AN INTRODUCTION TO THE NIST SMART GRID INTEROPERABILITY FRAMEWORK

AVI GOPSTEIN

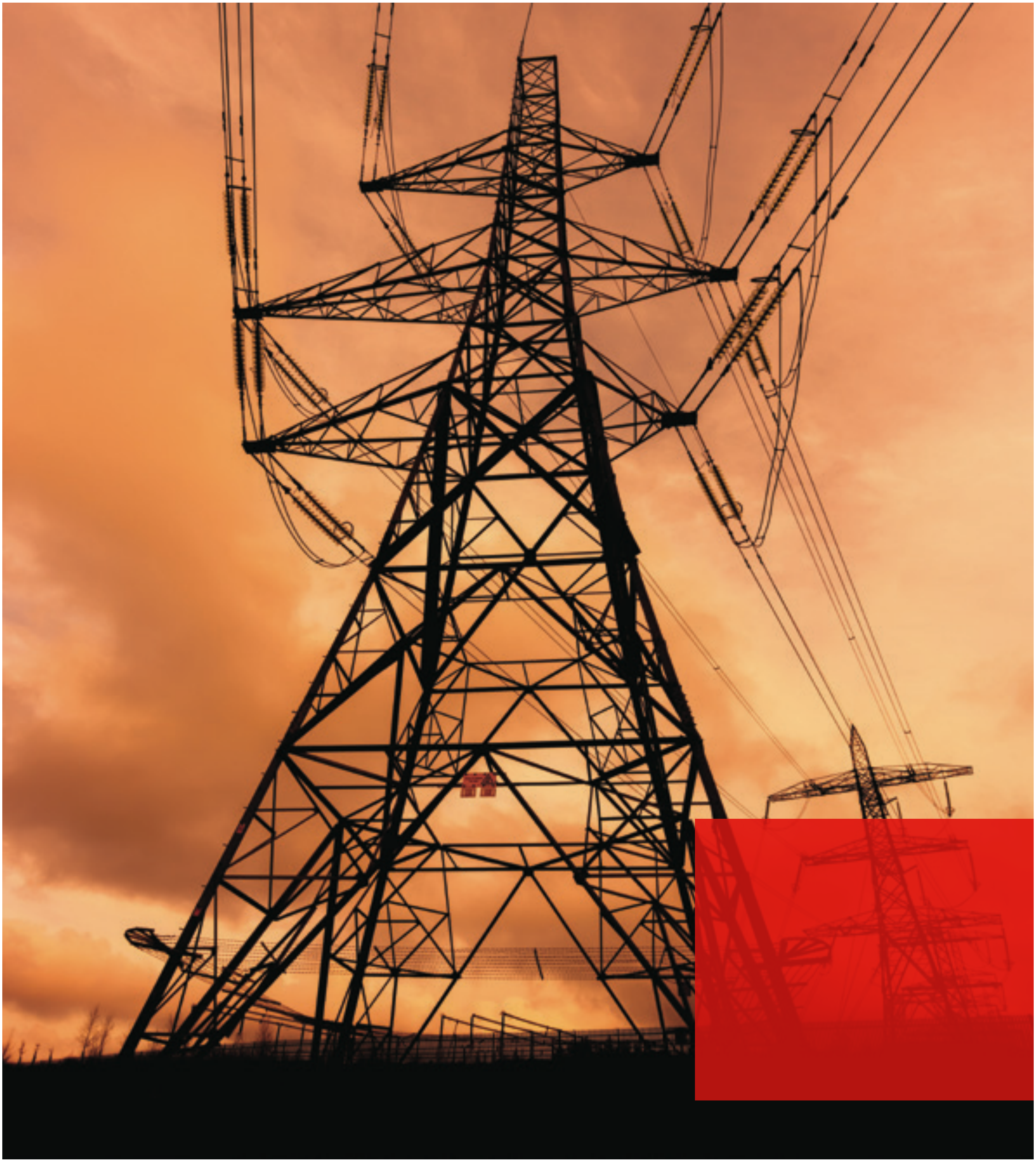
Technology is changing everything about our lives. Ubiquitous communications and improving information management technologies have changed how and where we work, our options for interacting and playing with others and how we shop for goods and services from groceries to transportation. But while modern communication has been transformational for our individual lives, its impact has been far less visible in the electric power grid.

