GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Grid Architecture Specification: Urban Converged Networks Reference Architecture

GMLC 1.2.1 v0.3

May 2020

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Grid Architecture Specification: Urban Converged Networks Reference Architecture

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Grid Architecture Specification

View Designation: GMLC 1.2.1 Urban Converged Networks Reference Grid Architecture v0.3

Structure Types:

x	Electrical Structure	x	Industry/Business Structure		Regulatory Structure
x	Digital (ICT) Structure		Control Structure	x	Coordination Structure
	Market Structure	x	Convergent Networks	x	Multi-infrastructure networks

Perspective Types

	Demand/Supply Flow	x	Industry Structure		Value Flow
	Grid/Circuit	x	Sensing & Measurement	x	Data Mgmt./Data Flow
	Analytics/Visualization	x	Control/Coordination		Protection
x	Communication Networks		Timing Distribution		Cyber-Security
	Component Class Specification	x	Component Allocation Model		Grid Dynamics
	Market-Control		Computation Resources		Other (name it)

Summary Overview

This document describes architectural (structural) elements for a set of urban infrastructures, with much of the perspective drawn from the point of view of the electric distribution system. The set of infrastructures of interest are electric distribution, natural gas distribution, water distribution, transportation, and communications. These are treated collectively as a core group of infrastructures forming a heterogenous multi-network that provides basic connectivity to urban environments. Each enables some form of transport: commodities (electricity, water, gas); people and things; and information.

Glossary

BTM – Behind the Meter

C&I – Commercial and Industrial

DA – Distribution Automation

DER – Distributed Energy Resource

DG – Distributed Generation

DS – Distributed Storage

E-R – Entity-Relationship

ICT – Information and Communication Technology

IoT – Internet of Things

LEN – Logical Energy Network

LNG – Liquid Natural Gas

PV – photovoltaic, e.g. solar electric generation

T/D – Transmission/Distribution

TOD – Transit Oriented Development or Transit Oriented Design

TSO – Transmission System Operator

Key Emerging Trends List

Document *Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid* contains the list of US utility emerging trends used as input to the architecture development. In some cases, cities and states are phasing out the use of natural gas, which has implications for increasing load on electric distribution systems.[4]

Key Systemic Issues List

The document *Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid* contains a list of cross-cutting issues (those affecting whole grids or major portions) used as input to the architecture development. Electric grids are only a portion of this architectural view but are central to the thinking here about convergence, meaning convergence of the other architectures with electric networks. This is especially true in the light of the emerging trends toward electrification of transportation, buildings, and ports.

Problem Domain Reference Model

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[4] Grant Smith, Cities Moving to Ban New Natural Gas Hookups, Environmental Working Group, December 3, 2019, available online: https://www.ewg.org/energy/22951/cities-moving-ban-new-natural-gas-hookups

The problem domain is the existing grid and while that term is broad, the issue has become nearly ubiquitous in recent years and so has application across regions and industry structures. The problem domain is described in detail in *Problem Domain Reference Model* (*GMLC1.2.1-v2.pdf*).

Scenarios and Point of View

The key scenario for this reference architecture is the convergence of core urban infrastructures, all of which provide some form of connectivity in urban environments. The core urban infrastructure networks are:

- electric distribution,
- natural gas distribution,
- water distribution,
- transportation,
- communication infrastructures.

Transportation includes roadways, urban rail, waterways (ship port; river/lake/canal boat/ferry; barge, water taxi); footpaths/trails; lanes for bicycles/scooters/skates/hoverboards; air lanes for Heli-taxis, life flights, traffic reporting and police helicopters, and the occasional sky crane.

The Point of View is a converged system view. Figure 1 is a problem domain reference model diagram depicted from a communications network perspective, that illustrates some of the relationships between the urban systems, the urban electric system, and the communications infrastructure.

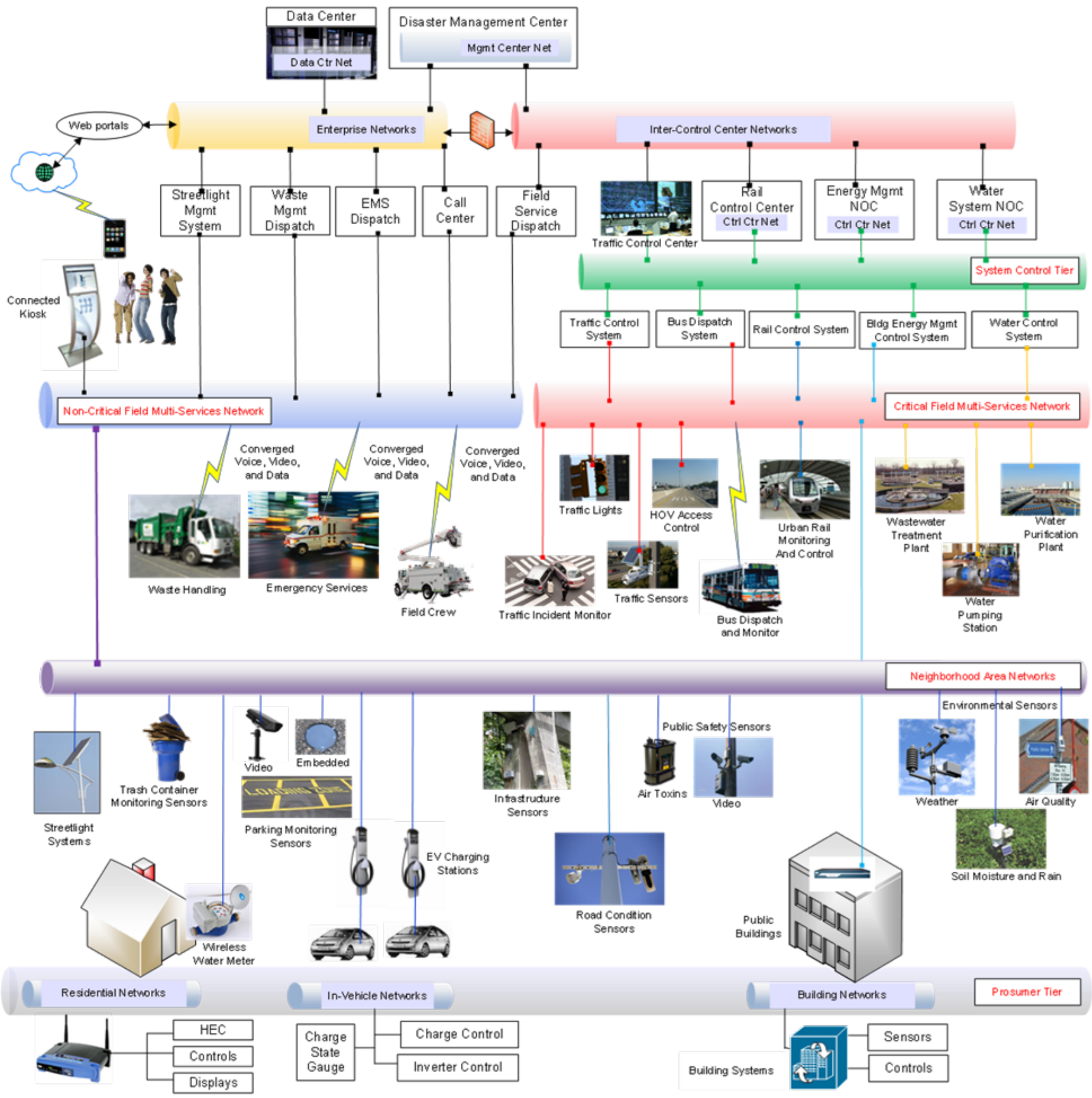

Figure 1 Urban Reference Model Diagram, Communications Viewpoint

Movement of Information

As with any complex system, there are many classes of information to be exchanged in the urban environment. In addition to information for socioeconomic activity, there is also information related to urban operations, such as traffic flow, infrastructure health monitoring, cyber security, physical security, public safety, and the coordination of city services, including routine services such as trash removal, as well as emergency and disaster services. Cities may also have telemetry for tracking environmental and weather conditions, and viral pandemic information such as human temperature tracking.

During emergency conditions, information flows may change to support disaster operational centers and coordination across organizational boundaries that is not needed during normal operations.

Business Context, Entities, and Relationships

In the urban environment there may be multiple models for ownership and operation of the individual infrastructures. Industry structures (ownership and operation) can be very complex, heterogeneous, and even duplicative (for example, multiple wireless telecom service providers in a single city). Some (such as cable tv/internet) may have city franchises. The city may own and operate some infrastructures such as water systems, but others may be owned and operated by various private sector companies, by cooperatives, or via municipal or regional authorities. A city-wide optical fiber network may be owned and operated by the unregulated arm of an electric utility. In some cases, infrastructures may be owned and operated by public/private partnerships.

In addition, operating modes may change between normal operation and emergency operation during times of crisis.

