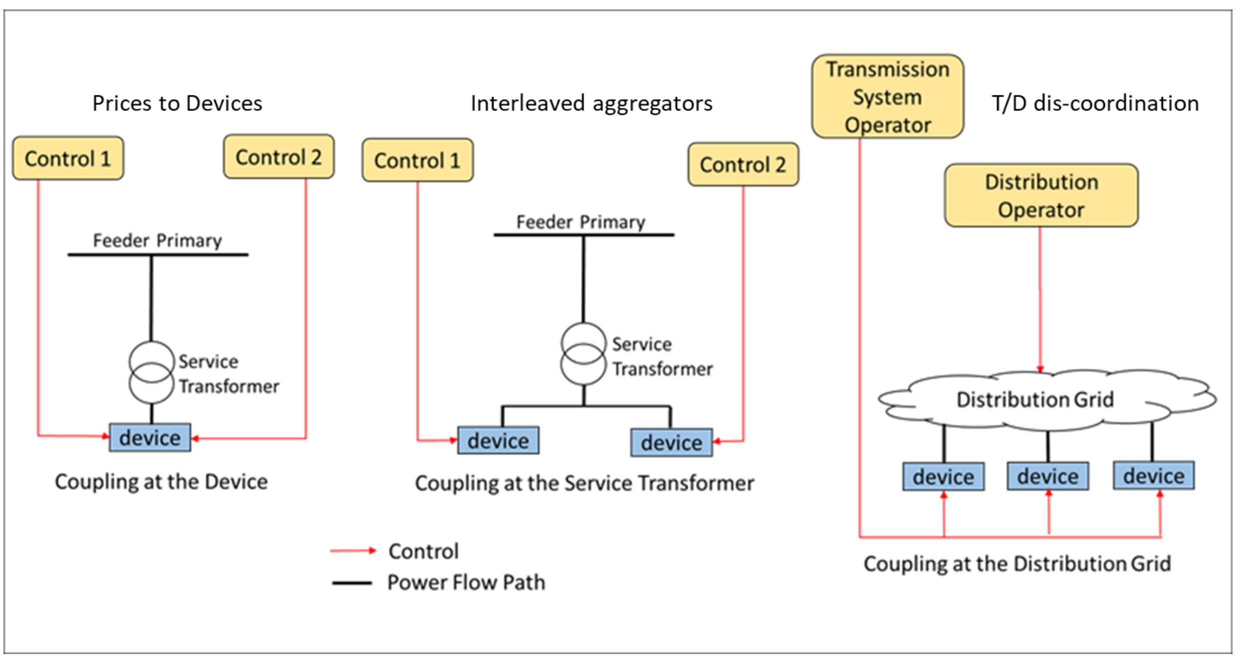

Figure 19 Three Mechanisms for Hidden Grid Coupling

Laminar domains and coordination provide a multi-scale distributed mechanism for coordinating large numbers of grid devices and edge-connected elements such as grid-connected rooftop solar PV. Figure 20 illustrates the superposition of LENs and Laminar coordination nodes.

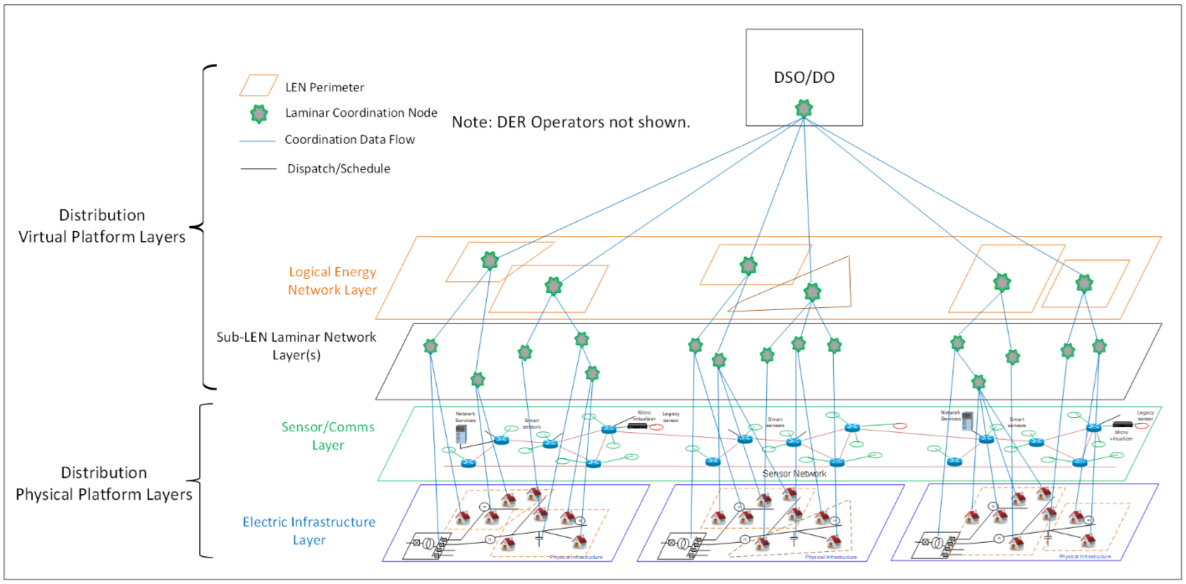

Figure 20 Grid Virtualization and Coordination Mapping

Figure 21 provides a physical schematic view of the relationship involving LENs, Laminar coordination networks, and electric infrastructure.