Even as utilities have modernized their own communications and information management systems to improve system efficiency and reliability through the use of new technologies, the outward appearance of the grid has remained largely static. For the most part, power is still generated at centralized facilities and then transmitted through a complex network of wires that are positioned and sized to carry electrons to far-away customers for instantaneous use.

But while electric grids may still look the same as 100 years ago, conditions have been far more dynamic underneath the surface. The form, function and business model of the grid are transforming as power systems adapt to changing technologies and societal expectations. This hidden evolution of a critical infrastructure that permeates every aspect of modern life will become more visible as technologies such as smart meters, solar photovoltaics and electric vehicles become a greater presence in our everyday lives.

Yet the ongoing evolution of power systems is far more complex than the adoption of a few standalone technologies. Modernizing an aging infrastructure with more capable and smaller-scale devices requires increased communication and information exchange within and between grid systems. Improved data availability allows utilities and system operators to better characterize grid functional needs and value the contributions provided by customers and third parties.

The transition to information-driven ecosystems has the additional benefit of accelerating modernization. Where the pace of power system innovation was once governed by the centuries-old timelines of large-scale construction projects and evolutionary learning-by-doing processes, a grid built around information exchange can innovate, incorporate new technologies and improve operations at a speed more reminiscent of information technology and software platforms. And while substantial innovation is necessary, the changes underway in the electric grid can bring with them a sense of uncertainty regarding the role and contributions of organizations and equipment throughout the grid — to say nothing of the value brought by new entrants. →



To address the changes taking place in the grid, earlier this year the National Institute of Standards and Technology (NIST) published an update to its Framework and Roadmap for Smart Grid Interoperability Standards[1]. This fourth release of the Smart Grid Framework addresses information exchange and physical interoperability within the context of accelerating technological change, rapidly falling prices for modern energy technologies, increasing proliferation of low-cost sensors and network-enabled devices, and an associated surge in the amount and granularity of available data. The document describes the relationship between interoperability and the functions of a modern and sustainable grid and provides a strategic framework to understand and address gaps — ranging from a lack of interoperability assurance through standards to limited assessments of operational and economic benefits — that currently limit the pace of grid modernization.

Energy is a complicated space that permeates every aspect of modern society, and the power grid is intertwined with issues that touch on everything from greenhouse gas emissions to cybersecurity. This complexity can inhibit progress towards modernization as stakeholders adopt sometimes conflicting positions or objectives for the grid. Yet even within this complex space, there are technical issues on which progress would be universally beneficial.

For example, improving the ability to manage and exchange information across the grid will yield benefits in overall system flexibility, observability and operational resilience. These benefits will also increase dramatically over time as our electricity, transportation and communications infrastructures become increasingly integrated. Efforts to enhance grid interoperability are therefore no-regrets strategies that have the potential to improve many aspects of grid function today and will unlock significant value in the future.

The NIST Smart Grid Framework was written to help all stakeholders understand the impacts interoperability will have on grid operations, economics, cybersecurity and standards. It provides conceptual models to help us understand different roles within the system and the relationship between energy delivery and information exchange (see **Figure 1**). The Framework provides strategies for enhancing interoperability and improving system cybersecurity. It is a lot to take in, so answering a few basic questions about the Framework allows us to focus our conversation and highlight a few key issues.

