ENERGY CYBER-PHYSICAL SYSTEMS

Research Challenges and Opportunities

Report from the Dec 16-17, 2013 NSF Workshop

Version 10.0

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July 31, 2014

Preface

The NSF CISE Program invited the academic community to participate in a NSF Workshop on Energy Cyber Physical Systems, which was held at the Water View Conference Center in Arlington, Virginia on Dec 16-17, 2013. With over 100 participants and as many written contributions, and with a day and a half of intensive discussions, the community has identified many research challenges and opportunities related to energy CPS. This report was prepared at NSF's request by the smaller group of Workshop participants listed on the cover of the report. It summarizes key discussions from the Workshop. All interested Workshop participants were also invited to submit comments and this feedback has been incorporated in this report. To augment the report, several written workshop contributions that were recognized as particularly insightful have been added as an appendix to the report.

The report writing team discussed the conclusions of the report from the Workshop held in 2009 on the same topic. This report may therefore be considered to be a follow-up to the 2009 report.

Acknowledgement

Many individuals have contributed to this report through written submissions, reviews and editorial suggestions. Particular thanks go to:

The writing team: Mladen Kezunovic (Coordinator), Anuradha Annaswamy, Ian Dobson, Santiago Grijalva, Daniel Kirschen, Joydeep Mitra, Le Xie.

The invited reviewers: Marija Ilic, Tariq Samad, Bill Sanders, and Marilyn Wolf.

The NSF Team: David Corman, Theodor Baker, Tho Nguyen.

Thanks are also extended to all Workshop participants who provided feedback on the report draft.

Executive Summary

This report summarizes the proceedings of the “Energy Cyber-Physical Systems” workshop that was sponsored by the NSF and held at the Water View Conference Center in Arlington, VA on December 16–17, 2013. Although the workshop focused on electric system, its interactions with other energy-related systems were also discussed. While other energy-related systems were not the main focus of discussion, the research issues and design requirements identified for the electric systems were assumed to be a good representation of the needs in other energy CPS areas. This report is intended to serve as a guide to those involved in technological and pedagogical research on energy cyber-physical systems, by capturing the ideas and opinions of workshop participants on what they identified as key research needs in this area.

The report first recognizes the limitations and constraints of legacy Energy Cyber-Physical Systems (ECPS), then projects future needs and requirements, and sets the objectives and goals of the report accordingly. The transition of the power system from a legacy design with centralized generation, meshed long-range transmission paths, and radial distribution with centralized control towards a new concept that incorporates distributed generation, distributed control, variable renewable resources, extended transmission and meshed distribution, flexible market constructs, energy storage, micro grids, and a more empowered consumer is a main challenge and focus for ECPS research. This transition in the power system design has a profound impact on the future ECPS because the power system physical and information infrastructure will be transformed, the control approaches will include distributed and/or decentralized approaches, and the system operation will place more emphasis on the role of loads (customer sites) that may contain generation and storage. The needs for improved cyber physical security across both the transmission/distribution network and large numbers of “smart” devices adds complexity to the ECPS design considering the very large number of devices involved. The report summarizes the Workshop discussions to provide further insight into the needs, barriers and future directions for ECPS research that is essential for the transformation of the nation’s energy systems to the cost effective, sustainable, and resilient infrastructure needed to power the nation’s future.

Next, the report focuses on the architecture needs and requirements for the future ECPS. Decision making associated with automated and operator-initiated control actions is going to be more and more decentralized going forward. This will have an impact on how the computational resources, data communications and user interfaces will have to be designed. Innovative ECPS designs that are scalable and flexible based on the prevailing computational requirements will need to be invented. The range of actors that will play an active role in controlling various aspects of the enhanced power grid will be extended to include, besides utility personnel, consumers, aggregators and non-traditional electricity market participants. How to merge the concepts of centralized and decentralized control, and still maintain verifiable system operation remains a major research challenge for ECPS.

The report then focuses on the core difference of the next generation ECPS requirements that are driven by monitoring, control and protection of the future electricity grid. New control loops will be established, both local and system-wide, which will create new spatial-temporal dynamics in the ECPS. The variability of the renewable generation requires a fresh look at the role of flexible loads and energy storage in compensating for this variability. The mentioned changes in the physical system requirements for control and protection have also a direct impact on the wholesale and retail electricity markets, and hence a tighter interaction between these markets may be needed in future ECPS design. This becomes particularly challenging when recognizing the huge expansion in computation, communication and data management that will be needed. The need to research and develop a ECPS layered control and protection architecture that allows predictive, adaptive and corrective actions is widely acknowledged.

