Smart Grid

System-of-Systems Architectures

Systems Evolution to Guide Strategic Investments in Modernizing the Electric Grid

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1 Introduction

The electrical power system which has served humanity efficiently for a century must now evolve to meet changing requirements: increasing renewable energy sources, decreasing fossil fuel usage, managing greater total demand, using electricity to fuel transportation, enabling more customer control of both demand and supply, dealing with security threats, and adapting to disruptive technologies. An established industry must adapt to rapid, unaccustomed rates of change.

1.1 System-of-Systems Architectures

Smart Grid designers face the challenge of planning the evolution of the grid's architecture from its current instantiation to meet the needs of a changing uncertain future. This challenge can be met by managing the evolution of the grid as a system-of-systems (SOS). A plan for the systematic evolution of Smart Grid architecture, as a system-of-systems, should be the basis for developing requirements and standards, making design decisions, procuring solutions, and managing the Smart Grid over the coming decades.

An SOS is defined as a collaborative set of systems in which its components 1) Fulfill valid purposes in their own right, and continue to operate to fulfill those purposes if disassembled from the overall system and 2) are managed, in part, for their own purposes rather than the purposes of the whole. The component systems are separately acquired and integrated to form a single system, yet maintain a continuous operational existence independent of the collaborative system. [1] A

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[1] Maier, M.W., and Rechtin E. The Art of Systems Architecting, 2nd Edition. CRC Press, London, 2000.

consequence is that properties, which do not belong to any of the constituent parts, will emerge from the combined system-of-systems. Moreover, the system-of-systems evolves as constituent systems are replaced.[2]

1.2 Central Principles of System-of-systems Architecture

Architects must enforce the following two central principles of the SOS architecture to ensure that the Smart Grid is not overwhelmed by change:

- The complexity of an SOS framework does not grow as constituent systems are modified, and SOS concepts for integrating constituents remain unchanged even as components are added and removed.
- The constituent systems do not need to be re-engineered as other constituent systems are added, removed, or replaced.[3]

These ideas are not new and form the basis of engineering design in many domains including software. We show how to evolve the architecture of the Smart Grid in a systematic, evolutionary manner, by adhering to these well-tested principles.

This paper describes four Smart Grid SOS architecture patterns and their benefits and risks. In this paper we propose a specific evolutionary trajectory for the architecture of the grid as it takes on the characteristics of these four patterns. Tradeoffs between different evolutionary trajectories are discussed and the risks in the specific plan proposed are described in detail. This paper is intended to provide a conceptual understanding of the architecture approach required for an evolving Smart Grid. The authors intend to publish an additional paper detailing how this approach can be used to evolve from the existing power grid architecture into future Smart Grid SOS architectures.

1.3 Trends that Impact Evolution of Grid Architecture

New trends in technology are impacting the Smart Grid as well as the systematic evolution of the grid's architecture.

Evolving to a System of Everything: The Smart Grid is evolving to include control of many devices that were not previously considered in designs for the current electric grid; these devices include distributed energy sources and storage, electric vehicles and appliances. Smart Grid architecture must at some level, consider the integration of vastly different types of systems that deal with all aspects of life from transportation to healthcare. We use the hyperbole, system-of-everything, to make the point that the grid is one of the focal points by which individuals and

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[2] Selberg, Scott A., and Austin, Mark A. *"Toward an Evolutionary System of Systems Architecture"*, Institute for Systems Research, 2008

[3] Selberg, Scott A., and Austin, Mark A. *"Toward an Evolutionary System of Systems Architecture"*, Institute for Systems Research, 2008

organizations monitor and control their lives and many systems and networks that are self-contained now will be connected in the future.

The Penetration of the Internet and the Web: Large segments of the public use the Internet as a core technology for their work, as an educational tool, and for social networking and recreation. Widespread access to broadband and increasing use of smart phones and tablet computers has resulted in large segments of the public, especially the young, viewing the Internet as a *system-of-everything*. This view is likely to strengthen as today's youth enter the workforce. Worldwide penetration of Internet and cellular data technologies will continue to make these technologies more powerful and affordable.

The evolution of Smart Grid architecture will reflect the evolution of Internet architecture because society will not want two competing systems-of-everything. Moreover, consumers and organizations will want tighter control of their electrical devices and information as energy tariffs based on time-of-day become common and they will expect to manage their devices using the same Internet protocols they use for other activities.