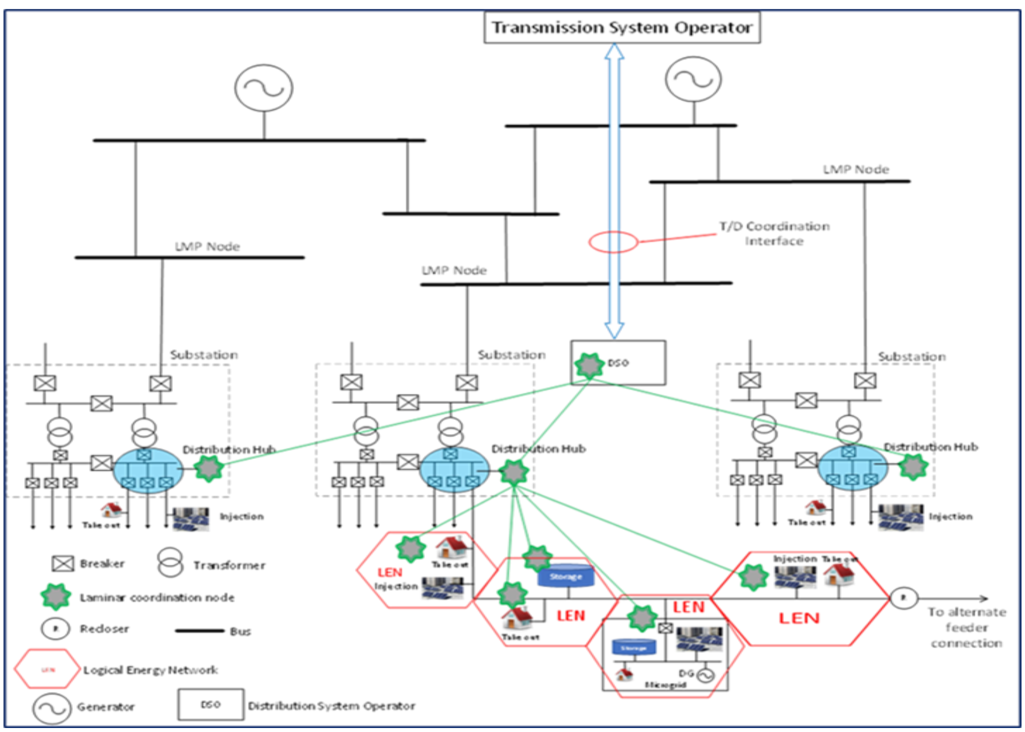

Figure 21 Grid Virtualization Schematic View

The use of virtualization with LENs and Laminar coordination makes the distribution system homologous with bulk energy system. As Figure 22 illustrates, each can be viewed as a stack with one-for-one correspondence of stack element types. The physical (electrical) interface has a clear corresponding cyber interface. This arrangement aligns with the TSO/DSO industry structure model described below.

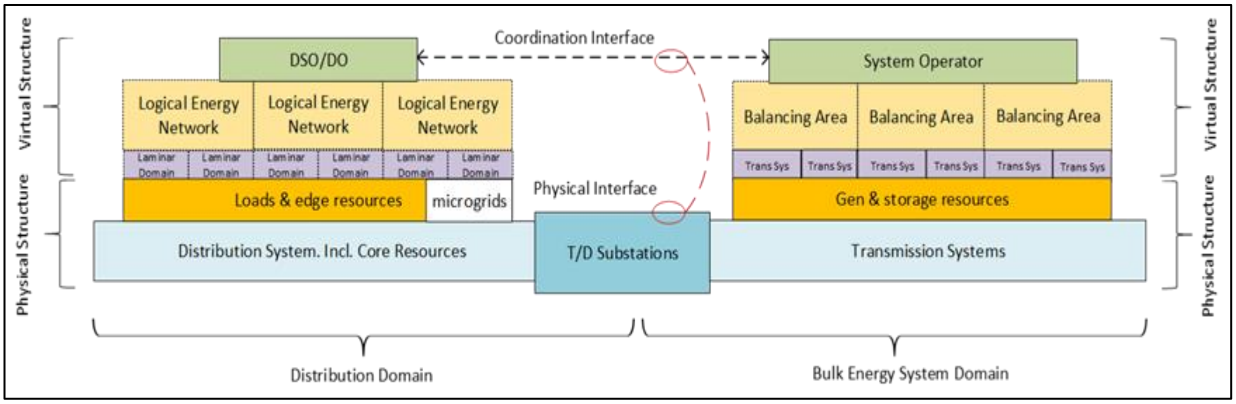

Figure 22 Grid Cyber-Physical Stack Model

Control

The grid has often been referred to as "the graveyard of advanced control theories." In my view, this is because in the past, advanced control theories were pushed to the sector without any real justification other than that they were "advanced," and their rejection was not because electric utilities were not sophisticated enough to appreciate them or too stodgy to change. However, in an S2 Grid, the need for advanced control derives from real internal and external needs, not the interest of control theorists.

The implications of decarbonization policies, consumer experience expectation shaped by modern electronics, and emerging technologies such as inverter-based resources, grid-compatible power electronics, the bifurcation of generation into bulk system-connected large scale resources and potentially vast numbers of distribution-connected small resources, bulk energy storage at all grid scales, shift of loads to nonlinear behavior, and ubiquitous communication connectivity changed old grid control problems and posed entirely new ones. These new problems include adding storage energy state management to the traditional grid flow control, balance, and regulation issues; variable grid structure and variable flow control; coordination of potentially huge numbers of grid-connected active devices and resources that are not owned by the electric utilities; mapping N-way logical power flows onto circuit level physical flows; operational coordination and synchronization between the grid and other coupled sectors (natural gas, transportation, buildings, etc.), and volatility exchange control between Transmission and Distribution, and between the grid and other coupled sectors. For these reasons, advanced control is the third part of the key triad mentioned earlier (the other two being buffering and power electronics).

Control of the S2 power grid entails a large number of control functions. Table 2 lists the control classes used in the S2 grid.

Table 2 S2 Grid Control Classes

• Dispatch & Curtailment • Load Sharing • Flow Control • Balance • Interchange • Frequency Regulation • Voltage Regulation • Reactive Power Regulation	• Stabilization • Synchronization • Volatility Exchange Control → T/D → Gas/Electric • State of Charge Management • Grid Structure Control • Structure Parametric Control • LEN (virtualization) control • Edge connector (inverter) control

Notably absent from this list is Demand Response (load turndown). This is because the concept of exporting grid constraints onto the users of electricity is contrary to the purpose of the grid and is no longer used. It was not effective in the S1 grid anyway.

Due to the effect of embedding bulk energy storage in the grid, the functions of balance, and frequency regulation are considerably relaxed, as compared to the S1 grid. Flow control is a more elaborate function than in the S1 grid because embedded power electronics is used at multiple levels to provide adjustable flow for circuit management purposes. This is more than just circuit switching and the justification for the added complexity is the increased operational flexibility that results.

Volatility exchange control is a new control function class, brought about largely by the existence of embedded storage in the grid, and in the case of gas/electric systems, the storage capabilities of the gas systems. Grid volatility control involves the use of embedded storage networks as describe above to decouple volatile power flow sources and uses. This works in both the bulk-to-distribution direction and the distribution-to-bulk direction, thus mitigating several problems, including aggregation of edge-based volatilities (from rooftop solar PV for example) into the bulk power system, duck curve phenomena, and any need to use load turndown to deal with VER stochasticity.

In the case of gas/electric systems, the variability of gas flows that support generation is mitigated by a combined control/management scheme as Figure 23 illustrates.