Another major concern is the dependability, security and resiliency requirements of the future ECPS. Complexity, methods for contingency analysis, modeling for resilience, uncertainties and implementation of dependability, security and resilience strategies are identified as important research challenges. The interdependencies between critical infrastructures for energy, transportation, gas and water management should also be considered. The key to achieving the design goals listed above is the development of metrics that will allow comparison, testing and verification of future ECPS solutions. CPS are both complicated and complex and considerable innovation is required to develop good metrics to quantify their performance. This observation leads to the conclusion that establishing performance criteria for the future ECPS is a high priority because they will help the research community better understand in what direction their research efforts should be focused.

The role of modeling and simulation tools and the need to rethink, enhance, and validate them to meet the challenges of ECPS research has been recognized. The validation of the models and the evaluation of ECPS solutions relies on test-beds, sufficiently accurate modeling of physics, and comparison with real data. In addition to the technical criteria, the assessment of risks and associated costs is essential for all future ECPS solutions. Hence, research into novel modeling, seamless simulation, testing and verification techniques of integrated CPS is needed.

The education needs for the next generation of researchers and users of the ECPS were discussed but not elaborated by the Workshop participants due to time constraints. The writing team decided to add a few widely recognized thoughts on the subject. The emphasis was placed on not only education in academic settings but also training for industry and outreach efforts to educate the public. Innovative research on how to convey fundamentals of multidisciplinary CPS design is necessary to be able to change the legacy thinking that was developed over the last 50 years in the energy sector.

Once the team had summarized the Workshop discussions, it was recognized that policy, market and regulatory issues have a profound impact on future technical solutions and vice versa, new market models and regulatory approaches are enabled by technology advancement. Several aspects of this problem are described even though they were not discussed at length at the Workshop. It was stated that clear guidance by incentives, full understanding of the risk of various CPS design alternatives, appropriate regulation, and societal benefits should be pursued by the bodies that are guiding research policies and appropriating research funds.

The report ends with several reflections of the writing team on the interdependencies between critical infrastructures, which poses a question as to how some fundamental research direction and results can be utilized across various domains in the future. While this may be a topic for a future NSF Workshop, it should be acknowledged in this report as a direction for future CPS research efforts.

The workshop participants produced over 100 written perspectives before the meeting and the writing team selected 21 of these written contributions to form an Appendix to this report. All the written contributions are available at the NSF CPS VO website.

In summary, the discussion at the Workshop and the report team’s reflections clearly indicate that the energy CPS has grown beyond the traditional paradigm and needs to be brought to the next, yet-unexplored level through both innovative fundamental research and demonstration of plausible solutions. To achieve that, the following broad research directions are recommended:

- Explore further the physical laws of energy systems and synergy with the CPS design properties, which is needed if the ECPS is to be effective and responsive to the future control needs.
- Recognize the shortcomings of traditional approaches and develop fundamentally new approaches that will meet new expectations for the performance of ECPS, including enhanced resiliency and cyber-physical security.
- Advance the fundamental understanding of hybrid control systems where the continuous dynamics are affected by structural (topology) changes.
- Focus on development of fundamentally new evaluation metrics and testbeds to support the validation of new solutions.
- Devise an educational and training program that will allow both academic and industrial specialists to make the transition from legacy systems to new paradigms for ECPS.

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1. Introduction

Since the beginning of the electric energy industry, power systems have been designed using an architecture that considered the following foundational elements:

- Bulk conventional generation to achieve economies of scale.
- A model involving generation, transmission, distribution, and the consumer.
- A "load-following" control paradigm, in which the consumer uses energy at will and the system responds to the consumer demand by producing matching resources.
- Just in time operation, with virtually no energy storage.
- Control and stability established by inertia of large synchronous generators.
- Centralized investment, planning, operation and control by electric utilities.
- Utility business model based on revenue according to sales volume.

Two major changes have occurred in the industry:

1) With the advent of digital computers around the 60's, the industry moved to digital control based on Supervisory Control and Data Acquisition (SCADA) systems.
2) During the 90's, deregulation of the industry resulted in the formation of wholesale electricity markets in some regions and countries.