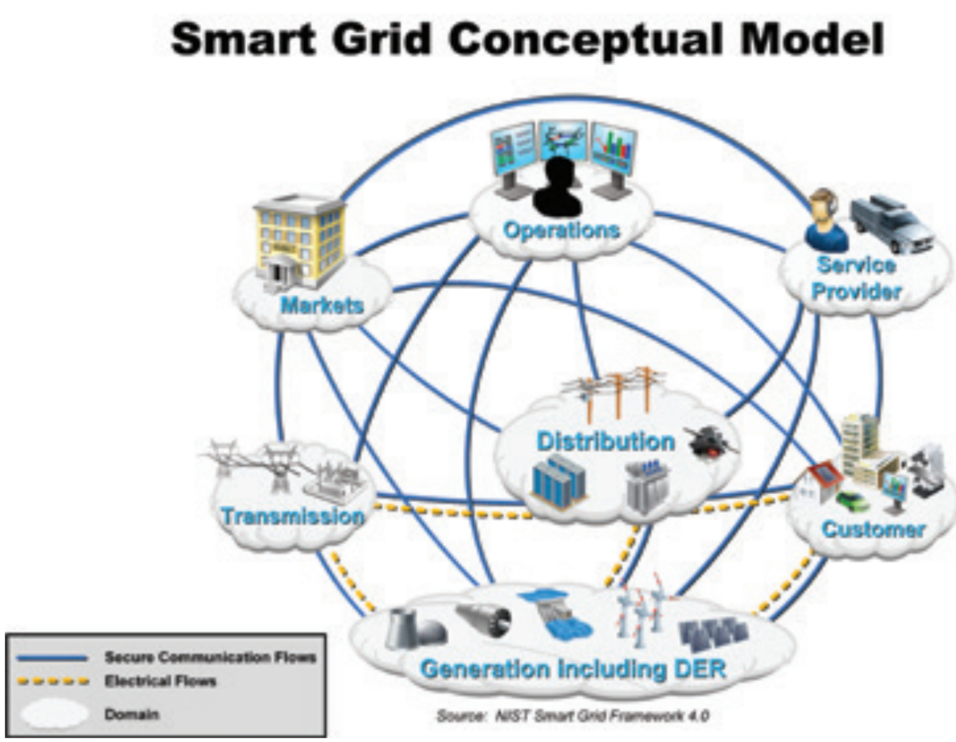


Figure 1 — The updated NIST Smart Grid Conceptual Model.

What is interoperability, and why does it matter?

Interoperability is the capability of two or more systems or applications to securely and effectively exchange and readily use information. There are, of course, stipulations to that statement, such as the information exchange must be timely and occur with little or no inconvenience to the user, but the fundamental point is simple: Interoperability enables the exchange of actionable information between equipment and systems and operators.

Interoperability is in fact a prerequisite for managing large numbers of diverse equipment — especially in aging infrastructures where new equipment must seamlessly integrate with decades-old systems that continue to provide useful, albeit potentially limited, function. The importance of interoperability in power systems gains urgency every day as the number of new technologies deployed across the system grows and capabilities increase substantially over the legacy equipment and systems with which they must integrate. While it is certainly possible for every new device to perfectly emulate the functions of an older piece of equipment that it replaces, the opportunities new technology creates — from automatic reclosers, to smart meters, to asynchronous generation and demand response — require harnessing and coordinating the sensing and control capabilities that emerge with each round of technical innovation.

It is through the coordination and aggregation of small capabilities that we can gain new function and maximize efficiency throughout the grid. For example, consider the thermostat. The purpose of a thermostat is to control the temperature in a room by actuating a heating or air conditioning system in response to measured temperature changes. That's it. It is specific in what it measures and how it works.

Now, consider a communication-enabled smart thermostat that is interoperable with other systems. That thermostat can be used to help manage distribution system congestion, thereby preventing circuit overload and improving system resilience. Managing that peak demand could also allow utilities to avoid spending precious capital on upgrading wires and grid systems to serve growing demand. Or perhaps that thermostat can be used to balance variable-generation renewables and clean our environment by timing its "on" cycles for when carbon-free power is available. Or perhaps, that thermostat can decrease a customer's heating and cooling costs by pre-conditioning a home or office to avoid peak rates.