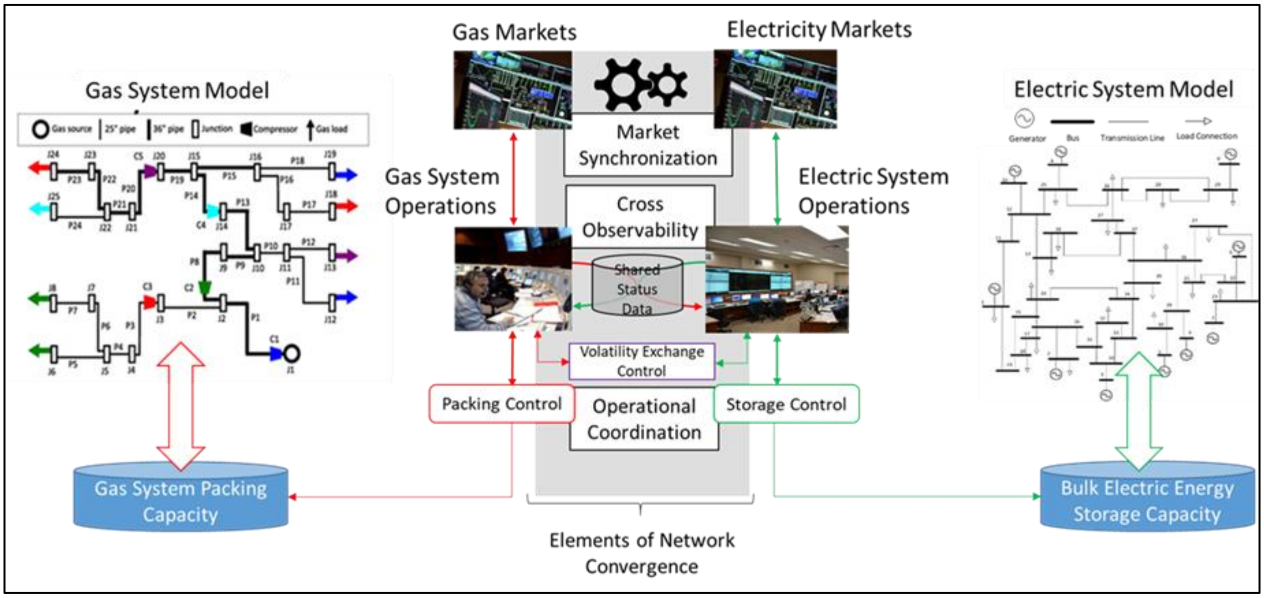

Figure 23 Gas/Electric Coordination

This arrangement is part of the larger issue of gas/electric infrastructure convergence that includes market timeline synchronization and cross-observability of the two infrastructures. Storage elements on both sides of the interface are coordinated to manage volatility exchange between the two systems.

Stabilization also involves embedded power electronics, especially at the transmission level. To some extent this is accomplished by real time control of the embedded storage network, but in addition, real time feedback control loops employing power electronic devices are embedded in the grid to dampen oscillations in transmission systems. Figure 24 shows a schematic illustrative example of this arrangement using a Unified Power Flow Controller (UPFC) and Phasor Measurement Units (PMUs) for sensing.

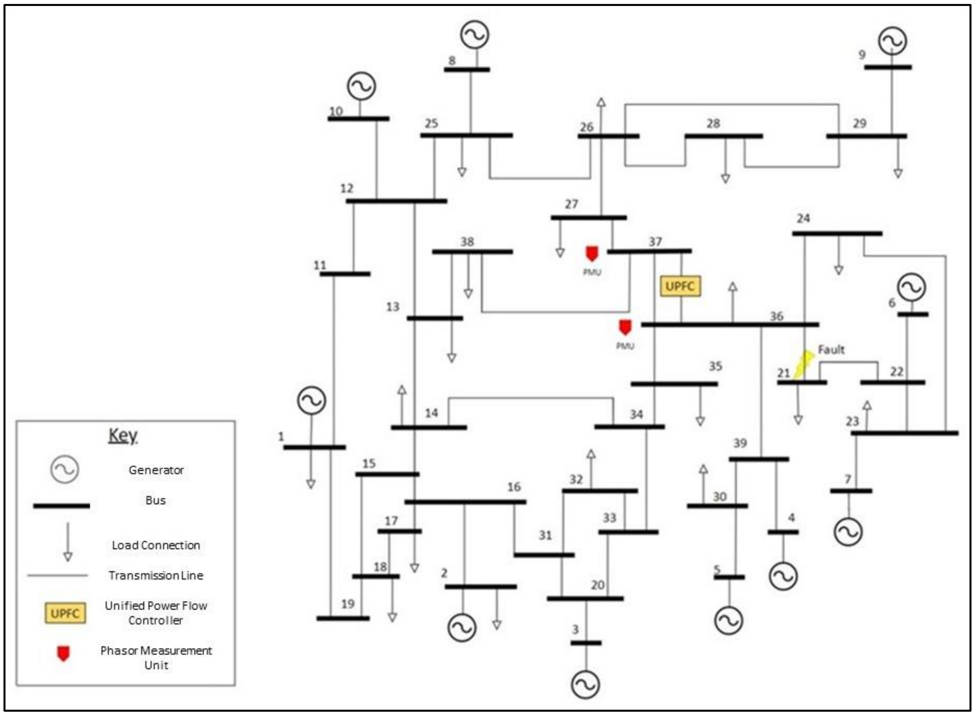

Figure 24 Embedded Closed Loop Stabilization Control

Control loops for stabilization make use of software defined networking to enable the damping controller to make adjustments to account for variations in communication network performance. These loops operate from real time grid data as Figure 25 shows (supervisory connections to damping controller not shown). The closed loop operates on a very short time cycle, too short for involvement of a control center.