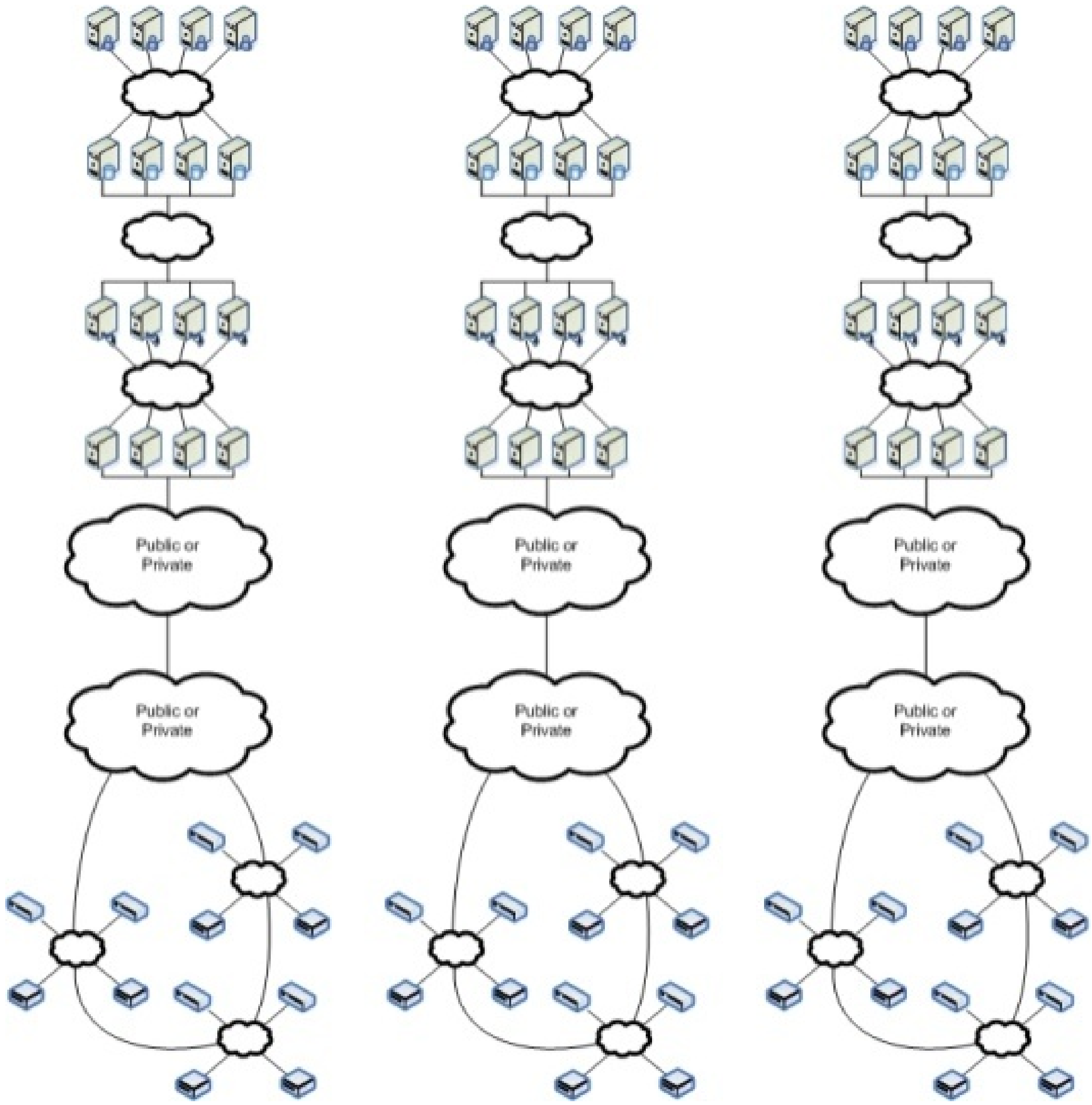
Continuous Evolution of a Heterogeneous Smart Grid: The information infrastructure supporting the grid will remain highly heterogeneous for several reasons. Different grid functions have widely different system characteristics such as requirements for security, timeliness and bandwidth; for example, these requirements are very different for fault protection and metering, and for demand response in homes vs. industrial facilities.