Regulatory/Public Policy Context

Regulations vary widely for electric distribution, since most distribution issues are regulated at the state level, but in the case of municipal utilities, the city has jurisdiction, and even when there is a separate PUC, coordination with the city government is necessary. Regulation for water and natural gas distribution have similar issues. Transportation has a complex regulatory structure as well. Many cities have public policies and regulations regarding renewable resources that drive adoption of DER. In some cases, cities and states are phasing out the use of natural gas, which has implications for increasing load on electric distribution systems.

A model for the US electric sector regulatory structure can be found in *Regulatory Structure Model.vsx*. Regulation of the other infrastructures involves several entities, some Federal (such as the FCC), some state level, and some local to the city in question.

Objectives

The objectives for this reference architecture are to indicate structural approaches that will:

1. Facilitate the enhanced usefulness of the five core infrastructures by treating them as a converged heterogeneous multi-network, organized with a common viewpoint on services and a seamless information management and coordination platform that opens opportunities for new functionality, flexibility, and value stream innovation.
2. Resolve the means to coordinate heterogeneous networks with disjoint owner/operators while preserving each one's information integrity and privacy.
3. Provide a network convergence model that provides for super-linear growth of network value as a function of the total number of users (urban population)

4. Provide architectural models for core network convergence consistent with modern urban planning approaches.

To the extent that the structural convergence can enable, support, or provide potential to improve recovery after some failure, they should also do so.

Core Urban Converged Network Architecture Principles

1. Cities are the result of interaction of human beings exchanging energy, resources, and information. The point of a city is to bring together people to facilitate interaction to create ideas and wealth. Cities are sustained by infrastructure networks such as roads, railways, and electrical distribution to transport people, energy, and resources.
2. Cities tend to evolve to approximately minimize time and costs for such transports. Mobility is essential for city viability and vitality. Most people want to get from point A to B in the shortest possible time and at the lowest possible cost and businesses want to do the same with their goods. Increasing reliance upon immediate access to information in a mobile environment sharing has implications for urban communication networks.
3. Urban infrastructure physical networks are essentially fractal-like space filling structures, necessary to reach the endpoints where the services they provide are accessed.
4. Cities are people and therefore are based on social networks. Such networks consist of socioeconomic interactions that increase super-linearly with population size (exponent 1.15), whereas the urban physical infrastructures increase sub-linearly (exponent 0.85) with population size, leading to economies of scale. The physical infrastructures are roughly an inverse nonlinear mirror image of the socioeconomic city.[5]
5. In an urban environment, the core infrastructures can converge to become a *connectivity services platform* for the city. Platforming, layering, and distributed coordination structure for the core infrastructures enable the development/evolution of value-add over-the-top applications.
6. While many infrastructure interdependencies exist, there is a systemic dependency upon electric and communications networks in particular that influences the concept of connectivity services platform.

General Architecture Principles

1. A good architecture is one that meets the needs of the stakeholders (especially the users) to their satisfaction, does not violate established principles of system architecture, and takes into account the relevant qualities and properties as the stakeholders require.

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[5] Items 1-4 are paraphrased form the work on cities in Chapters 6 and 7 in the book SCALE The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies, Penguin Press, NY, 2017.

2. Good architectures have conceptual integrity (adhering to a set of core principles, clean of unnecessary complexities or 'exceptions,' similar problems are solved in similar ways, etc.).
3. Conceptual integrity is best achieved by a small cohesive team of like-minded architects. Architecture should be the product of a single architect or small team with an identified leader.
4. Essential functionality drives complexity, not architectural “elegance.”
5. Architectural structures should have formal bases where possible to minimize ad hoc configurations with unknown properties.
6. Architecture should not depend on a particular commercial product or tool.
7. Architecture should produce enforceable key constraints.
8. The architect must be cognizant of the global system when optimizing subsystems.
9. Stakeholders should be involved in the process as much as possible, giving frequent and honest feedback on all aspects of the system architecture.
10. Each component should be responsible for only a specific feature or functionality, or aggregation of cohesive functionality. Components should be coupled only through explicit structure, avoiding hidden coupling where possible.
11. Reference architectures should inform interfaces.
12. The system architect is not a generalist, but rather a specialist in managing complexity.

Core Architectural Concepts

In addition to the guiding architectural principles, a set of core concepts inform the urban converged network architecture specifications below.

Convergence – Network convergence is a systemic phenomenon that transcends issues such as integration. System integration is the connection of various components and subsystems so that the resulting overall system can deliver a specified set of capabilities and optimized value. It is essentially an engineering activity. Convergence is the transformation of two or more networks or systems to share resources and interact synergistically via a common and seamless architecture, thus enabling new value streams.[6] An aspect of convergence is that not all the new value streams may be known in advance.

Network convergence has been applied to single network types, most notably, communications networks (“convergence in the bit stream”) and more recently to electric networks. This specification

[6] P De Martini and J D Taft, Value Creation Through Integrated Networks and Convergence, PNNL-24152, February 2015, available online: https://gridarchitecture.pnnl.gov/media/advanced/Electric%20Networks%20%20Convergence%20final%20version%20%20Mar%2015%202015.pdf

develops a new concept: the five core physical infrastructures are treated as a convergence of heterogeneous networks in urban environments.

Other networks reside as applications on top of the core infrastructures: EV charging networks, financial networks, logistics networks: cold chain networks; waste removal systems; people moving and goods transport; social networks; IoT; edge computing and cloud services. Other individual applications reside on top of both layers of networks: public building energy management, parking management, traffic management, emergency notification, public safety monitoring, disaster management, port electrification, etc.

While convergence may occur or be designed as N-way, this document shall consider convergence between the electric network and any of the others only. A general N-way convergence for five infrastructures would involve 10 convergence paths, whereas we shall only consider four.

Infrastructure Constraints - The five core infrastructures vary in terms of physical and regulatory flexibility, thus causing them to have differing degrees of constraint in terms of how they may be changed to suit the evolution of a city. Figure 2 illustrates a ranking of the infrastructures in term of physical change constraints.

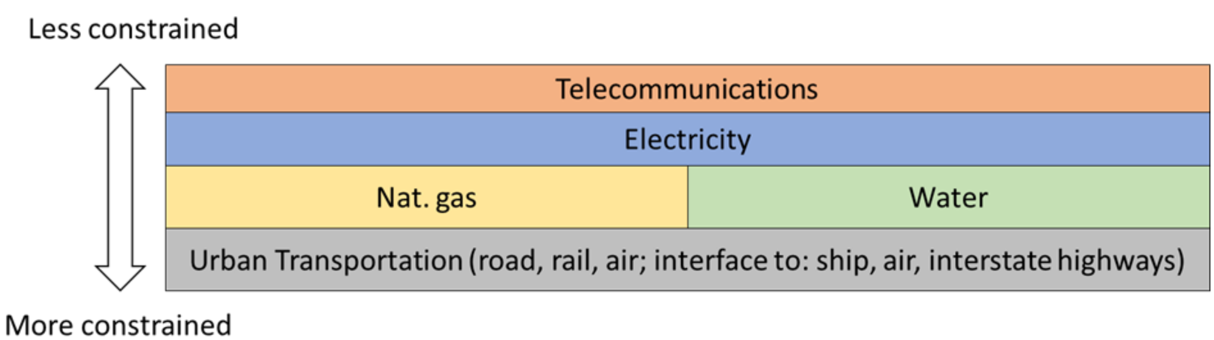

Figure 2 Infrastructure Change Constraint Ordering

This suggests that traditional city structure will tend to form around the transportation infrastructure and socioeconomic activity will bear a strong relationship to the same. This and Core Urban Converged Network Architecture Principle #2 described above are reasons for the emergence of Transit Oriented Development (TOD) in city planning.[7]

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[7] Federal Transit Administration, see https://www.transit.dot.gov/TOD

Commuting – Historically (from as far back as ancient Greece and Rome) people have spent on average an hour commuting to and from work, which, given a specific transportation mode (walking, driving, train, etc.), set an effective average limit on the size of a city. Improvements in transportation have not decreased *average commute times* but rather have increased *commuting distances*.[8]

Urban Infrastructures and Urban Resilience

Given the ability for many people (basically information workers) to work from any location, including home, the balance of loadings on the various infrastructures can change. A shift in emphasis from transportation infrastructure to communication infrastructure could be driven by a newly recognized need for urban resilience in the face of disasters. While Transit Oriented Development has been viewed as a paradigm for urban planning, in fact this could become less relevant in a future where teleworking becomes widespread. Given such a trend, the stress on the electric system would potentially change in two ways: a decrease in demand as electric vehicle usage drops off due to reductions in travel to/from work, and an increase in demand due to expanded use of telecommunications. Dominance of one trend or the other has implications for the architecture and design of the electric system (more charging stations vs. more power for telecom infrastructure). The balance of these trends for any particular city is unknown and likely to change over time, so that structural future-proofing of the electric infrastructure is a concern.

Mitigating this would be the reasons why cities exist in the first place (see Core Urban Converged Network Architecture Principle #1 above).