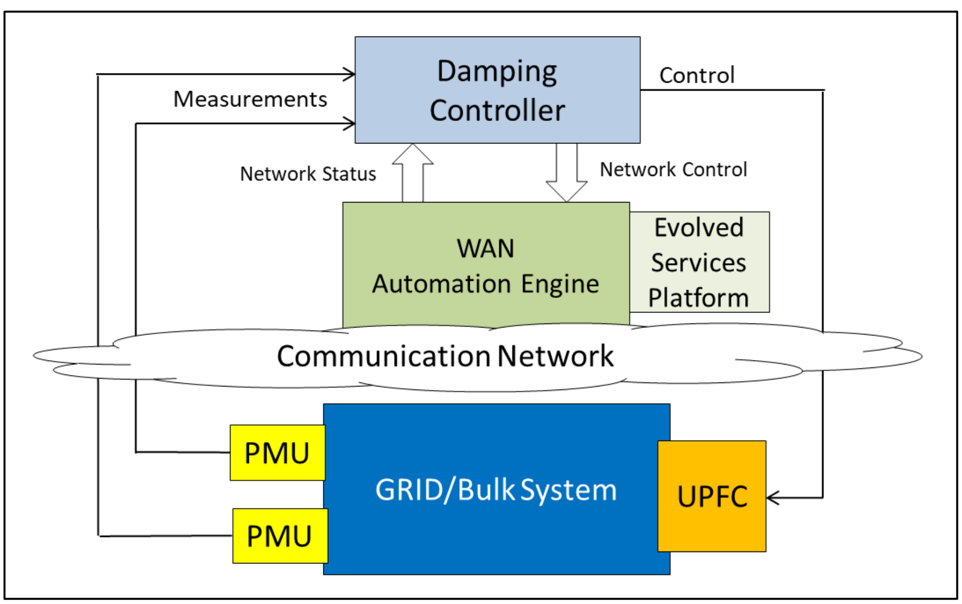

Figure 25 Stabilization Control with Software Defined Network

Due to the fast grid dynamics created by the connection of VER at both bulk and distribution levels, now control cycle times are sub-minute, sub-second, and even sub-cycle, all the while being much more agile than 20th Century controls. While there was a time when things did not happen in time periods shorter than about five minutes on distribution systems (except for protection), S2 grids cannot operate that way. Consequently, control is mostly **fly-by-wire**, meaning that automatic control operates on feedback of grid state data produced in real time by operational instrumentation. The discussion above on control of embedded storage networks illustrated this concept for a substructure of the grid but the principle is applied in general across both transmission and distribution systems. While human supervision is still used, human operators are not inside the control loops due to the needed speed of operation.

It is in this fly-by-wire control that the advanced grid control methods primarily manifest and, combined with the other elements of the key triad, make the physical S2 grid a step change from the S1 grid. As shown in the section on buffering, fly-by-wire grid control uses real time state feedback working on very short (fast) time cycles to manage the dynamics of the mixed stochastic and deterministic grid. No market mechanisms are included inside the fly-by-wire control loops.

Market mechanisms for operational control are used only on a limited basis, since the time scales needed for proper control response even at the distribution level are sub-minute to sub-second, too fast for market optimizations and clearings. In addition, due to increasing complexity and sheer numbers of elements and constraints to be included in short cycle time control, the scale of computational resources required vastly exceeds practical limits, and so neither centralized market-based optimizations nor transactive energy methods are used at the distribution level. Also, in an environment where some of the generation is essentially zero-marginal cost, traditional electricity markets and market rules do not apply well. Finally, the use of optimization in general leads to operational problems when the large signal baseline, upon which the market small signals implicitly depend, shifts dramatically (such as during large scale adverse events).

The S1 conceptual view of DER and grid modernization (never actually realized) often relied upon a magic box called optimization to make everything work. According to its proponents, it would coordinate tens of millions of grid-connected devices, unlock loads of latent value, and avoid the need for grid infrastructure investment. Unfortunately, optimal solutions may well be brittle, meaning that a slight change in underlying conditions can make the formerly optimal solution invalid. Optima can be broad and nearly flat, in which case being off optimum a bit makes very little difference in outcomes. Or, optima can be sharp, in which case a slight shift makes a very large difference in outcomes. Also, optima may well be found at the edge of the feasible solution set (think linear programming to help visualize this concept even though the grid problems are nonlinear) so that a slight shift in conditions can leave a formerly optimal solution outside the bounds of feasibility.

The better the optimum is, as compared to other solutions (an economist might say the more value it yields), the sharper the optimization peak is. Correspondingly, the likelihood is greater that a shift in underlying conditions will cause the formerly optimal solution to fall outside the set of feasible solutions and thereby fail badly. In other words, optima that make the biggest difference are also the most brittle.

Consequently, the S2 Grid uses robust solutions instead of strict optimizations, in line with Postulate 5. A robust solution is one that is relatively insensitive to variations in external factors and model parameters. Such a solution is often suboptimal from the standpoint of traditional grid techno-economic objectives but is superior to the traditional “optimal” solution under conditions of volatility, subsystem or component failure, and external system stress – essentially, it is more resilient than the strictly optimal solution. Where optimization is needed, the S2 Grid finds a solution in the vicinity of the centroid of the associated optimization problem feasible solution set - in other words, more interior to the feasible solution set than the traditional optimum.

Distribution level voltage/reactive power regulation is performed by a combination of grid embedded power electronics, substation level control and control of inverters connected to the grid. Inverters are used to connect non-utility resources (mainly solar PV) to the grid and are managed by a combination of coordination signals originating from the grid and local autonomous inverter control. Inverters are constructed and operated in several modes (see Figure 11), not just grid following or grid forming. No market functions are involved in the real time operation of the inverters for the same reasons as described above. Connection of non-utility inverters the grid comes with grid code requirements for control and coordination by the distribution utility operator for purposes of grid reliability.

The issue of grid structure control for distribution grids was discussed earlier (see Figure 14). In addition to controlling structure, various grid parameters are also controlled, including power flow settings, connection point power injection and withdrawal limits, and voltage/reactive power regulator settings. The circuit structure control network operates “underneath” the LEN/Laminar structure, as Figure 26 illustrates.