The Smart Grid will evolve continuously over decades; there will not be a single massive replacement of the current grid. Information technologies for sensing, metering, actuation, communication, and computation are developing continuously and rapidly. So, there is no ideal single point in time for a wholesale replacement of all devices. The architecture must be designed for continuous adaptation.

2 Smart Grid SOS Architecture Patterns

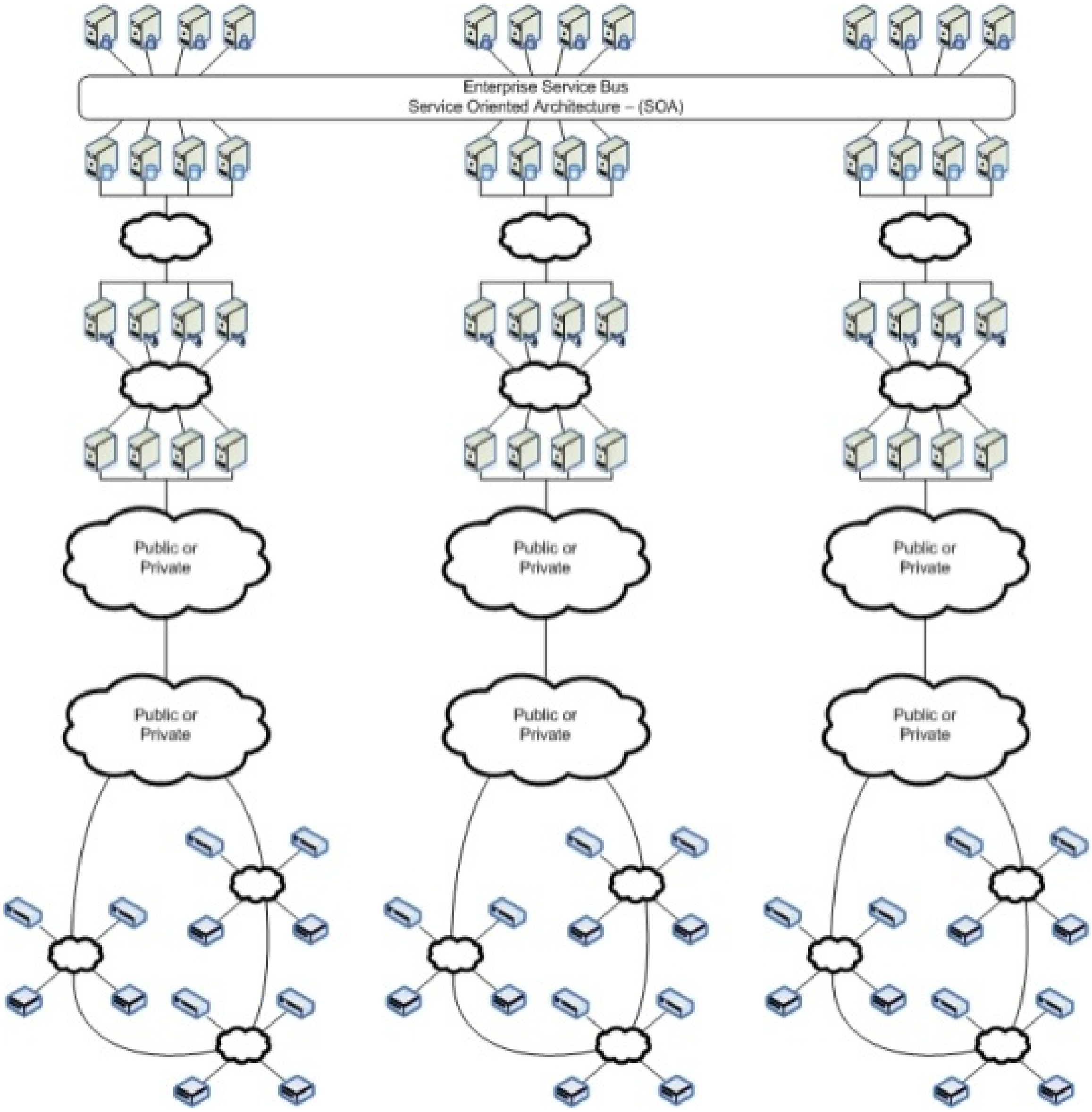
2.1 The Silo Architecture

The current SOS architecture of the electric grid can be characterized as a collection of silos. Different functions of the grid such as billing and energy distribution use different information silos that are integrated by a thin IT layer. The silo architecture worked well for utilities for decades because each silo served the needs of a business unit, and different business units in a utility had very different needs. Utilities operated efficiently with little integration across silos.