Federated, Distributed Platform – the operation of the core infrastructures as a platform implies the need for a federation of individual operational systems that provides the means for coordination without compromising the individual infrastructures, should allow for system and organizational boundary deference, and should be able to operate in a fragmented manner in the case of a disaster. Since the infrastructures are owned and operated by various entities, this points to the need for information exchange interfaces that support modularity, and which preserve each entity's data privacy, confidentiality, and integrity. Federation is a means to combine the appropriate functionalities of disparate operational systems and distribution is a means to provide resilience in the face of system fragmentation.

<u>Distributed vs. Decentralized Systems</u>

A decentralized system is one in which the elements are separate (usually geographically dispersed but not always) and act independently, with perhaps some small amount of supervision to provide set points, etc. A distributed system is a decentralized system in which the elements cooperate to solve a common problem. This implies some form of communication among the decentralized elements. A centralized system is one in which all the computing, logic, control, data analysis, etc. is performed at a

[8] See SCALE, p333.

single element. A centralized system is a degenerate form of distributed architecture and distributed systems may have a central element that participates in the overall processes, this latter being sometimes characterized as a hybrid of central and distributed architectures.

Distributed and mixed entity coordination/control – this is an especially complex question in the urban setting, since there are almost certainly multiple owner/operators for the core infrastructures. In many cases (transportation, telecommunications) there may be multiple competing owner/operators. The city may or may not own and operate some of the infrastructures (electric distribution, gas distribution, city streets, urban rail, water); in other cases, these will be owned and run by private sector organizations. Each of these entities already has its own operations and control arrangements and will not allow them to be subsumed into a central coordination and control mechanism. Further, these various operations systems will not be compatible or interoperable and will differ significantly in capabilities and technical sophistication.

Situational awareness with heterogeneous networks – the need for situational awareness is fundamental. This involves more than just grid power state. Cross observability, the sharing of system state information across a well-defined interface between two infrastructure operational systems, is not a common process, even though the technologies needed to do this are not exotic.

Sensing/measurement infrastructure layer – sensing and communications for the infrastructure networks must be structured as a platform capability rather than a set of application silos.[9] This is in part a resilience issue (siloed systems with backend information integration are inherently brittle) and is in part a future-proofing issue. By treating the sensing and measurement of the infrastructures combined with the operational communications capability as two layers, it is possible to define a platform model for connectivity infrastructures.

This model works well when the underlying infrastructures are all owned and operated by the city. The platform layers can supply telemetry to a common management platform layer situated above the layers shown in the figure. Other city telemetry (weather, public safety monitoring, infrastructure health, etc.) can easily be incorporated into this model.

When any of the underlying infrastructures is not owned and operated by the city, as is often the case, then the situation becomes a bit more complicated. In such a case, data fusion may have to occur at a higher level in the platform structure.

Normal vs. Emergency Operations – cities have extensive plans for operations during emergencies, but the use of transport services is not organized on a coordinated basis. While some cities may have

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[9] J Taft and P De Martini, Sensing and Measurement Architecture for Grid Modernization, PNNL-25249, February 2016, available online: https://gridarchitecture.pnnl.gov/media/advanced/Sensor%20Networks%20for%20Electric%20Power%20Systems.pdf

disaster or emergency operations centers, little has been done to provide for either infrastructure telemetry to the emergency centers or for coordinated operation of transport networks to support city emergency services and operations. The emergency centers themselves are a resiliency issue, in that as central hubs, they can become single points of failure themselves. Redundancy in the form of backup centers or a distributed network of emergency coordination nodes with hot failover capability could resolve this issue.

Architecture Specifications

The architectural views are presented in terms of (black box) components, structures, and externally visible characteristics.[10] These views are not designs but can be used as precursors to such.

Key Components

Key component classes are defined in the Component Class Models. They include:

Grid Architecture Component Class Specification – Storage v0.2

Grid Architecture Component Class Specification – Microgrid v0.1

Grid Architecture Component Class Specification – Digital Communications Network v0.1

Grid Architecture Component Class Specification – Inverter

Grid Architecture Component Class Specification – Load

Grid Architecture Component Class Specification – Solar PV

Grid Architecture Component Class Specification – Electric Vehicle

This set is **not intended to be an exhaustive list of component types used in urban infrastructure networks**. Rather it is intended to provide definitions of key component types (especially those that are new or are just emerging in importance in electric power delivery systems). Many of these newer component types have multiple or ambiguous definitions; the Component Class Model documents provide clarity on the definitions used in this specification.

Specification 1: Heterogeneous Infrastructure Platform for Urban Connectivity Services

The base for the urban connectivity services structure is a set of core infrastructure networks: electric distribution, natural gas distribution, water distribution, transportation, and communication. Note that we are concerned with the infrastructure networks here, not what is being conveyed by them. Each of

[10] See http://gridarchitecture.pnnl.gov/basic-terms-and-principles.aspx for explanation of basic terms and concepts.

these networks provides the means to convey something: commodities such as electric energy, water or natural gas; people and things; information. In that sense they provide a common capability: they connect source and use nodes, nodes that interact, etc., and as such have a common set of internal functional requirements. The term connectivity is commonly used for electricity, communication networks, and for transportation (rail connectivity for example) but is not as common for describing gas and water delivery. Nevertheless, it is a useful and evocative term for the common capabilities of these infrastructures.

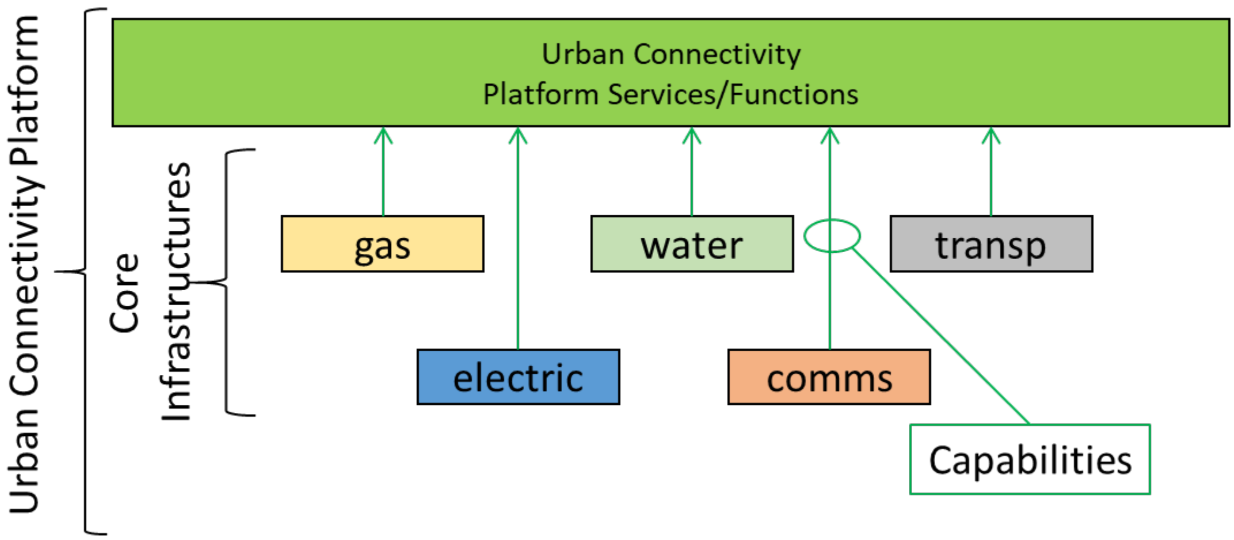

Figure 3 Transport Services platform model

Two layers of “applications” are stacked on the Connectivity Platform. One (the middle layer of Figure 4) is another set of networks which make use of the core networks: logistics networks (delivery systems, warehouses, etc.); financial networks (banks, ATMs, brokerages, markets); IoT, edge and cloud computing networks, EV charging networks, and even social networks. Application networks are those that have some form of network structure but have a specific purpose, as opposed to the networks that have a wide range of possible uses or applications. An example would be a logistics network: it has components such as vehicles, warehouses, and operations centers, and a network structure connecting then with pickup and delivery routes. This network is superimposed on the transport and communications infrastructure for specific purposes, such as food delivery. Consequently, these are also described as over the top networks.

The upper layer of applications are not networks such as the elements of middle tier are; instead they are more like “point” applications such as port electrification, city parking management, emergency services, etc. that draw upon the capabilities of the core infrastructure networks, especially electricity and communications.