Today, two fundamental goals are causing major changes to the electricity infrastructure:

- *Environmental Sustainability*. In order to address energy sustainability concerns and strategic objectives of CO2 emission reduction, clean sources of energy need to be incorporated into the production of electricity, most notably, renewable energy. Many renewable energy sources such as wind and solar are spatially distributed, highly variable, and less predictable. They are also often integrated with the grid through power electronics interfaces and thus inertia-less. In addition, energy efficiency and conservation are a major part of the sustainability targets. This goal is strategic and imposed by our desire to move toward a model of electricity production that can sustain us into the future.
- *Effective Management of Pervasive Data and Extracted Information*. Advances in sensing technologies, communication infrastructures, data processing, computation, software, and embedded systems, allow for complete cyber-control of the energy infrastructure. The role of pervasive data and extracted information in development of more powerful and advanced applications such as state estimation, optimization, planning, etc., and ability to support novel application even those not conceived today is an unexplored opportunity. The goal of exploring this opportunity is a natural progression of society with similar transformation in all industries including other cyber-physical domains. The main difference is that the energy infrastructure may require high performance and embedded information management resources that may reside outside the custom designs used in the past, hence new levels of the integration will be needed.

These goals raise the question of whether the fundamental control and management architecture of the Energy Cyber-Physical System (ECPS) needs to be reviewed in order to enable the objectives of further economic efficiencies, higher reliability, and environmental sustainability. Such requirements on architecture could unleash innovations at all layers of ECPS, much like the information technology revolution that occurred in the past decades.

This section provides a background of the issues surrounding ECPS today. The prevailing properties of the legacy ECPS are addressed first. The limitations and constraints are discussed next. Future needs and requirements are outlined at the end [1]. While most of the comments provided in this section are centered on power systems, many of the features discussed may be found in other types of CPSs. The power system ECPS is selected to illustrate some of the most demanding requirements and research needs in the entire ECPS ecosystem.

1.1. Legacy Energy Cyber-Physical Systems (ECPS)

Legacy systems are characterized by the following features:

- Legacy ECPS date back to the mid-sixties when the energy management system (EMS) concept utilizing computers to aid system operators was introduced.
- The key control paradigm was to implement extensive power system monitoring to aid operators in performing control through manual execution of switching and control actions.
- Automated control included Automatic Generation Control (AGC) making sure the system frequency was maintained through balancing the load and generation. At a faster time scale, the inertia of spinning generators provided energy storage to absorb changes. A variety of automatic controls on generators, capacitors, and transformers maintained voltage magnitudes.
- The power of computers was used off-line to perform various contingency studies, allowing operators to develop what-if scenarios, and thus making sure that they could optimize system operation while maintaining operational reliability.
- Protective relaying was implemented as a distributed automation function to detect faults and immediately issue commands to circuit breakers to disconnect the faulted part.
- Experienced power system operators (dispatchers) used an intuitive understanding of the various operating conditions and operating rules to enable them to steer away from abnormal conditions.
- Besides operators, other utility staff were engaged in mostly off-line efforts to set relays, analyze disturbances and plan maintenance primarily using non-operational data, and to perform simulations to optimize day to day operations.
- The deregulated environment has delegated the generation scheduling and economic operation to the Independent System Operators, hence creating a need to cost-effectively coordinate operation of interconnected power systems.
- Blackouts have been relatively rare and when they occurred it was typically due to a combination of interacting factors, including electrical faults compounded by failures in the information processing system. Large cascading blackouts were rare but of substantial risk due to their large impact.
- The load was usually considered a passive element of the system and the main task was to plan and meet the energy needs while maintaining stable and secure operation
- The information and communication technologies (ICT) used to implement ECPS have not conceptually changed over the years except for some obvious upgrades that were driven by advances in ICT technologies, and the increased capabilities of power electronics.
- The regulatory and policy framework protected the customer interests through State regulatory commissions and power system operation performance through FERC and NERC.
- The use of renewable generation, while at a relatively low level, has alerted the industry that traditional ways of monitoring, controlling and protecting the system will no longer suffice.

1.2. Limitations and constraints

Legacy systems suffer from the following limitations and constraints:

- The lack of a well-coordinated and integrated ECPS that utilizes the most advanced technology and new control paradigm limits the ability to optimize the operation of the system.
- The high level of penetration of variable energy resources such as wind and solar, and the lack of flexible resources from the demand side (such as demand response) to effectively deal with the impact of variability makes the traditional "load-following" paradigm unsustainable.
- Centralized control and distributed protection have created a lack of coordination, causing occasional unreliable system operation and sometimes resulting in cascading outages leading to blackouts.
- The inability to process the large amount of data currently available and relate it to grid physics and engineering is leading to a fundamental conceptual constraint where data and models cannot be well matched.
- There is insufficient scientific and engineering understanding of complex heterogeneous CPS networked systems making the goal to operate them at low cost and with reliable performance difficult to achieve.
- Based on the realization that the system is entering an undesirable operating state that needs to be rectified, reactive control is often not sufficient to maintain robustness and predictive or adaptive control is more appropriate.
- The legacy approaches and solutions are preventing innovation from flourishing and bringing benefits in both improved reliability and reduced cost to the customers.
- Inelasticity of the demand to electricity prices is preventing customers from benefiting from interactions with both the retail and wholesale markets.
- The lack of redundancy in ICT solutions creates limited Quality of Service (QoS) and fault-tolerant capability resulting occasionally in ICT system failures or lack of performance.
- Monitoring of high fidelity power system dynamics, urgently needed to offer adequate monitoring control and protection, is feasible with synchrophasor and related technologies, but there is a gap in fundamental understanding and engineering solutions to realize this potential.
- Increased importance of cyber-physical security is not well supported by existing practices of ICT system design and personnel awareness.
- The behavioral aspect of the customer reaction to price signals and social values associated with sustainable living are not well understood and create uncertainties.
- The principles of efficient standardization and interoperability as a condition for cost-effective open system designs are not embraced, often preventing competition.
- High risk of stranded assets caused by a lack of understanding of fundamental principles of complex systems design is impeding the introduction of new ICT solutions.
- Testing and certification of products and system solutions is very limited, leaving future upgrades vulnerable to unmanageable modifications and excessive costs.
- Lack of computational capability to implement some advanced control and optimization concepts creates barriers that can only be overcome through proven HPC technologies.
- The lack of scalability of distributed generation, microgrids, energy storage and customer controlled loads at a mega scale creates challenges going forward.
- High penetration of versatile hardware and software control solutions such as FACTS and switching of transmission lines makes new control opportunities but coordination of control is also more difficult.

- Inefficient collection, processing and sharing of data, lack of historical records, and lack of data-oriented probabilistic models make it difficult to predict or correct future prevailing conditions based on statistical properties.
- The trained workforce that can innovate, evaluate and implement solutions in a multidisciplinary CPS environment is lacking.

1.3. Future needs and requirements

The following future needs were identified by workshop participants.

- *Scalability.* The physical power system and its cyber solution will be expanding requiring a design that can be scaled up for several orders of magnitude without restricting the Quality of Service (QoS) or other design properties affected by the expansion
- *Sustainability*. This universal need poses the question of how to select the best ECPS solution in the future.
- *Reliability and Availability*. While some major improvements in reliability and availability were achieved over the years, it is difficult to quantify reliability/availability in a manner that enables it to be optimized subject to cost. Deterministic reliability/availability rules need to evolve into more complex risk-based and performance-based criteria.
- *Robustness*. With the introduction of variable and distributed renewable resources, maintaining system robustness with an increase in scale is a challenge.
- *Resilience*. The need to have risk-based and self-healing control features is emphasized when cyber-attacks or large-scale cascading blackouts or natural disasters that cause large-scale cascading blackouts occur.
- *Carbon footprint*. Higher penetration of renewable generation is essential to minimize the carbon footprint and maintain national energy security.
- *Market flexibility*. To allow flexibility of the load, its direct participation in the market is needed
- *Energy efficiency*. Both the efficiency of the operation as well as design efficiency remain challenging goals.
- *Energy security*. The reliance on a domestic supply of energy is a must to achieve economic and societal stability.
- *Affordable cost*. This continuing goal is becoming more challenging when desirable technological solutions are not yet creating economies of scale
- *Public acceptance*. The behavioral aspect of a relatively uneducated public are creating a need to focus on explaining to the public the technological and societal opportunities created by new solutions.
- *Consumer empowerment*. Consumers will need to be better informed and more involved than they are today if the potential of distributed energy resources and other end-use assets and technologies is to be realized.

1.4. Objectives and Goal of this report

The objective of the report is to summarize discussions from the ECPS Workshop held on Dec 16-17, 2014.

The goal of the report is to present research challenges and suggest directions for future NSF-funded ECPS research efforts. The report complements the earlier report from a 2009 NSF Workshop [2].

2. The Science of Developing Energy CPS

2.1. Background

Conventionally, the design and control of electric energy systems have been hierarchical and administered at the top level by humans. However, the electric power industry is undergoing profound structural changes as our society increasingly emphasizes a more sustainable utilization of energy. With many more dispersed, heterogeneous, and variable resources such as wind and solar, as well as enhanced sensing, computing, and actuation capabilities, it becomes necessary to revisit the design objective of cyber-physical energy systems. One of the key challenges is that of aligning various objectives at value through interactive coordination of many decision makers in the future grid. The new design objectives will need to reconcile such complex interactions among heterogeneous devices and decision makers (e.g. renewables, distributed generation, demand response, electric vehicles, storage, CHP).