Beyond the relatively simple capabilities of thermostats and other demand-response devices, the increasing availability of DERs that both generate and store power will transform grid-edge services. Opportunities for customers to provide and be compensated for these services will expand dramatically as adoption of behind-the-meter solar photovoltaics, electric vehicles and other highly capable systems become more widespread.

All of these capabilities — and the value they bring to different stakeholders — are enabled through interoperability. Conceptually, the most important thing to understand is that interoperability is a tool for unlocking new value across the power system. That value can come from improved operations and efficiencies, avoided costs due to decreased outages, or integration of new resources and economic opportunities into energy and grid services markets.

Why is now an important time to publish the fourth Smart Grid Framework?

We are at an incredibly interesting time in the technological arc of the grid. Electric utilities and their customers are both connecting large numbers of small-scale and controllable devices to the power system. The rapid growth, diversity and capability of these grid-connected devices add to the complexity of managing the system and demand a greater focus on interoperability. This explosion of technology diversity is occurring alongside the emergence of software-defined platforms for grid services and therefore amplifies the importance of interoperability for the safe, efficient and resilient operation of our diverse power systems.

The move toward connecting large numbers of smaller-sized equipment in the distribution system is just the next step in a decades-long trend exhibited by the bulk power system. Data from the U.S. Energy Information Administration (EIA) [2] shows that the typical sizes of grid-connected generators have fallen dramatically over the past 20 years, breaking sharply with the previous 100-year trend of increasing generator size. →

Comparing generator additions to the bulk power system over the final 40 years of the 20th century with the first 20 years of this century (see **Figure 2**) illustrates some important trends: First, new generation capacity is being installed roughly twice as fast today as it was in the recent past; and second, the size of each new generator has shifted dramatically smaller. While most new generations built from 1960-1999 relied on generators larger than 500 MW, more than two-thirds of generations built this century is based on sub-200 MW generator technology.

The trends seen in this data are the result of decades-long dynamics that have driven power sector investment towards smaller-scale devices while simultaneously accelerating construction of new generating capacity. Stimulated by regulatory and technological changes that have altered the fundamental calculus of infrastructure finance [3], the combination of individually smaller generators with larger overall capacity additions yields substantial growth in the number of devices that modern power systems must accommodate. For example, in 1970 there were about 4,500 generators connected throughout the entire U.S. electric grid, with just over 200 additional new generators built that year. Contrast that to the more than 80,000 generators connected to our bulk power system today, with more than 4,500 new generators built each year. The management and coordination of all these assets into the operations, economics and security of our power system demands high levels of interoperability.

And yet, the fundamentals that drive investment towards smaller and more numerous bulk generators are even more pronounced in a distribution system undergoing perhaps even more dramatic changes. Where generators once had to be as large as possible to maximize the physical efficiencies of conventional thermal cycles, new technologies from combined cycle to power electronics-driven asynchronous generation can achieve even higher efficiencies at much smaller scales. Where merchant operating rules and system variability increase financial risk for new gigawatt-scale generators, customer-sited distributed energy resources (DERs) have become increasingly economic as technology costs decline and new regulations like FERC Order 2222 [4] expand market access. And where early utility business models depended on the large-scale aggregation of customer loads to manage uncertainty in the system [5], emerging business models are built around understanding and addressing the energy needs of individual customers [6].

All of this creates an environment that is primed to intensely expand the number of DERs connected to the system as well as the roles these resources will play in the new grid. Indeed, this transformation is already well underway. Since 2015, utilities across the country have seen dramatic growth in the number and capacity of customer-sited DERs connected to their systems [7] and industry forecasts are for the combination of distributed generation, demand response and electric vehicles to transform grid-edge services over the next five years [8].