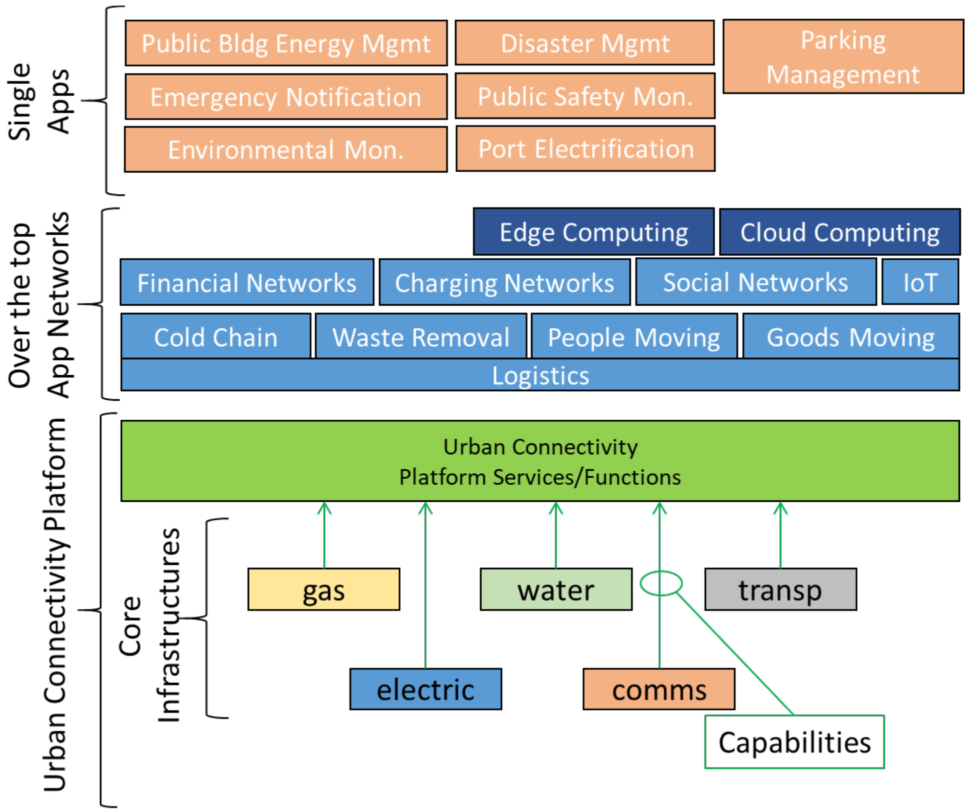

Figure 4 Urban Connectivity Services and Applications Stack Model

Figure 5 shows interdependencies among the five core infrastructure networks. Gas distribution is shown as not dependent on transport in urban settings since LNG transport is for bulk carriers such as ships. We do not consider propane here since our focus is on core infrastructure networks. Propane distribution falls under the concept of over-the-top application networks (see Figure 4).

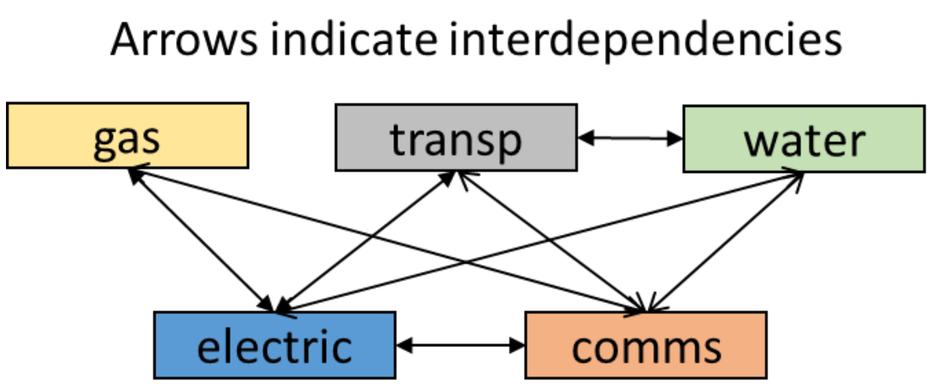

Figure 5 Core Infrastructure Network Interdependencies

Inspection of the diagram of Figure 5 shows that while various interdependencies exist, all the core infrastructures are dependent on two in particular: electricity and communications. We may therefore provide a three-level ranking of the core infrastructures in terms of dependency upon each infrastructure type, with electricity and communications networks seeing the most dependencies; transport and water next, and gas seeing the least dependencies.

One consideration in developing a federated platform approach to connectivity services in an urban environment is the regulatory structure. In addition to the regulatory body or bodies concerned with electric distribution, the other core infrastructures also have regulatory oversight, and in total this may involve several regulators, including Federal regulators such as the FCC (see Regulatory Structure Model for the United States Electric Sector, Visio file *Regulatory Structure Model.vsdx*). This can greatly complicate the issue of arranging collaboration and coordination among infrastructure owner/operators.

Specification 1 details:

1.1 Urban networks and the applications that use them are organized in a three-tier structure.
1.2 Electric distribution, natural gas distribution, water distribution, transportation infrastructure, and communications networks jointly form the connectivity services platform for urban environments. This is the bottom (foundational) tier of the structure.
1.3 This core set of infrastructures forms a *heterogeneous network platform* providing connectivity services to a city.
1.4 Layered on top of the connectivity services platform is a set of “application” networks. These networks are partially physical and partially logical (virtual) and exist over the top of the connectivity platform. They make use of the connectivity services platform in a manner analogous to how software applications make use of hardware and operating system in a computer or smart phone.
1.5 A third tier of point applications (non-network) is layered onto the stack and may make use of the base connectivity services platform or any of the layer of over the top application networks.

Specification 2: Platform Internal Functional Component Allocation Model

When treated as a platform, the core infrastructures have certain operational requirements in common (at least in generic terms; specific details vary according to the infrastructure, of course). This means that such a converged platform may have a common set of functions that apply to all five infrastructures. Figure 6 illustrates the allocation of common functions for the set of infrastructures to a management platform that in a converged setting would jointly manage the set of infrastructures.

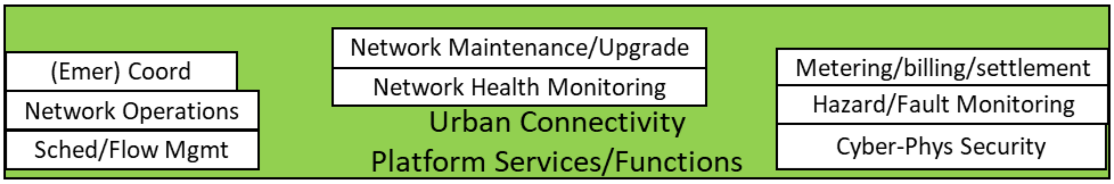

Figure 6 Platform Common Function Component Allocation Model

In practice, it is unlikely that such a set of functions would be implemented in a single common seamless arrangement any time in the next decade. Instead however, it is certainly possible to arrange a federation of these functions across the set of infrastructures, using a manager of managers structure, such has been employed to solve a similar problem with communication networks.

The manager-of-managers model as used in communications networking is generally a layered hierarchical model with an element manager layer at the bottom, a network manager layer in the middle, and a service management layer on top.[11],[12] The top layer provides a number of functions, including event correlation, process automation, and coordination across multiple network manager event management systems.

The same structure can be applied to the urban connectivity service platform. In the case the middle layer would be the operations management systems (and even whole operations centers) of the owner/operators of the individual infrastructure networks. The upper layer (service management layer in the model describe above) would provide the mechanism to federate and coordinate across infrastructures as needed. This could be for normal operations or could be reserved for use only during emergencies. Such a structure preserves the organizational and system boundaries but provides a structure for coordinated operation. Negotiation among the parties would be necessary to specify the function allocation and interfaces, but there are no essential technical barriers. Figure 7 illustrates the structure of this arrangement.

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[11] Cisco Systems, Network Management Systems Architectural Leading Practice, available online: https://www.cisco.com/en/US/technologies/tk869/tk769/technologies_white_paper0900aecd806bfb4c.html
[12] Douglas W. Stevenson, Network Management What it is and what it isn't, April 1995, available online: http://www.sce.carleton.ca/netmanage/NetMngmnt/NetMngmnt.html

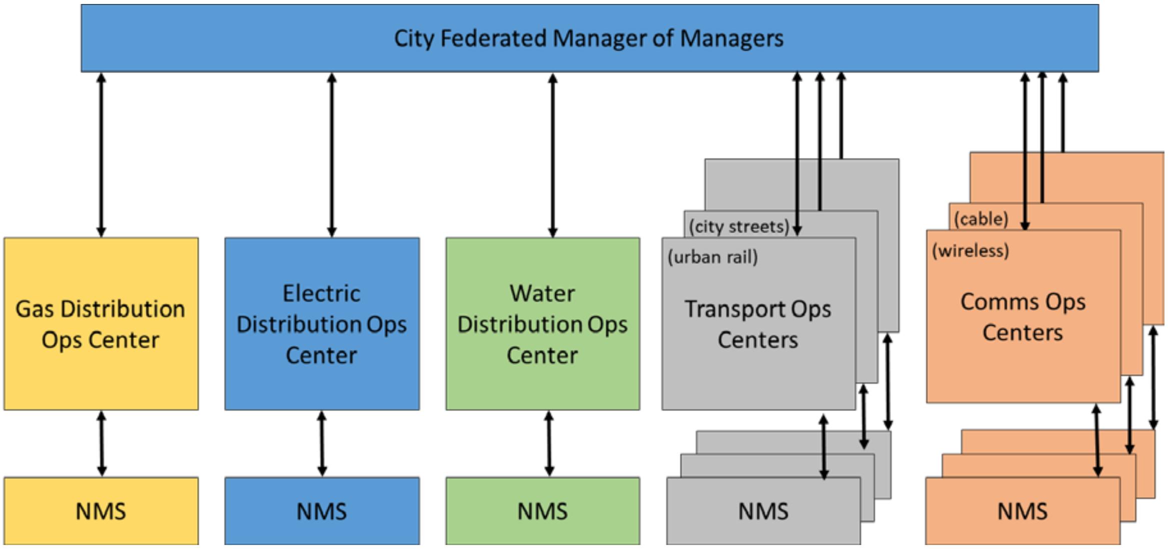

Figure 7 Multi-Party Federated Infrastructure Network Management Structure

Specification 2 details:

2.1 Provide a set of platform common services for core infrastructures, including:

- 2.1.1 Network operations
- 2.1.2 Scheduling and flow management
- 2.1.3 Network health monitoring
- 2.1.4 Hazard/fault detection and management
- 2.1.5 General and emergency event correlation and management

2.2 Use a layered structure to separate multi-system level (city-scale) network management functions from infrastructure-specific functions.