The silo architecture, though adequate in the past, will be inefficient in the future for several reasons. One reason is increasing demand by a number of stakeholders for greater control of energy usage. From the 1960s to 2010, utilities and ISOs controlled generation and distribution, and they specified well-defined interfaces to consumers; customers turned switches on and off, paid bills, and called utilities when power failed. In the future, utilities will coordinate activities by multiple stakeholders across multiple interfaces. For example, integrating distributed generation requires new interfaces. If the silo architecture is retained then separate interfaces will have to be developed between each type of stakeholder and silo. Moreover, these unique interfaces will have to evolve independently as requirements evolve. The challenge is to design an evolutionary path from today's silo architecture to an evolving SOS architecture.

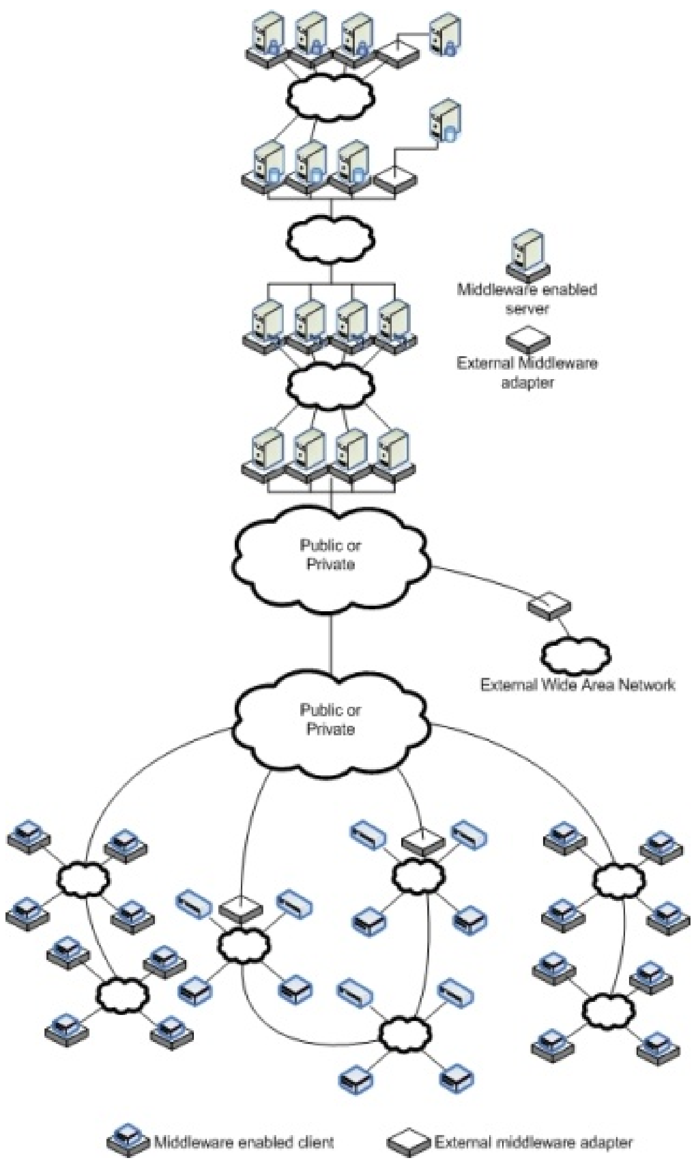
2.2 Integration using Enterprise Service Buses



A step toward the next evolution of the Smart Grid is to integrate the back office using an Enterprise Service Bus (ESB). Some utilities are taking this step. Though the step appears simple, it requires considerable cost, time and effort from IT staff and business units. Most importantly, integration using an ESB requires a discipline that enforces enterprise-wide standards on data models and IT services. If this discipline is not enforced, the ESB merely serves as an integrated physical communication opportunity, but all the problems of the silo architecture remain.