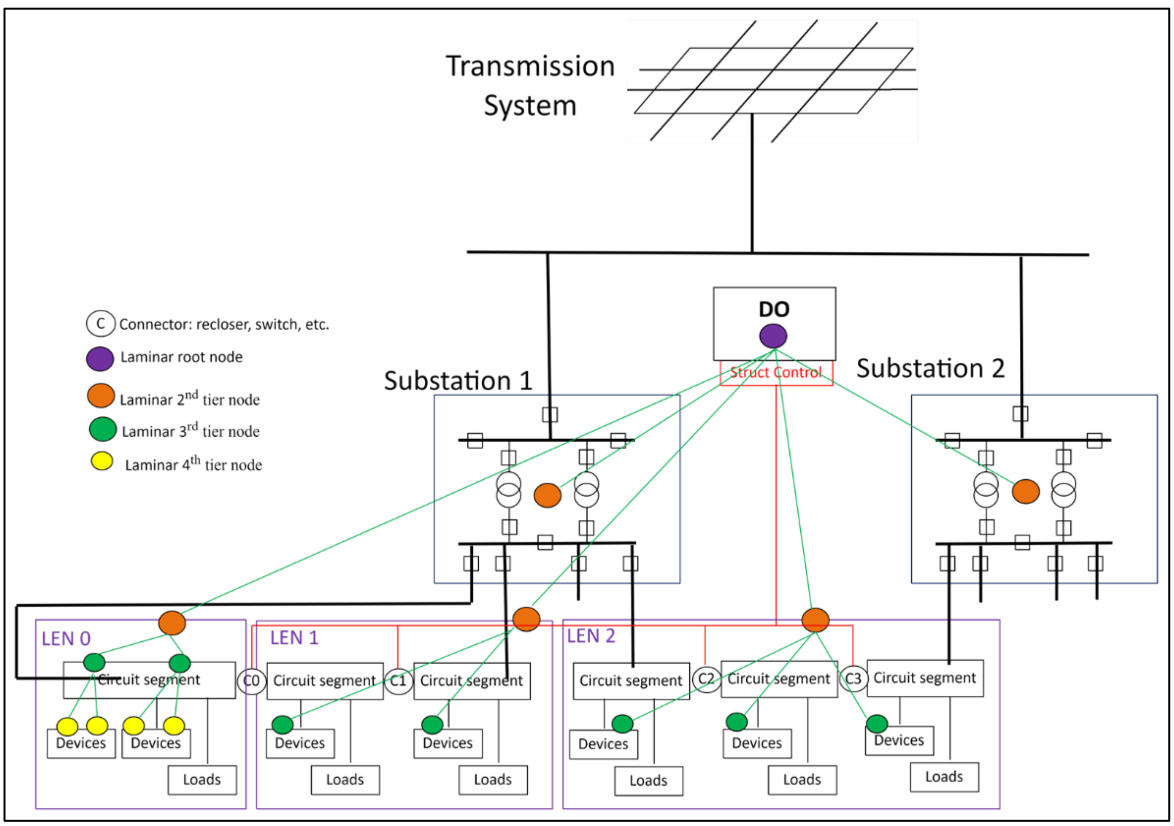

Figure 26 Structure Control Under LEN/Laminar Structure

Digital Superstructure

The S2 grid eliminates the concept of siloed application systems in favor of layered platforms with distributed applications. For distribution this means that the electrical infrastructure, the sensing devices, and the multi-services communications network are layers in a "distribution platform." Authorized applications are connected to the platform to obtain necessary data independently of other applications. This eliminates the S1 grid approach of back-end integration of siloed application systems by decoupling the applications, which greatly reduces system brittleness and integration costs. Figure 27 shows the platform model.

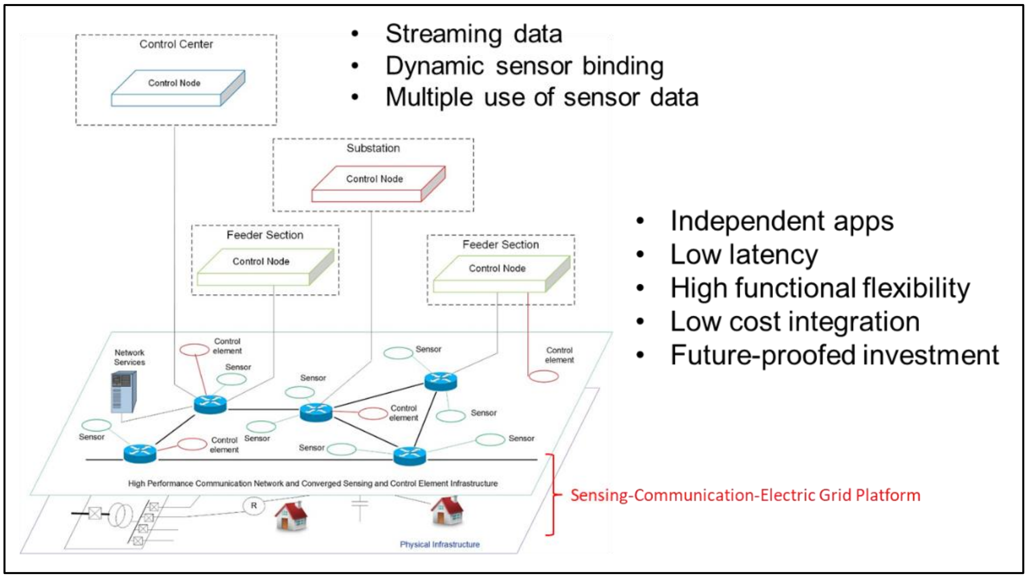

Figure 27 Distribution Platform Model

By converting siloes to layers, another benefit is created. This structure completely changes the locations and functions of device interfaces and provides clear definitions of their functions, thus simplifying and finally resolving the device interoperability issue.

Transmission systems use a similar structure for PMU networks but with a somewhat more complex data sharing mechanism due to the need to cross organizational boundaries. Figure 28 shows the simplified version (regional communication network not shown) of this structure. Note that each entity has its own version of platform layers, depending on whether or not it owns any PMUs.

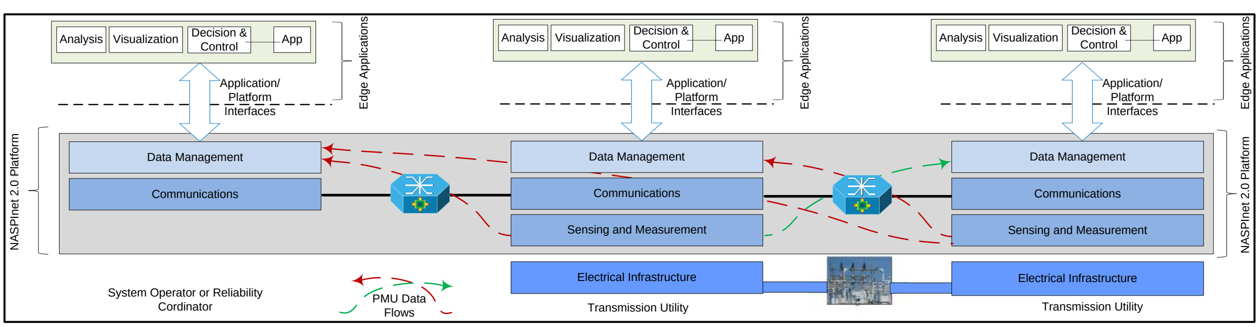

Figure 28 Transmission Platform Model

Due to the muti-organizational nature of the bulk power system, a federated registry provides the necessary information for an entity to access data streams from across the platform when the sources are owned by another entity. Figure 29 shows the basic structure of the registries and meta-registry. Here each entity maintains the registry entries for its own data sources and controls access by other entities.