2.3 Use the top layer of the network management structure (service layer) as the means to federate across multiple infrastructure networks with separate owner/operators while respecting organizational boundaries and sovereignty. This may be activated in emergencies to provide cross-infrastructure event correlation and coordination.

Specification 3: Sensing and Communications Platform Layers

For those cities that own/operate multiple core infrastructures, it is possible to employ the sensor/communications layer model for infrastructure telemetry. This can be done even if the actual communications service is supplied by a third party. Assuming for the moment that this model can apply to all four (non-communication) infrastructures, this layer can supply sensing and telemetry transport services as a set of platform layers (see Figure 8). Appropriate sensing for each infrastructure can be connected to the communications network, and authorized applications can then subscribe to data streams from the sensors it needs. Each infrastructure owner can control access to the data from the sensors it owns but can also share on a controlled basis as desired. In effect, this can be a layer that resides beneath the bottom layer of Figure 7.

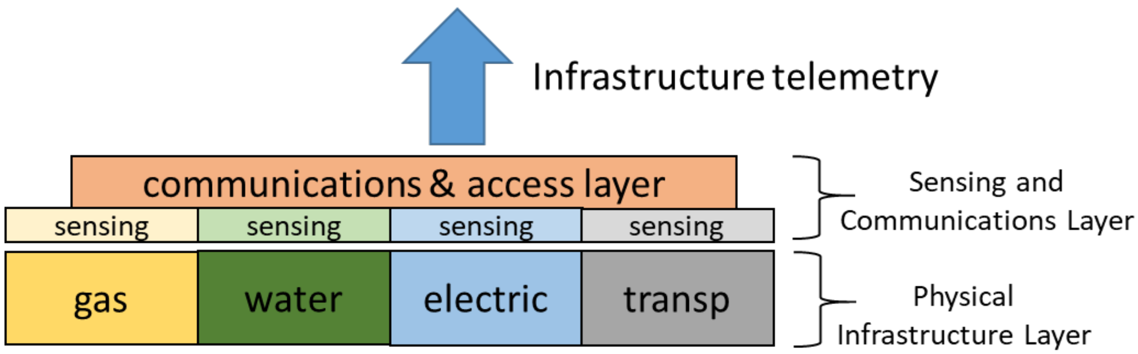

Figure 8 Sensor/Communications Layer Model

In this manner, the city could supply telemetry transport as a service (TTaaS) to the infrastructure operators, whether they are part of the city or are third parties. Cyber-security and network management leading practices apply, of course. Also, infrastructure operators should not cede responsibility for collecting or handling telemetry data to third parties such as DER operators.[13] If a third party communications service provider is supplying the data transport, it must be bound by the same reliability and obligation to serve requirements as the infrastructure owner/operators.

In the case of an emergency, data from infrastructure telemetry could be temporarily supplied to the emergency operations center(s) so that situational awareness for infrastructures could be provided on a real time basis (see **Normal vs. Emergency Operations**, above).

Figure 9 illustrates the concept for multiple infrastructures with a single sensor/communications layer.

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[13] JD Taft, Roles and Responsibilities for Distribution Grids: DER Sensing and Communication Networks, PNNL-26596, February 2017, available online: https://gridarchitecture.pnnl.gov/media/advanced/Roles_and_Responsibilities_for_Dist_Sensing_final.pdf

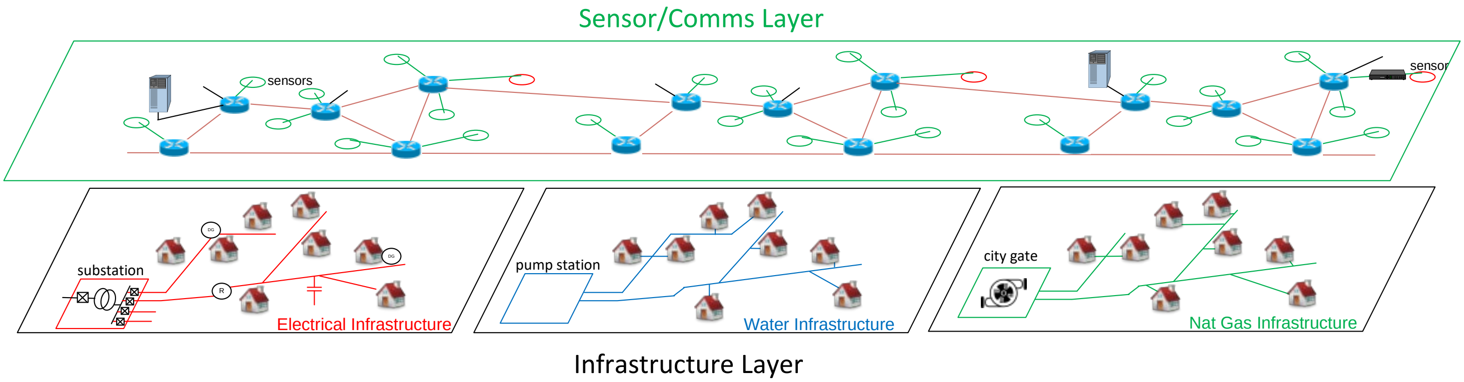

Figure 9 Sensor/Comms Layer for Multiple Infrastructures

Specification 3 details:

3.1. Treat sensing and communications network layer as a structure associated with the physical infrastructures.
3.2. Provide a set of functions and services for network, sensor, data, and security management as part of this layer.
3.3. Combine the infrastructure layer and the sensor/communications layer to form a platform.
3.4. Decouple applications (analytics, control, forecasting, measurement & verification) by having each authorized application separately access the platform for the operational data it needs.
3.5. Enable data flows as needed by using data streaming and publish/subscribe network mechanisms and protocols.
3.6. Protection and control devices may be included in the platform.

Specification 4: TOD and Transactive Oriented Grid Architecture[14]

Transit Oriented Development (aka Transit Oriented Design) is a city planning approach that intends to bring together people and city resources, so residents are within easy walking or cycling distance of public transportation to the rest of the city, thus reducing usage of automobiles. Essential elements of this approach are:[15]

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[14] The material in this section was originally developed by Paul De Martini.
[15] Transit Oriented Development Institute, http://www.tod.org/

- Walkable design with pedestrian as the highest priority
- Train station as prominent feature of town center
- Public square fronting train station
- A regional node containing a mixture of uses in close proximity (office, residential, retail, civic)
- High density, walkable district within 10-minute walk circle surrounding train station
- Collector support transit systems including streetcar, light rail, and buses, etc.
- Designed to include the easy use of bicycles and scooters as daily support transport
- Large ride-in bicycle parking areas within stations
- Bikeshare rental system and bikeway network integrated into stations
- Reduced and managed parking inside 10-minute walk circle around town center / train station
- Specialized retail at stations serving commuters and locals including cafes, grocery, dry cleaners

Central to this approach are the availability of urban transit networks (typically urban rail), dense networks of streets and paths, and a focus on organizing around transit hubs (such as rail stations). Consequently, transportation connectivity is a core element of such an approach. Figure 10, from Energy Innovation Technology & Policy LLC[16] graphically illustrates a set of core principles for TOD.

Figure 10 TOD Core Principles   source: energyinnovation.org

[16] Energyinnovation.org, Cities for People Insights From the Data, available online: https://energyinnovation.org/wp-content/uploads/2015/05/C4P-Insights-from-the-Data.pdf

One of the theories of TOD uses three characteristics to describe TOD architectures:

- Connectivity – density and directness of transport paths
- Accessibility – market access
- Availability – transportation system's ability to perform on demand

Transactive Oriented Grid Architecture

For electric power systems in the urban environment, grid design and management can be modified to support the integration of DER, smart buildings, etc. In this model, the concept of TOD is adapted to a grid where energy transactions are possible.[17] In Figure 11, a Transmission/Distribution substation transformer bank and associated bus section and feeder are defined as a transactive hub. Distribution level energy transactions are defined at this hub, with energy transactions being scheduled at the hub via power injections and take outs. Transmission/distribution transactions are scheduled at an interchange point associated with an LMP node on the high side of the transformer.