All of these trends point to the need for interoperability. From coordination of a generator fleet that will soon surpass 100,000 individual turbines and inverters to the integration of millions of DERs and other devices into grid-edge operations, the need to exchange and use information in our power system has never been greater.

NIST examined the relationship of earlier Smart Grid Frameworks to these changing conditions and evolving expectations for power grids, and it was clear that a major update was required. This revision was structured to examine the burgeoning innovation and informational needs of emerging grid architectures and provide readers with models they can use to understand associated interoperability strategies, requirements and standards. Considerations of system operations, economics and cybersecurity across four representative architectures provide context for the interoperability-enhancing strategies provided.

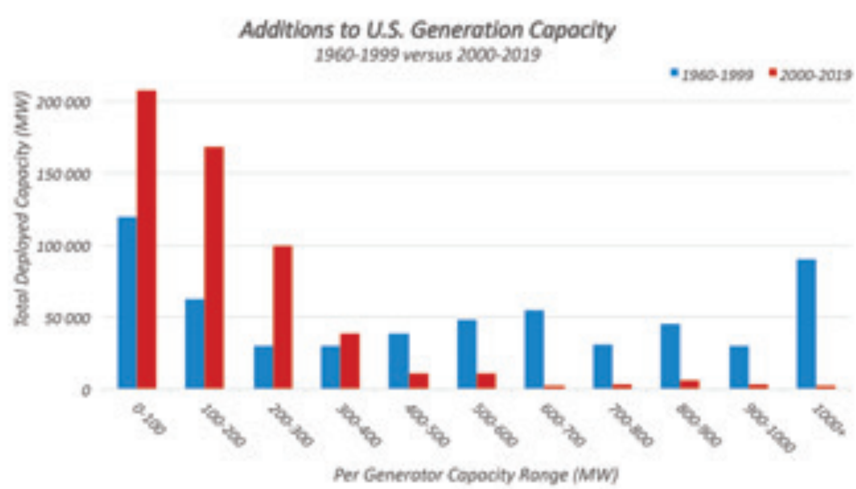


Figure 2 — Additions to U.S. bulk generating capacity, 1960-1999 versus 2000-2019.