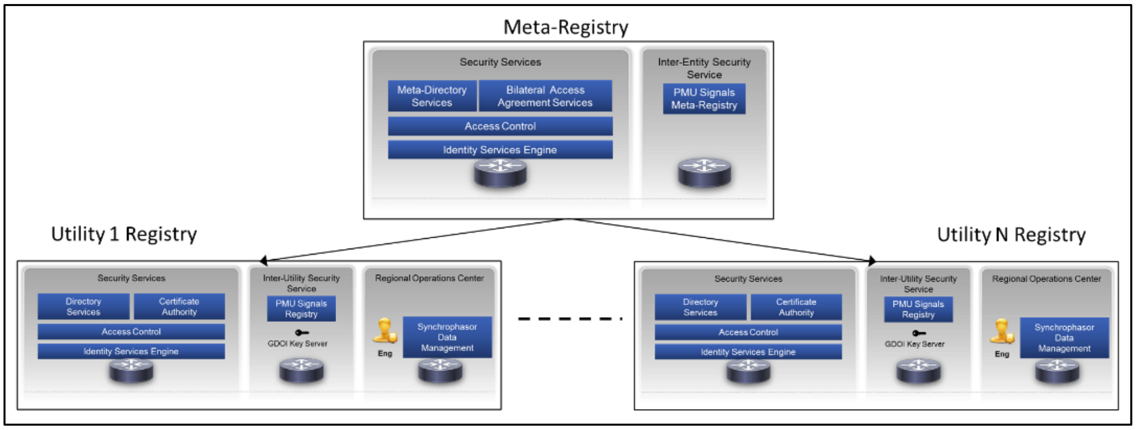

Figure 29 Shared Data Registry Federation

Sensing and control are synchronous throughout both distribution and bulk power systems. Note that this is not the same as AC synchronization. All sensor sampling and control outputs are clocked to operated simultaneously. This mode of operation makes the sensing and control systems fully deterministic and eliminates the need to try to match up time-stamped data packets after the acquisition of the data.

Synchronized sampling and control requires distribution of timing information uniformly across entire interconnections with 8 nanosecond accuracy and no more than 100 microsecond maximum divergence from UTC.[16] Doing so means that timing must be distributed through the communications networks. Figure 30 shows how timing synchronization is achieved across organizational boundaries.

[16] Universal Coordinated Time

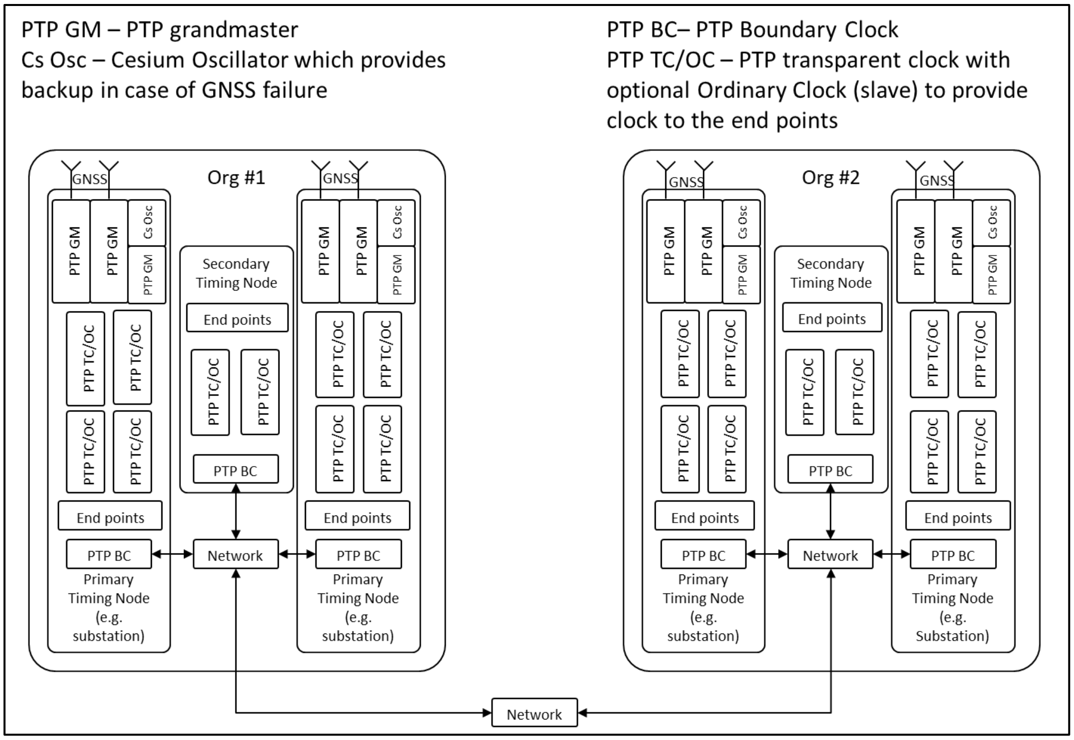

Figure 30 Network Timing Distribution

Data transport latency and jitter are issues, but are minimized through distribution of controls in the grid, as opposed to trying to centralize control.

Industry Structure

Distribution systems are managed by Distribution System Operators (DSOs). Each DSO is responsible for managing reliability and resources within its service area and each DSO treats the bulk power system to which it is connected as a resource, to be used in combination with any internal resources.

Transmission System Operators (TSOs) manage and optimize regional bulk energy systems, including generation resources and transmission systems. Each DSO has an interface to the bulk system and TSO, located at a T/D interface substation. TSOs only see a single aggregate load or resource for each DSO at the T/D interface, do not receive telemetry from the distribution system, and do not dispatch distribution level resources. The operational model for the TSO is essentially to provide a service to each of the DSOs and can accept services from the DSOs if available. This arrangement prevents unsustainable scaling of information flows to the TSO and, in line with the layered decomposition model, avoids tier bypassing and hidden coupling. The TSO performs its dispatch of resources as needed to meet the agreements with the DSOs, using whatever optimization methods are appropriate, be they market-like or control-like or hybrid (varying by region and regional industry structure). As discussed in the Control section above, optimization is not strict - rather it is robust and therefore slightly suboptimal.

DSOs coordinate and aggregate physical DER resources at the distribution level and are responsible for distribution level reliability. They aggregate distribution level resources into a single resource at the T/D interface and manage power flows in the distribution system. The DSO is responsible for providing sufficient information for the TSO to allow the TSO to manage its resources and meet the agreement with the DSO. Third party aggregators of DER resources deal only with the DSO and do not participate in bulk power system wholesale markets if they exist. Figure 31 is an Entity-Relationship depiction of this industry structure.