[17] P De Martini, Transactive Oriented Grid Architecture, July 10, 2019, available online: https://newportcg.com/wp-content/uploads/2019/10/De-Martini-TESC2019-Grid-Architecture-Presentation-062619.pdf

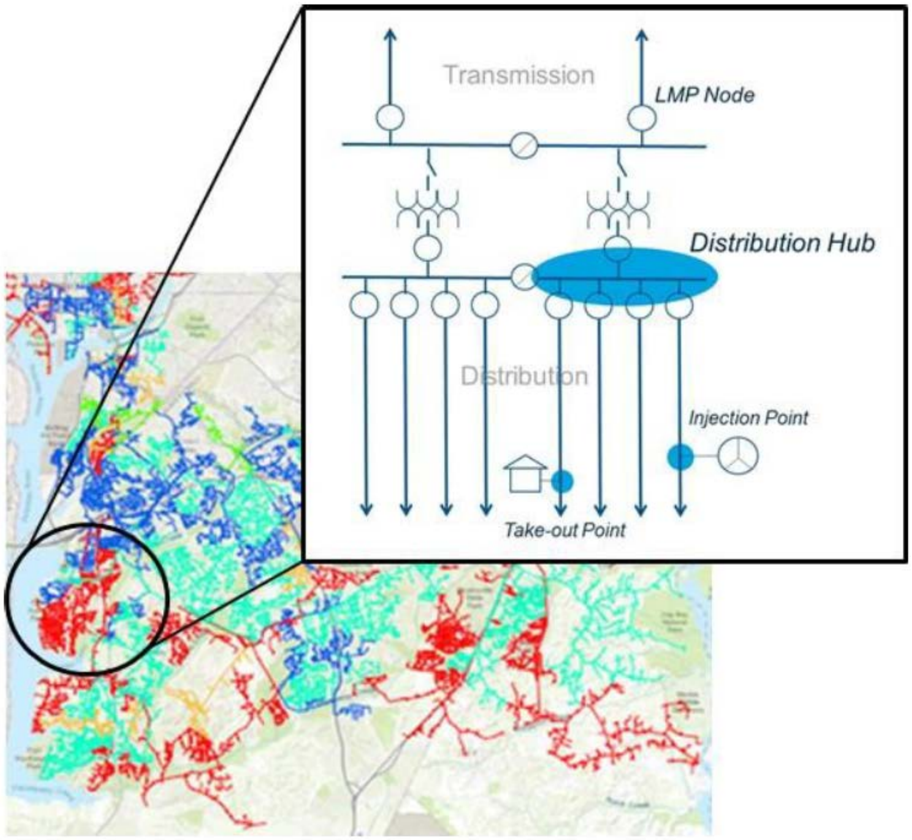

Figure 11 Transactive Energy Hub   source: P De Martini

The distribution circuits are the dense walkways and the transmission system (partially shown) is the homolog of the urban rail system in the TOD paradigm. T/D substations form the transportation hubs (train stations) for logical energy flows around the city. Note that multiple logical flows resolve to single deterministic physical flows, just as in the variable structure grid reference architecture.[18]

A network of transactive energy hubs with associated circuits and the necessary coordination and control mechanisms, market mechanisms, etc., can be formed across a city of region.

The corresponding characteristics for such a network are:

- Connectivity – bulk power system deliverability to a specified node, DER power deliverability across distribution to a bulk power system node
- Accessibility – potential number of buyers and sellers, potential volume and value of transactions, ease of transactions, and ease of access to markets
- Availability – dependability under normal and atypical operating conditions

[18] https://gridarchitecture.pnnl.gov/media/zip/Variable_Structure_Reference_Grid_Architecture_package.zip

Figure 12 is a composite view showing the combination of electrical infrastructure, Logical Energy Network virtualization zones, Laminar coordination network, and TSO/DSO Transmission/Distribution coordination with the Transactive Energy Hub model.

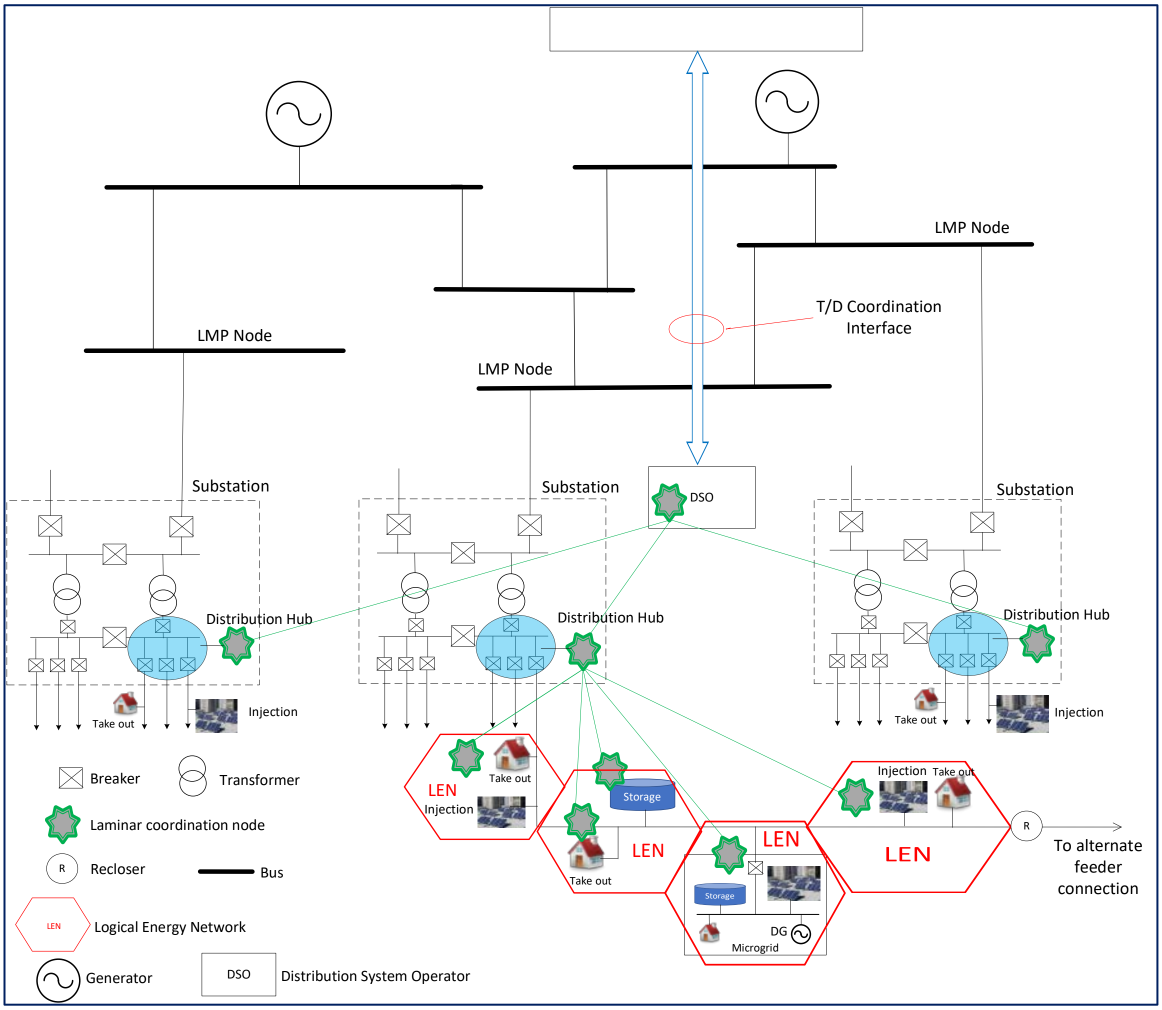

Figure 12 Composite Transactive Energy Hub Multi-Structure Model

The Transactive Energy Hub model is compatible with the LEN, Laminar Coordination Framework, and TSO/DSO structures described in the High Resilience and High Penetration DER/DA/Storage Reference Architectures.[19] Note that the Transactive Energy Hub model provides clarity on the structure as regards energy flow scheduling and market-like mechanisms in a manner completely compatible with the general coordination and virtualization schema.

[19] https://gridarchitecture.pnnl.gov/library.aspx

Specification 4 details:

4.1. A T/D substation transformer bank, bus section and feeder circuits form a transactive distribution hub.
4.2. Distribution level energy transactions are scheduled as either injections or take outs at this hub.
4.3. Transactive hub substations have an LMP node at the transformer high side.
4.4. Transmission/distribution transactions are scheduled as interchanges at a point associated with an LMP node.
4.5. Coordination of energy transactions are in accordance with the Laminar (layered decomposition) model, with market clearance as a coordinating mechanism.
4.6. Markets and coordination mechanisms are distributed and capable of operating on fragmented grids if enough connected infrastructure exists (see Availability bullet above).

Specification 5: Convergence with the Electric System

Since the electric system is so crucial to operation of other infrastructures, and provides a useful example, consider how the electric natural gas systems may converge. Here we extend our view beyond the local distribution systems because an aspect of convergence that affects the local distribution systems is how the use of gas to power electric generators can affect even local gas operations. Figure 13 shows a combined electric/gas arrangement.