2.2. Multi-scale Integrative View

The electric energy systems in the U.S. and most regions around the world have been in place for several decades with trillions of dollars in assets. Therefore, the design of new cyber-physical energy systems must be backward compatible and incrementally deployable. Such a design will need to integrate legacy infrastructure with the new cyber and physical components.

Design of future cyber-physical energy systems will require a systematic multi-scale approach to integrating physics-based and data-driven models of distributed energy resources to enable ubiquitous provision of electricity services at value in restructured power systems. Today’s modeling of electric energy systems is either purely based on first principles which suffers significantly from the ever-increasing complexity of non-uniform devices, or is purely based on data-driven approaches which does not incorporate fundamental insights into the physics of electric power networks. In sharp contrast, the future design of electric energy systems will need to seamlessly integrate physics-based and data-driven modeling of energy resources. Further, where electricity markets exist, the reconciliation of these two elements with increasingly complex market mechanisms creates an additional layer of complexity. Such a design provides the intellectual basis for many system-theoretical breakthroughs and their application to electric energy systems.

2.3. Expandable and Flexible Architecture (Both Physical and Cyber)

The design of cyber-physical energy systems should accommodate not only today’s legacy infrastructure, but also dramatically different future architectures. In particular, the information and communication infrastructure will likely evolve at a faster pace than the physical energy infrastructure. Therefore, how to design a cyber-physical energy system that allows for asynchronous expansion/upgrades of cyber infrastructure and physical infrastructure requires major efforts from the research community. With deep penetration of distributed cyber and physical technologies, energy CPS systems research must tackle diverse issues:

- How do we provide incentives for active participation by customers?
- How do we schedule and control energy exchanges across multiple layers with quantifiable performances?
- How do we standardize the design process to enable plug-and-play in ways that are compatible with the long lifecycles of energy system components?

- How do we enhance the operation of the grid so that it can be operated closer to its stability margin without compromising reliability?
- How do we integrate flexible markets with cyber-physical energy systems, all the way from retail to wholesale?
- How do we design the market mechanism and policies for cyber-secure energy systems?
- How do we open technological opportunities for new and established industries to innovate, grow and profit from the changing grid?
- How do we ensure that the security and privacy of grid operation as complex cyber systems are introduced at all levels?

Such a design paradigm needs to daw upon progresses in multi-scale integrative view of future energy systems. In particular, how to provide the “tearing,” “zooming,” and “linking” capability of the future modeling and design needs to be carefully studied [3].

3. Architecture

3.1. Background

Energy Cyber-Physical Systems (ECPS) are infrastructures that produce, transport, store or consume energy and have a tight linkage with communications, computation and control. In this category are infrastructures such as electric power grids and gas networks.

ECPSs can range from small devices (such as home appliances) to very large (continent-scale) energy delivery systems. ECPS are usually networked in some manner. For instance, the entire electrical grid can be considered as a large ECPS composed of bulk interconnection, distribution networks, building and network circuits, distributed sources, storage, and loads. Large ECPSs systems are critical infrastructures and represent enormous financial investment.

ECPSs have been designed to meet the objective of producing, transporting and delivering energy. Their design was based on a set of given assumptions and requirements and considered technological limitations at the time of their initial design and subsequent incremental upgrades. Engineers and stakeholders got involved at various stages to determine how the infrastructure would be built, controlled, and operated. The infrastructure designed in this manner has continued to evolve, becoming ever larger, more interconnected, and more complex.

3.2. Requirements

When combined, the two goals mentioned in the introduction of this report, environmental sustainability and effective management of pervasive data and extracted information, cause unprecedented changes to the foundational elements on which electricity systems have been developed and the manner in which they are currently operated. Table I summarizes the trends as well as the high-level features of emerging ECPS. These features can be further analyzed in order to develop sets of specific solution requirements.

As listed in Table I, paradigm shifts are occurring in the electricity supply system. These trends suggest that the existing control and management architecture must be reviewed and that a set of requirements needs to be developed to understand how technologies map to functional and performance requirements.

3.3. High Level Needs

As sensing and communication systems are deployed across the grid, traditional consumers become more aware of their energy consumption patterns and behavior and recognize the opportunities to make some decisions regarding their interactions with the energy delivery system. As new physical devices are deployed, such as PV sources and storage, the consumer acquires new degrees of freedom to control energy. Some consumers may become prosumers, e.g. economically motivated agents that can produce, consume or store energy, and who optimize an energy-related objective function, such as minimizing cost, maximizing profit, maximizing comfort, etc.