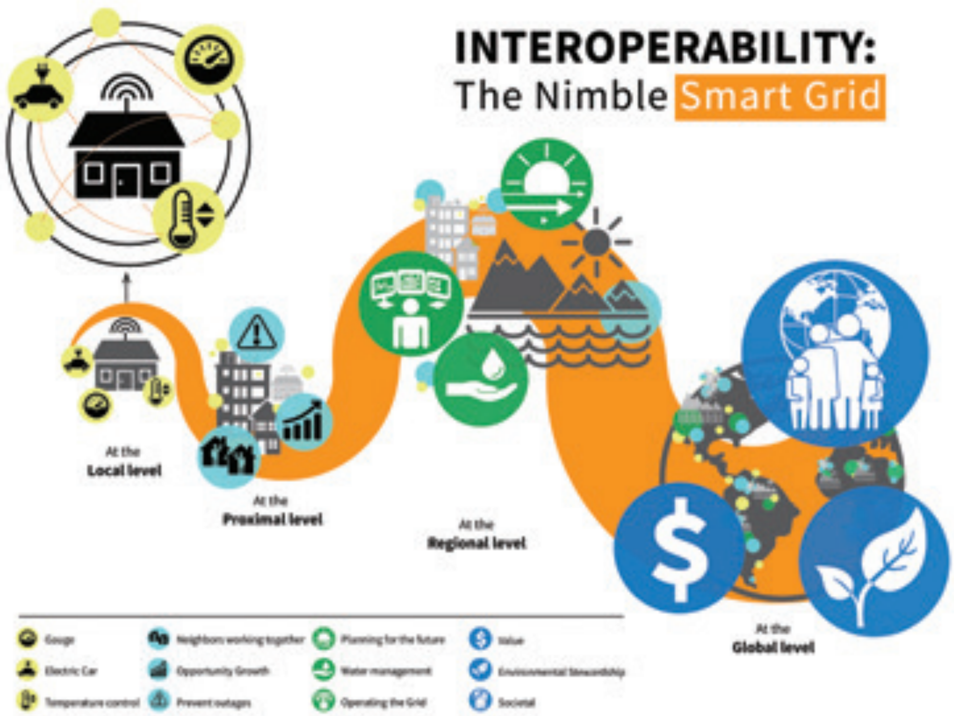


Figure 3 — Interoperability across scales.

Who benefits the most from an interoperable grid?

In short, everybody benefits from improved interoperability because the benefits of interoperability are not a zero-sum game. Interoperability is foundational to ensuring that diverse, distributed and decentralized stakeholders realize the smart grid's benefits. From reducing the cost of integrating new equipment into utility systems [9] to aggregating distributed resources for accessing wholesale markets [10] or providing novel grid services [11], interoperability should be viewed as the mechanism through which maximum function and value can be derived across the full spectrum of grid equipment and interactions.

Consider again the example of a communications-enabled thermostat and the range of impacts it can have on the grid. While each of those impacts is based upon the same fundamental action of turning an HVAC on or off, the value of that action is derived from the scale and purpose behind how — and with what other devices — that thermostat's activity is coordinated. For example, if the goal is managing congestion or other operational constraints on a local distribution feeder, the context for thermostat actuation must derive at least in part from information about the relationship between current energy demand and the physical limits of the local infrastructure [12]. Conversely, optimizing thermostat controls to reduce greenhouse gas emissions instead of feeder congestion is possible, but doing so involves utilizing different information models and establishing interoperability with a different set of actors [13].

The ability of a simple device like a thermostat to contribute to so many grid functions illustrates the breadth of value propositions enabled by interoperability. Opportunities to create value through coordinated actions will grow as new device capabilities are complemented by the emergence of software-defined platforms for new grid services. As illustrated in **Figure 3**, the range of possible grid services depends on finely tuned coordination across multiple devices, grid domains and geographic footprints.

Interoperability empowers customers, utilities and entrepreneurs to provide cost-effective solutions for some of the most challenging issues in our energy system. The NIST Smart Grid Framework aims to stimulate innovation in grid services by introducing a concept of Interoperability Profiles that formally link system objectives and device function with requirements for information exchange. Clarifying interoperability requirements and capabilities in this way brings value to all stakeholders through the coordinated management of energy technologies to maximize our ability to address challenges from grid resilience, to energy costs, to climate change.

How does improving interoperability address climate change?

The functions of interoperability are primarily about information exchange and physical compatibility between elements of a broader system. Because production of electricity and heat emit more greenhouse gases worldwide than any other economic sector [14], using interoperability →

to coordinate action across the grid introduces new sources of flexibility that fundamentally change the system characteristics.

Power systems must become substantially more flexible to maximize the environmental benefits of renewable and clean energy investments [15], and an interoperable smart grid does that by enabling the communication and information exchange necessary to dynamically adjust operations across the generation, transmission, distribution and customer domains. This flexibility not only helps power systems better utilize new clean energy resources but also maximizes the potential for displacing high-polluting resources in grid operations [16].

Interoperability is also a key enabler of highly distributed grid architectures. Most of the energy used in conventional electricity generation never actually reaches the customer because of physical losses in power generation, transmission and distribution [17-19]. But distributed resources can avoid many of these losses and so can deliver electricity more efficiently to the consumer than power generated at remote installations [20, 21]. Using low-carbon DERs at the customer site amplifies these benefits.