Integration of the back office results in considerable efficiencies in utility operation. Back office integration does not, however, solve the problems of multiple interfaces between different types of agents actively participating in consuming and producing electrical energy. Moreover, the ESB architecture doesn't move towards the utility customer's need for an integrated system-of-everything. Thus, the ESB architecture is a good step, but not the final step, in the evolution of Smart Grid architecture.

2.3 Adapter Architecture



Another possible next step in the evolution of Smart Grid SOS architecture is what has been proposed by the Department of Defense for use in network-centric warfare. A central feature of this architecture is that it provides each participant a user-defined operational picture (UDOP) for situational awareness. As a battlefield situation unfolds, possibly in unpredicted ways, UDOP provides each combatant with the information that he or she needs, while ensuring that combatants are not overloaded with data irrelevant to their operations. The DOD is using network-centric architectures to integrate Army, Navy, Marine, and Air Force operations to help provide overall situational awareness.

Major benefits of this architecture are the enforcement of protocols that guarantee (1) security throughout the system, and (2) rapid delivery of high-priority information. The DOD enforces standards for these protocols; vendors must design and test any new IT components to guarantee system-wide security and performance.

The challenge for utilities is to derive the benefits of DOD's network-centric architecture while dealing with a marketplace that is very different from DOD's operational environment. The Smart Grid consists of a collaboration of multiple utilities, independent system operators (ISOs) and many new market entrants. As the electric grid gets increasingly integrated across states and even countries, the number of collaborating utilities and ISOs will increase. New types of stakeholders, such as manufacturers of electric cars, distributed energy generators and energy storage devices participate in designing new interfaces to the grid. Control by a single agency of multi-state, multi-national, and multi-vendor integration, while possibly desirable, is more difficult to implement in the Smart Grid than in DOD networks. This can be accomplished by using adapter architecture.

The adapter architecture has several critically important features; most notably, it supports the continuous evolution of a heterogeneous system-of-systems. The architecture does not, however, adequately meet the public's needs for a system that integrates all devices. Nor does the adapter architecture sufficiently exploit the huge opportunities provided by open Internet technologies. Protocols layered on top of the Internet are not ideal for all applications; however, these protocols will evolve over time to meet the demand for security, performance and other features required by many applications including the Smart Grid. Though the adapter architecture goes a long way towards meeting Smart Grid requirements, the architecture does not go far enough to meet the technological or societal needs of a utility's customers.

2.4 Architecture Based on Open Standard Service Mechanisms

A great deal has been written about Service-Oriented Architecture (SOA). A definition of SOA, offered by Roy Schulte of Gartner who coined the term, is that an SOA system satisfies the following five principles:

1. Components can be added, replaced or modified individually without affecting the remainder of the system.
2. Components must be distributable (i.e., run on arbitrary servers and communicate with each other by messages or service invocations).
3. Component interfaces must be defined using standard metadata and the interfaces must be discoverable by application developers.
4. A component can replace another with the same interface.