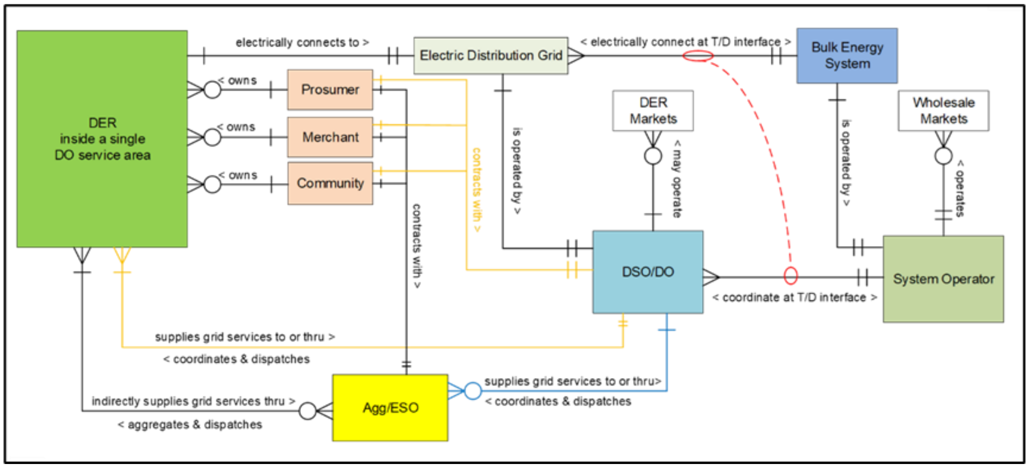

Figure 31 TSO/DSO Entity-Relationship Diagram

The DSOs are system controllers for their respective distribution systems, and they treat the TSO and bulk power system as essentially an energy cloud service. If the TSO uses wholesale markets as part of its optimization and dispatch mechanism, then the DSO participates on behalf of the distribution system and its load and resources. Figure 32 depicts this arrangement for a TSO (in this case an ISO) and one DSO.

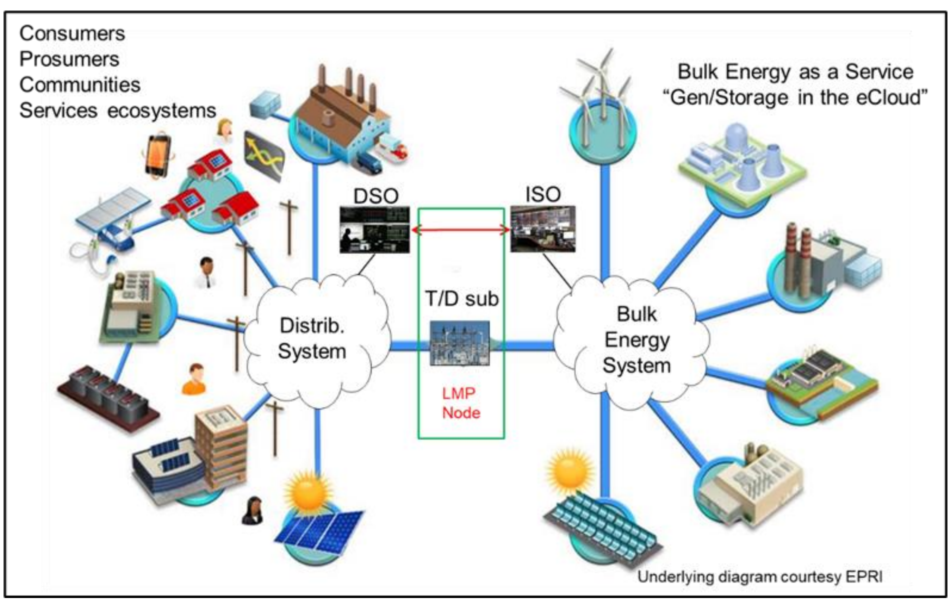

Figure 32 TSO/DSO Schematic View

The DSO and TSO continually reach agreement on energy, power, services, and financial exchange at this interface. The TSO treats each DSO and related distribution system as a node and its observability terminates at the T/D interface.

The TSO/DSO T/D interface arrangement creates a virtual partitioning. The DSO determines the degree of coupling that is necessary on a coordination cycle-by-coordination cycle basis. Figure 33 shows this partitioned structure in simplified form.

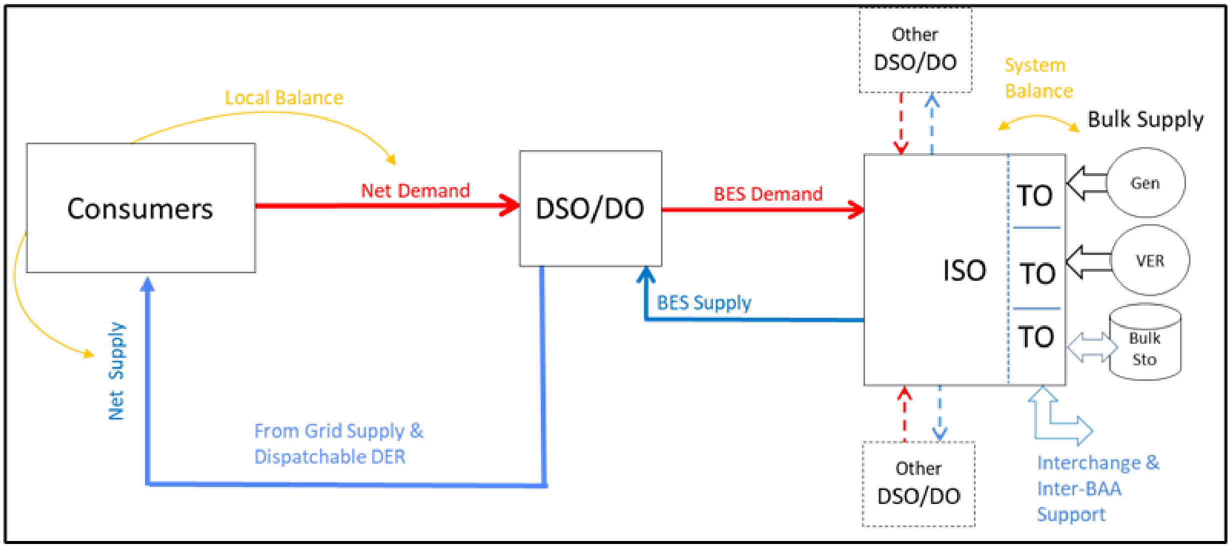

Figure 33 TSO/DSO Partitioning Model

From the viewpoint of the TSO, it sees it own resources and a set of aggregated nodes (the DSOs and T/D interfaces). Each DSO sees its own resources plus the resources of the bulk power system that it can draw on via the TSO and the T/D interface. Hence the role of the TSO is not as a regional system controller, but as a regional resource manager to a set of system controllers (the DSOs). System control has become distributed by moving to the DSOs.