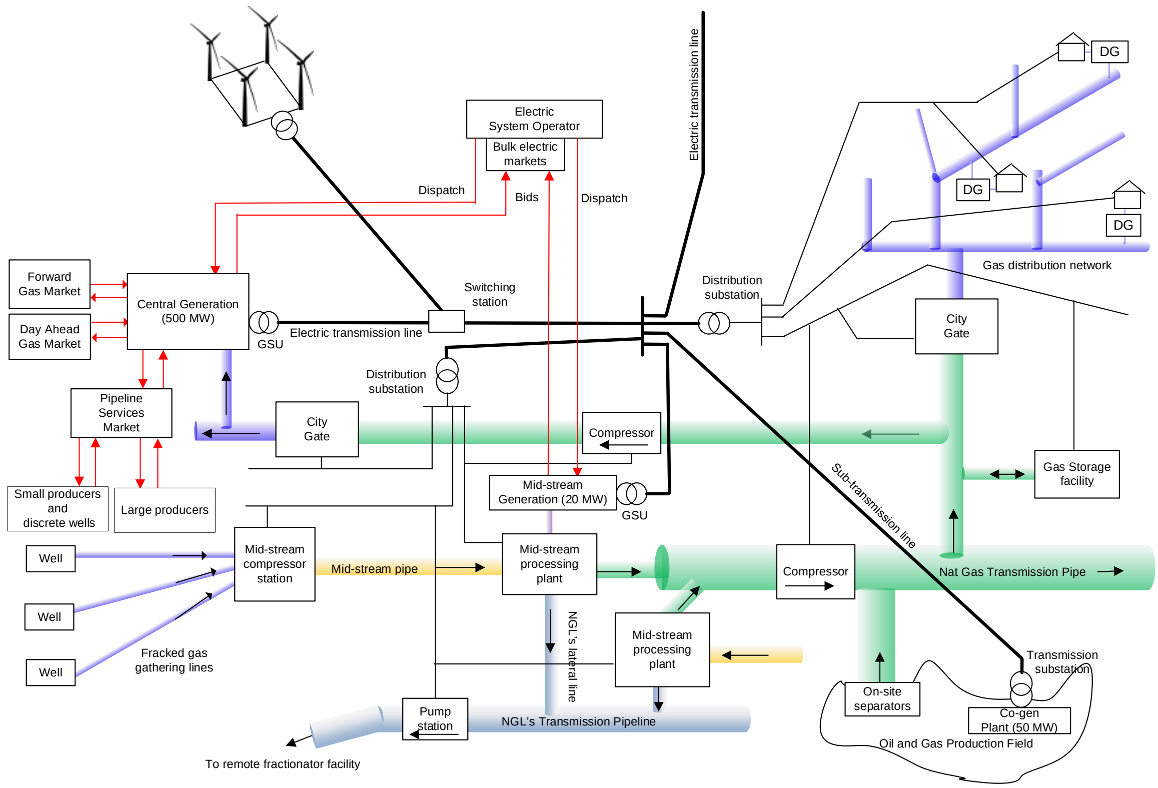

Figure 13 Portion of a Regional Combined Gas-Electric System

Note that both bulk gas and electric systems and gas and electric distribution are included.

Figure 14 illustrates a convergence model for gas and electricity. Convergence take place at several levels:

- At the physical level, various interconnections exist to transport gas to the generators. In the case of gas fracking, it may be possible to put small electric generators (less than 20 MW) at the midstream gas processing plants, creating inner resilience loops.[20]

[20] GMLC Grid Architecture core team, Grid Architecture Specification: High Resilience, PNNL-SA-141676, February 2019, available online: https://gridarchitecture.pnnl.gov/media/zip/High_Resilience_Ref_Arch_March_2019.zip

- At the market level, synchronization of gas markets and electricity markets has become crucial – this involves synchronization of the markets so that electric generator operators do not have to bid generation into the electricity markets without knowing if they have gas supplies for the generators.
- At the control level, cross observability (the sharing of network state information from one infrastructure to the other) help resolve congestion and flow issues in a coordinated manner.
- In terms of coupling, joint management of storage on both sides could provide superior means to deal with the mismatch in volatility between gas and electric systems.

In a case where the data systems and operational processes for joint coordination and control merge into a seamless platform, the convergence can lead to the possibility of new services, such as markets for volatility control, that do not exist now.

The implications for the emergence of such a platform are large: since each infrastructure is owned and operated by a different entity (in fact several entities may be involved) and since multiple regulatory jurisdictions must also be involved, the questions of how such a platform is put into place, and how it is operated are as yet undefined. Given that Transmission/Distribution coordination is still not a resolved issue within the electric power industry, a platform such as is implied in Figure 14 is not likely to develop immediately but could by 2030. Arm's length arrangements that fall short of full convergence certainly are feasible now.

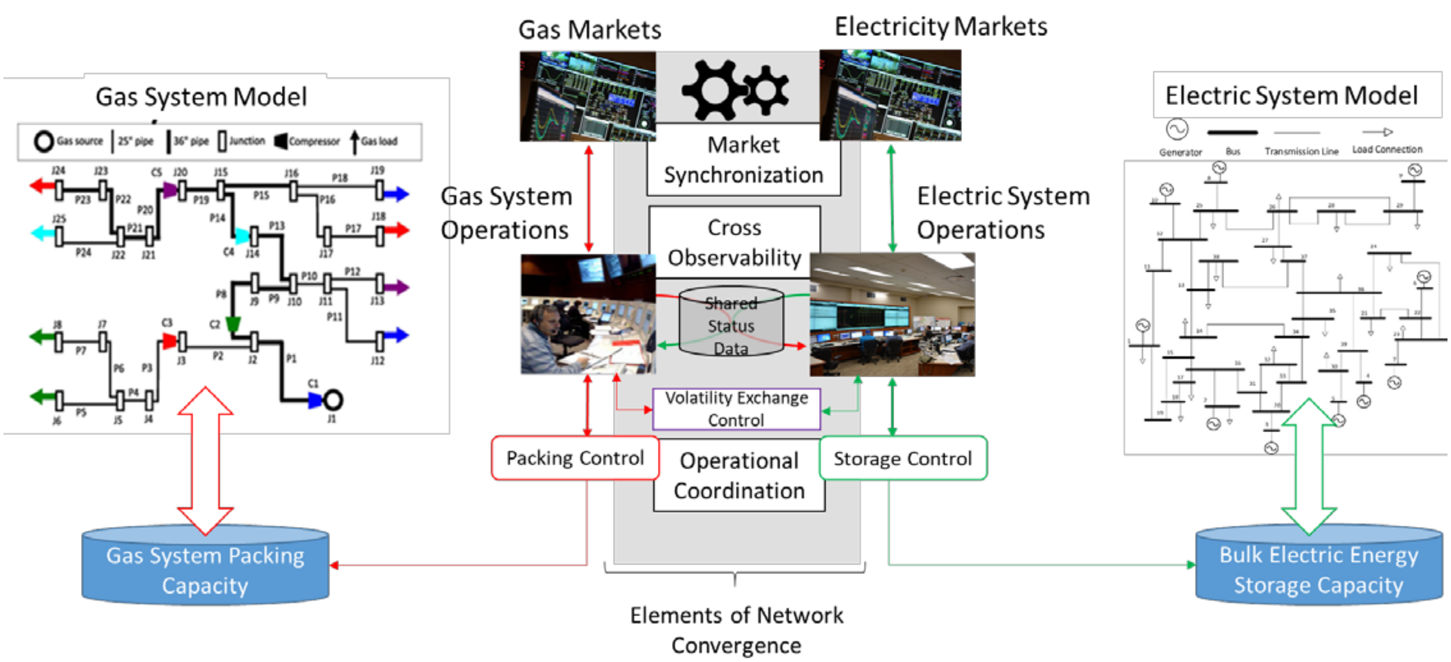

Figure 14 Convergence of Gas and Electric Systems

Specification 5 details:

5.1. Where markets for electricity and Infrastructure X exist, provide a means to synchronize market closings so that each can bid appropriately and avoid unnecessary uncertainty in either supply or demand.
5.2. Provide cross-observability between the electric system and Infrastructure X. This does not mean allowing each to take data directly from deep inside the other – rather it means sharing appropriate and agreed-upon state information at a standardized interface.
5.3. Where operation of either infrastructure can impact operation or reliability of the other (generally due to interconnections), provide a coordination mechanism for control level cooperation to ensure smooth joint operation. If buffering (storage) is an issue, use joint buffer management to decouple inter-infrastructure volatilities.