But even if we decarbonize the entire power sector, sustainability targets will still require decarbonizing the transportation, industrial and building sectors through electrification [15]. Doing that will require understanding and managing interdependences and information exchanges between previously distinct systems, and an interoperable smart grid capable of integrating diverse resources and technologies would provide an enabling platform for these interactions.

Do all these new devices and interactions create cybersecurity problems for the grid?

Cybersecurity is a complex issue. The large number of organizations involved with operating the grid, and the increasing number of devices connected to the system, mean that no single organization can guarantee secure operations. But that complexity does not mean that it is impossible to have grid cybersecurity. We can learn a lot from existing cybersecurity practices and guidelines, and secure operations can be achieved through a combination of engineering strategies and cybersecurity risk management and mitigation techniques.

The Smart Grid Interoperability Framework suggests two complementary paths to achieving grid cybersecurity: The first path focuses on securing organizations through a risk management approach built upon the core functions and outcomes of the NIST Cybersecurity Framework [22]. The second path focuses on securing new information exchanges through the application of engineering protections previously described for more traditional interfaces [23].

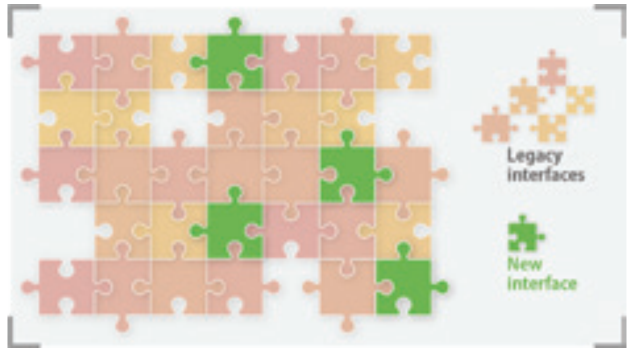


Figure 4 – Understanding cybersecurity strategies for new interfaces.

Both cybersecurity strategies in the Smart Grid Framework rely on extensive prior guidelines and references developed by NIST in collaboration with power systems and cybersecurity experts. This approach of building from existing knowledge carries with it an important lesson for securing the grid – that even as organizations and communications evolve in a modernized grid, the cybersecurity requirements for protecting the system can be derived at least in part from those already in use.

The idea that cybersecurity protections for new interfaces can be informed by the protections already in use for similar conditions is illustrated by the cartoon in **Figure 4**. The concept is pretty simple – just as new pieces can be fit into an existing puzzle, new devices can be securely integrated into the grid by adopting existing protection strategies from interfaces with similar characteristics. In short, the cybersecurity wheel doesn't need to be reinvented for each new device.

Some final thoughts

The electric grid has never been static. It is an always-changing system operating in a dynamic environment governed by the intersection of technology, policy, economics, and innovation. Today, the ability to innovate derives as much from the opportunities created by improved interoperability as from the individual technologies we often think of. The NIST Smart Grid Interoperability Framework helps us think about the complex technical interactions that are already changing the way we operate, make money from and secure our electric grid, while providing a roadmap for how to advance and leverage interoperability to maximize the benefits this transition will bring to all of us.

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ABOUT THE AUTHOR:

Avi Gopstein leads the Smart Grid research program at the National Institute of Standards and Technology (NIST) with a focus on facilitating modernization of how energy is produced, managed and consumed. Gopstein led development of NIST's Smart Grid Interoperability Framework 4.0, which addresses topics from device interoperability and cybersecurity to economic models for power systems and distributed energy resources. Prior to joining NIST, Gopstein served as a diplomat in the State Department's Energy Resources Bureau, where he focused on sustainable expansion and transformation of energy systems worldwide — especially through private sector investment. During that time he led the State Department's contributions to the U.S. Government's Power Africa initiative and also served as the U.S. delegate to the International Energy Agency's Committee on Energy Research and Technology. Before joining the government, Gopstein worked as an engineer in fields ranging from aerospace to biotech and has earned engineering degrees from Maryland and Case Western Reserve Universities.