Prosumers, such as homes, buildings, microgrids, EVs, etc. are new decision makers. The control and management architecture must support decision-making by prosumers. Prosumers are spatially distributed and numerous. A decentralized coordinated control and management architecture will support the decisions of prosumers, while coordination protocols can ensure security and reliability in the operation of the grid. A decentralized architecture would represent a significant departure from the traditional centralized or hierarchical control of the grid. Certainly, applications such as demand response have as underlying concern the question of who will respond and how the responder will make decisions.

Table I: Summary of Energy CPS Requirements

Domain	Trend or Paradigm Change	Future Requirements
Sources	• From fossil fuel to renewable • From bulk centralized to partially distributed • Highly Variable	Green Distributed Stochastic
Information	• Can control entire system through software • Increased digital control • Cyber-security issues • Personal information, privacy concerns • Available sensing and data	Cyber-Controlled Cyber-Physical Cyber-Secure Private Big Data
Actors	• Consumers can also produce and store • Consumers seek their own objectives • Massive number of actors and devices • Traditional actors have new roles of interacting with new actors	Producer/consumer (Prosumer)-based Decision-Makers Decentralized, Layered Architecture
Delivery Systems	• New dynamics of legacy systems • Interdependencies with other systems	Integrated background

A decentralized control and management architecture requires explicit recognition of the consumer as a decision-maker. Decision makers will require data and information in order to make decisions. The information architecture hence follows or is derived from the control and management architecture. In order to move information and make it available to the decision maker at all locations and times and with a certain quality, a communication architecture needs to be developed. Thus the information architecture must inform the communication architecture.

4. Control and Protection

4.1. Background

One of the main hallmarks of a cyber-enabled electric grid is the increased deployment of feedback and communication among stakeholders of the grid. This in turn implies that loops are being closed where they have never been closed before, across multiple temporal and spatial scales, thereby creating a gold mine of opportunities for control (see Figure 1 at the end of this section). Control systems are needed to facilitate decision-making under myriads of uncertainties, across broad temporal, geographical, and industry scales—from devices to power-system-wide, from fuel sources to consumers, and from utility pricing to demand-response. Efficient and reliable loop closure necessitates new control themes, architectures, and algorithms, all of which embrace complexities due to large-scale, distributed, hierarchical, stochastic, and uncertain features, all of which are widespread in the grid. These architectures and algorithms will need to provide the smarts, and leverage all advances in sensing, power electronics, communication and computation.

We present various research challenges that can occur in control and protection using two different viewpoints. We first explore a grid wide perspective, and presents challenges from emerging topics, the most dominant of which includes Markets, Demand Response and Storage, and Smart Distribution Systems. Next, the challenges are outlined from a dynamic systems perspective.

4.2. Emerging Topics

Due to the urgent need to enable integration of renewable energy such as wind and solar into the power grid, fundamental changes are called for in several areas, the most dominant of which are markets, coordination of heterogeneous assets including Demand Response and Storage, and the design of smart distribution systems. The main challenges in these areas are control-centric and are enumerated below.

4.2.1 Markets

An electricity market represents a system of entities that are involved in the trading of electricity. As electricity cannot be stored in large quantities at the current cost of energy storage, and any electricity that is produced must be consumed, the electricity market is responsible for ensuring transmission of electricity in a reliable and whenever possible, efficient manner. Emerging challenges in energy CPS are due to the introduction of new actors into the market including renewable energy generators, storage providers, and demand response-compatible consumers. This in turn necessitates the use of new models, new tools, new architectures, and new solutions for market analysis and synthesis.

Wholesale markets and retail markets are two major components of the electricity market. Power generating companies that sell electricity to suppliers and transmission and distribution system operators who typically purchase electricity to compensate for losses in the associated grids participate in a wholesale market. Markets typically consist of various decision levels, most important of which are a day-ahead market (DAM) and a real-time market (RTM), each producing its own financial settlements in which ISOs are responsible for both day-ahead auctions that are run daily for each hour of the following day, as well as real-time auctions that are run every 5 minutes during the day. In some cases, there are additional intra-day market based adjustments. Generators participate in these markets by submitting offer curves consisting of generation levels and energy prices as well as start-up costs, no-load costs, minimum up and down times, and other technical constraints and costs. The most common and powerful tool for determining optimal solutions to financial settlements in both the DAMs and RTMs is optimal power flow, whose use is ubiquitous in electricity markets since deregulation. The retail electricity market manages the final stage of the power sale from electricity providers to end-use consumers such as small businesses and individual households.

Electricity markets also include markets for ancillary services: frequency regulation, operational and contingency reserve. Some of these markets are co-optimized and simultaneously cleared. Because of the need for more precise and fast balancing under higher penetration of renewable, ancillary markets are currently being enhanced with provisions for fast ramping flexibility.