Specification 6: Data Architecture

Convergence is facilitated by the information plane. The realization of convergence is also explicit in the information flow across converged infrastructures. We prescribe the data architecture for the urban converged architecture based on the objectives for the urban converged architecture given in the beginning of this document. The data architecture enables the following objectives:

- *Heterogeneity*: by translating representation and information across the connected networks in the urban connectivity platform.
- *Flexibility and value stream innovation*: by enabling state information from one network applied for improved understanding and optimization in another network.
- *Coordination of information*: by providing structures for systematic data flow, and integrity and privacy structures.
- *Super-linear value growth*: by offering a networked connectivity of information itself leading to a multiplier effect commonly referred to as "Metcalfe's Law".[21]
- *Recovery after failure*: by rapidly enabling reassembly of state information to optimize the reconstitution of networks and infrastructure.

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[21] Attributed to Robert Metcalfe the inventor of Ethernet by George Gilder. The "law" is a rule of thumb that for *n* people in a network, the value to a user grows as n^2. Carl Shapiro and Hal R. Varian (1999). Information Rules. Harvard Business Press. ISBN 978-0-87584-863-1. Subsequent work suggests that the value growth law is better represented as n ln(n) [see B. Brisco et al., Metcalfe's Law is Wrong, IEEE Spectrum, July 2006] or has a scaling coefficient of approximately 1.15 [see G West, Scale, chapter 8].

For converged infrastructure and networks to provide value greater than the sum of the individual networks, we note that the information must be used to optimize the performance of each of the networks and be used to create new value. This new value is mediated in the information plane.

Data Inputs and Outputs in the Converged Architecture

Data is created in the Sensing and Communications Platform Layers (**Specification 3: Sensing and Communications Platform Layers**). The movement of the data is enabled via the communication layer. Data is then exchanged at “interface points” which support situational awareness as a basic capability. The interface points in the architecture also enable interoperable and coordination operations. Next, for the converged operation of the urban converged platform (**Specification 1: Heterogeneous Infrastructure Platform for Urban Connectivity Services)** and to support the core platform components (**Specification 2: Platform Internal Functional Component Allocation Model),** the physical interface points exchange data moving the data into a uniform information layer. While information may be exchanged and stored in a peer-to-peer manner across pairwise infrastructures, the data architecture supports logical access to the data across the infrastructures – in effect, enabling the data backplane which is analogous to the “over the top” application networks discussed above.

To create enhanced coordination of information for super-linear value growth and added functions such as recovery after failure, situational awareness and interoperability should leads to control functionality. This suggests a data architecture with corresponding layers of sensing, state exchange on the information backplane, and finally a centralization of the information for control and decision logic, as shown in Figure 15.

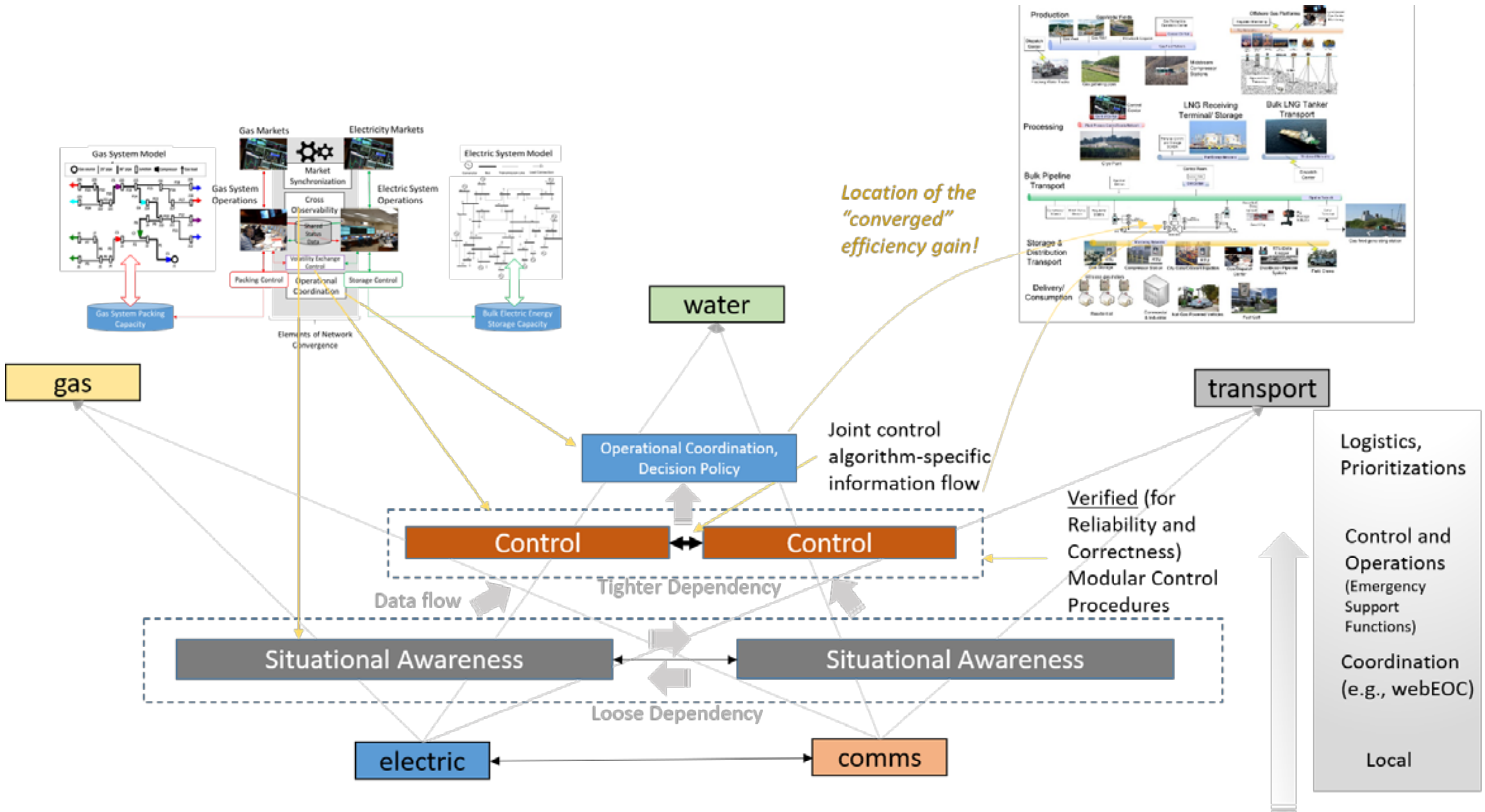

Figure 15: Data Architecture Layers

We note that there is a tradeoff space in which loose coupling of networks offers resilience (through independence and substitution) while tighter coupling enables optimization (through reuse and removal of redundancy as discussed in the "Core Urban Converged Network Architecture Principles" discussion earlier in this document). The data architecture supports this tradeoff space through the layered structure. The information plane supports data collection and presentation at the lowest layer offering loose dependency and situational awareness. One layer up, the data exchanged across the interface points allows greater visibility for control and state exchange. Finally, the information components are integrated into a single logical view of the converged system for decision making and policy enforcement. To support such a data architecture, we specify the following components.

Specification 6 details:

6.1. Sensing and data collection points explicitly feed into data architecture established for each constituent network.
6.2. The communication layer offers access points for data with explicit interfaces for read (situational awareness of state) and write (control) functionality.
6.3. Data for the constituent networks are offered with a common interface to decision logic and applications. This common interface must provide a logical converged view of all constituent networks but may be (typically) implemented through distributed access to the access points (specified in the previous item).
6.4. Data representations use systematic methods and forms that support the meaning of data so that it can be shared/accessed in useful ways without massive and constant special code development.

List of Attached Documents and Reference Papers

Document Name/File Name	Description	Version/Date
Problem Domain Reference Model – GMLC1.2.1-v2.pdf	Problem Domain Reference Model Document	11/2019
Regulatory Structure Model.vsdx	Regulatory Structure Model for the United States Electric Sector	1/11/2019
Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid	Standard list of trends and general systemic issues	Nov. 2019
P De Martini and JD Taft, Value Creation Through Integrated Networks and Convergence, Electric Networks Convergence final version Mar 15 1015.pdf	Theory of network convergence applied to electric networks	March 2015
P De Martini, Transactive Oriented Grid Architecture, July 10, 2019, available online: https://newportcg.com/wp-content/uploads/2019/10/De-Martini-TESC2019-Grid-Architecture-Presentation-062619.pdf	Description of the Transactive Energy Hub architecture concept	2019
G. West, SCALE, Penguin Press, NY	Concepts of scale as a general principle; with application to cities	2017
Component Class Specification: Storage	Extended component definition	V0.2
Component Class Specification: Microgrid	Extended component definition	V0.1
Component Class Specification: Digital Communications Network	Extended component definition	V0.1

Document Name/File Name	Description	Version/Date
Component Class Specification: Inverter	Extended component definition	V0.1
Component Class Specification: Load	Extended component definition	V0.1
Component Class Specification: Solar PV	Extended component definition	V0.1
Component Class Specification: Electric Vehicle	Extended component definition	V0.1

Version History

Action	Date	Description	Author(s)
created	3/22/2020	Originated as the 1.2.1 urban converged networks architecture specification top level document	GMLC 1.2.1 team
update	5/28/2020	Added data architecture section; text edits/corrections, added composite architecture diagram	GMLC 1.2.1 team

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