Network Convergence/Sector Coupling

In urban environments, multiple interconnected infrastructures are converged into a super-infrastructure that provides a set of connectivity/transport services, as well as multi-infrastructure sensing/measurement and control. Management of this super-infrastructure uses the layered platform approach described above but with an additional layer of "over-the-top" application networks. Figure 34 shows the urban services platform layer structure.

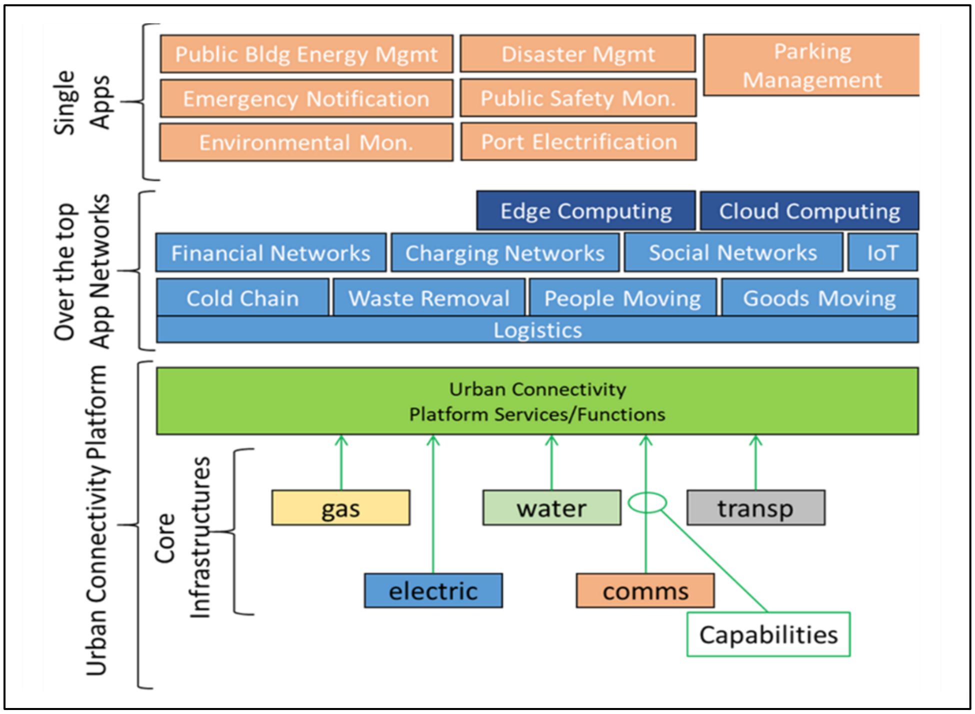

Figure 34 Urban Connectivity Services Platform

At the physical levels, the physical infrastructure/sensing/communications layering is still used, but extends across multiple physical infrastructures, as Figure 35 shows.

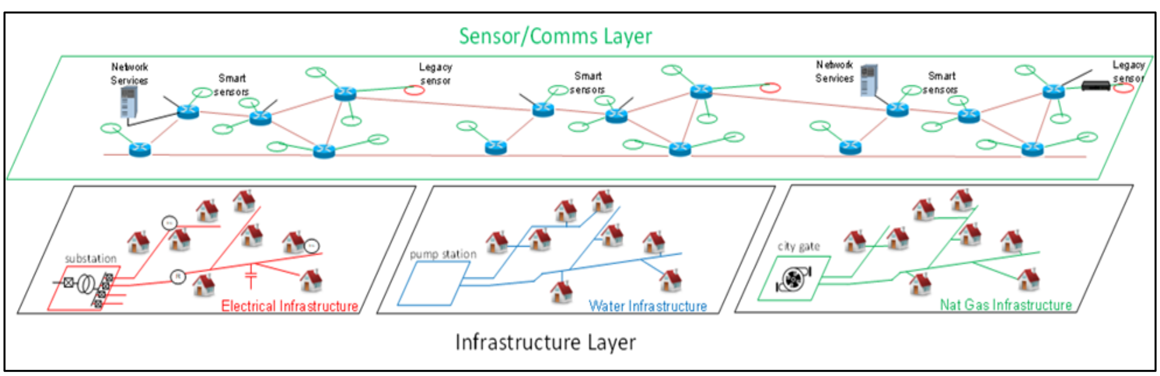

Figure 35 Multi-Structure Layered Platform Model

As with the previous layered platform models, shared multi-service communications networks are crucial elements.

Summary Comments

This document presents a set of related concepts for an S2 grid that is very different from the present-day grid in the US. Using a philosophy of abundance thinking and focus on service to consumers, it postulates a grid that uses ubiquitous bidirectional bulk energy storage to provide buffering that decouples resource and load volatilities, thus changing grid operations significantly. The key triad of storage, power electronics, and real time control forms a core grid component that is used widely throughout the grid to change essentially all of its operating characteristics, from loosening frequency regulation, to reducing ready reserves, to eliminating the need for demand response. It changes the fundamental grid control problem from power flow with constraints on voltage and frequency to one where the focus is on power flow and storage state of charge while managing system frequency loosely and still regulating voltage closely. The use of storage as a buffer simplifies the use of VER and makes it possible to maximize the VER contribution. The deployment of nuclear technologies along with use of gas turbine generation ensures the grid is not compromised under extreme stresses.

The role of the system operator is greatly changed and the new role of DSO changes the way that DER is managed and how third-party aggregators interact with the grid entities. The roles of electricity markets and market-like functions is greatly reduced, compared to S1 grids.

This paper is not a prescription or prediction for the future grid. It does show how the grid can be significantly remade and it also shows how changes to the grid are interconnected. The essential ultra-large-scale complexity of the grid is why linear incremental change cannot succeed – it is not possible successfully to make isolated changes as if they do not have any effect on other aspects of the grid.

If there is to be an S2 grid, it may not look like the depictions in this paper but certainly must embody significant systemic changes in a cohesive manner. This will not be simple, and the transition from the S1 grid to an S2 grid will present an additional huge level of challenge. It is one we must meet to get to the grid we need for the 21st Century.