Main challenges include:

- Many of the current practices in DAM and RTM may be viewed as suboptimal solutions to a stochastic multi-stage, dynamic programming problem. With increasing penetration of renewables and the correspondingly increasing intermittency and uncertainty in the underlying market operations, the central question is the realization of market mechanisms that can provide optimal solutions despite the strongly stochastic and temporal variations. The challenge is to maximize operational efficiency, while guaranteeing security even in the presence of possible loss of load and varying generation without falling back on very conservative decisions, which is often the solution to these problems at present.
- Currently, fast reserves, which are needed to track desired regulation signals typically issued every five seconds, are procured in the hour ahead or day-ahead markets. Such a practice directly comes into question with growing penetration of renewable generation – a 30% increase in renewables, for instance, implies a three-fold to four-fold increase in fast reserves. In addition, this increase also necessitates the use of reserves across all time-scales. New entities from Demand Response (such as flexible building loads), electrified transportation (such as electric vehicle batteries) will have to be incorporated in the market structure. New dynamic market mechanisms need to be designed that provide efficient market price signals and maintain energy balance in real time by absorbing positive and negative fluctuations in renewable generation.
- Given the significant impact that increased uncertainties stemming from renewables can have on market transactions, accurate forecast modeling is a crucial ingredient in determining resource dispatch. Given improved forecasting techniques able to predict weather, demand, and renewable generation at higher time resolution and over longer horizons, market models need to be developed to handle multiple time-scales and uncertainties.
- Also needed are dynamic market mechanisms that represent renewable energy sources, with their uncertainties, in market bidding, model the impact of intermittency and uncertainty on ancillary services, integrate suitable demand-response models into both DAMs and RTMs and storage and plug-in hybrid electric vehicle costs into the market architecture.
- A significant opportunity for new market mechanisms may occur in the retail market. Whether price-based, incentive-based, or bilateral ‘transaction’-based, new Demand Response solutions that allow customers to participate in a variety of different ways and alleviate emergent grid situations are needed. The cyber infrastructure (by which we mean the information, control, computation, and prediction) needs to be adaptive and much more distributed in order to support a more flexible retail level market with potentially millions of decision-makers. Also, an important issue is how to aggregate flexible demand from retail to wholesale and how to disaggregate from wholesale to retail.
- Any innovations in electricity markets entail additional, frequent, and judicious information exchange between various stakeholders in the grid. These in turn introduce new challenges in the cyber-physical domain, pertaining to computational, communication and information

systems. New safety-critical components may be necessitated in these markets thereby raising issues of bandwidth, reliability, and cyber-security. All of these challenges need to be addressed by the Energy CPS community as well.

4.2.2 Coordination of heterogeneous assets

The proliferation of assets having quite different characteristics creates a set of new challenges:

- Development of a modeling framework that captures heterogeneous aspects in demand-response—startup and shutdown, delays and time constants, and dependencies on environmental factors and among related systems, so as to enable fast adjustments and realize power balance, and function as a surrogate for ancillary services.
- Coordination of storage in one area with the varying generation in another area resulting in varying tie-line flows with minimal information exchange.
- Adaptive solutions for sudden changes in available storage from electric vehicles.
- Optimal management of interconnected loads and distributed energy resources (including renewables) both in grid-connected and islanded modes.
- Determination of the optimal number of levels of aggregation, the minimal set of information exchange between levels, which leads to a desired balance between abstraction and accuracy.

4.2.3 Smart Distribution Systems

The introduction of more sophisticated control and communication devices in the distribution grid also introduces opportunities and challenges:

- Distributed control using FACTS and fast storage for improving operational reliability, risk mitigation, and preventing cascade failures.
- Design of DG clusters in terms of the type of sensors and communications and control architectures that can enable efficient and reliable power flow. Appropriate contractual structures need to be designed that facilitate these goals.
- Protection against manipulation of smart meter data.
- New topological complexities: resulting from system changes due to micro-grid operations and “mesh” structure.

4.3. Fundamental scientific challenges

An Energy CPS is best characterized as a system of distributed systems that is large-scale, of multi time-scale, hybrid, distributed, hierarchical, and highly uncertain and time-varying. The utopian goal of efficient and reliable delivery of green, and affordable power at all points of the grid is best realized through a number of fundamental scientific investigations grounded in control systems and the physics of grid engineering, and can be grouped under the topics discussed next.