5. Services can be used multiple times by disparate applications or the same application.

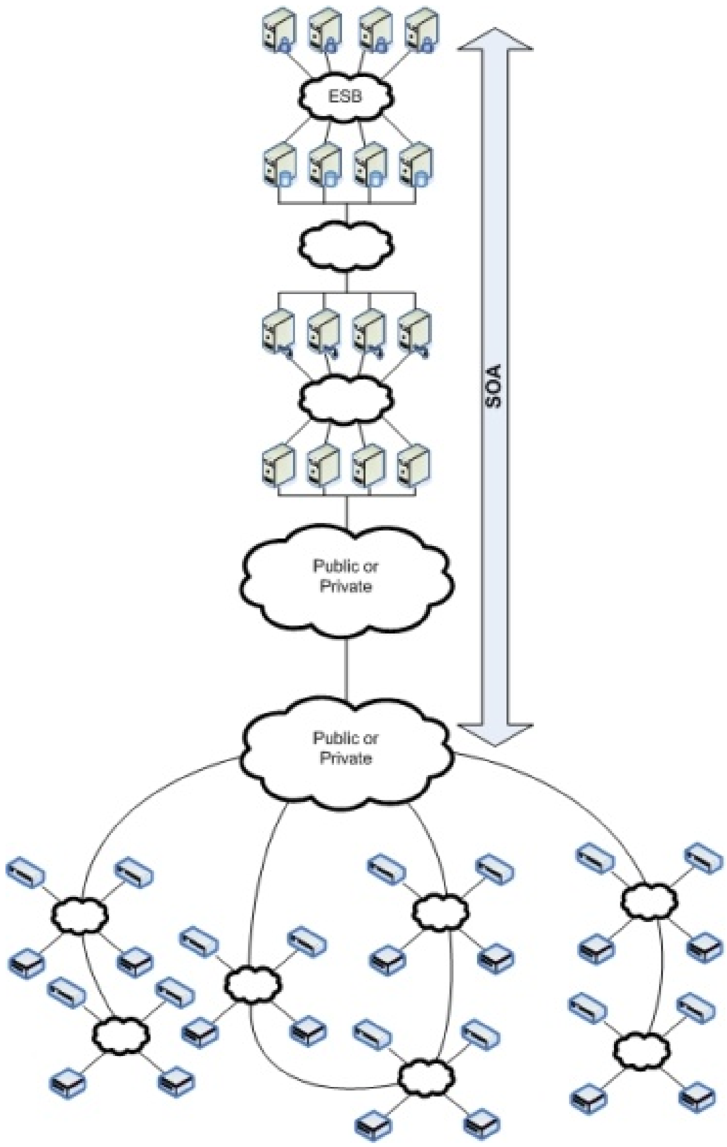
These characteristics also satisfy the two main principles of System-of-Systems architecture.

Services can be organized in business domains so that some services are only available to those within the same domain; however, a central point of standard services is common metadata for service interfaces regardless of the business domain in which the service lies.

Adapter architecture is a service-oriented architecture. The central differences between adapter architectures and ones based on standard open services are the protocols by which the services are invoked. Since IT infrastructure for the Smart Grid will evolve incrementally in order to satisfy customers' needs for a system-of-everything; therefore, leaving two options:

1. Ensure the mechanisms for specifying, invoking and maintaining services for the Smart Grid are the same as, or consistent with, mechanisms for invoking other services.
2. Have two mechanisms for managing services, one for the Smart Grid and the other for everything else, and build bridges between Smart Grid and everything else.

There are advantages and disadvantages for both approaches. An advantage for the two-mechanism approach is that a Smart Grid IT infrastructure is designed specifically for the particular needs of the Smart Grid. A disadvantage of this approach is that all the thousands of utilities and other agents participating in the Smart Grid will have to adopt either a single standard (or a very small number of standards) designed specifically for the Smart Grid, and build integration layers between the Smart Grid standard and protocols to manage both business and personal needs in other domains.



The development of a Smart Grid system-of-systems based on Internet technologies (e.g., Representational State Transfer [REST] or Web-services) requires an understanding of the key points of interoperability across the entire Smart Grid. The silos in the current infrastructure can be architected in layers, with layers across different silos having the same interface. The new architecture must specify standard interfaces at each layer so that different business functions are designed in the same way and reuse components. The architecture must also specify common services such as network management, security and diagnostics; these common services should be accessible to all systems and devices used to execute different business functions.

3 Summary

Strategic investments in modernizing the grid must be based on a plan for transitioning today's silo architectures to a system-of-systems architecture based on widely adopted standards, common services and loosely coupled systems. Strategic investments will pay off only if designed for a carefully planned trajectory of grid architecture.

Successful execution of a transition plan requires early and ongoing investments in Smart Grid standards, unified infrastructure and the co-evolution of processes to support migration from centralized to distributed operation. Massive changes in architecture, operations and training will be required over the transition period; therefore, utilities should adopt an evolutionary approach that does not exceed the there capacity in these domains.

A transition plan that some companies are adopting is to first move from a silo architecture to an enterprise service bus (ESB) architecture and then move incrementally to an open-standards based architecture, developing and adopting standards and common services in steps. The utility should, however, have an overall architecture transition plan including designs for system-wide security and system-wide timeliness at every step of the plan, before making incremental changes.

Each of the four architectural patterns discussed in this paper has benefits and risks. Each transition from one architectural pattern to another involves substantial costs, takes time, and requires expertise in both the grid and IT architecture. Utilities must, however, develop architecture plans in the context of a Smart Grid SOS trajectory to ensure Smart Grid solutions invested in today will be able to participate as part of the Smart Grid system-of-systems in the future.

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