4.3.1 Cross-layer design and analysis

- Power system control has typically been organized in a primary (automatic and local) layer, a secondary (automatic and centralized) layer, and a tertiary (manual and centralized) layer. This structure may need to be revisited to better integrate renewable energy as a dispatchable resource and provide alternatives to expensive ancillary services.
- Multi-layers of defense against cyber and natural attacks via hierarchical objective functions.

- Integration of economics and distributed control policies to incentivize and align all stakeholders to realize global outcomes.
- New mathematical frameworks that combine engineering and economics, control and optimization, and centralized and decentralized approaches, and engender robustness of massively networked large-scale systems.
- A multi-modal architecture that realizes, distinguishes, and transitions between a normal and emergent state, and launches the corresponding sequence of corrective, restorative, and healing actions.

4.3.2 Hierarchical coordination of heterogeneous and distributed multi-agents

- Distributed, real-time closed-loop architectures that accommodate uncertainties in renewable generation and match supply to demand by making use of ubiquitous real-time information, and decomposing global objectives into coordinated local algorithms.
- Scalable algorithms that are decentralized and deployable at a huge distributed scale supported by local decisions and global coordination.

4.3.3 Interplay between communication and control

- Determination of the proper degree of decentralization of communication and computation and integration of decentralized and centralized decision-making so that the distance to failure is minimized. In some cases, real-time control must be performed over networks that do not provide strong real-time guarantees. The complexity of decision-making is shown in Figure 1.

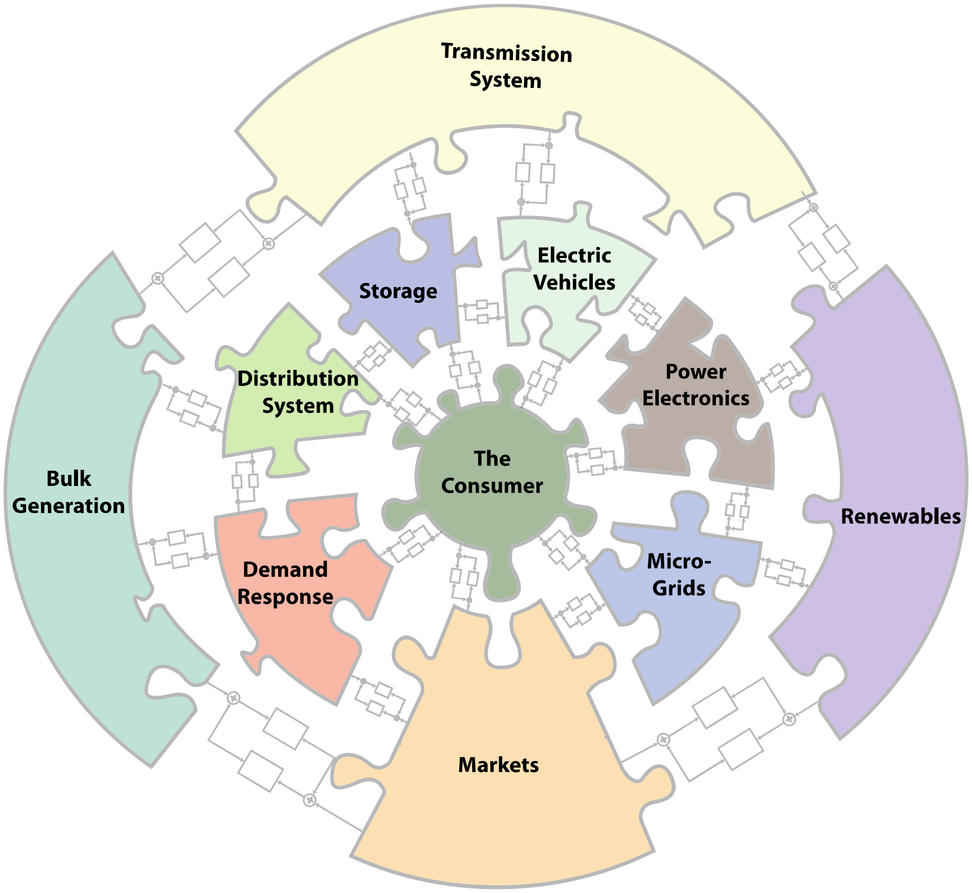

Figure 1: Control of Smart Grids – New Opportunities in an Energy CPS [4]

5. Resilience

5.1. Background

Resilience broadly relates to the performance of the cyber-physical power grid when there are initiating failures or attacks. Resilience is the key infrastructure property that limits widespread blackouts and societal disruption arising from both naturally occurring and malicious failures. Maintaining and strengthening resilience is an essential precondition for transforming our nation's energy system and for national security.

There are multiple useful aspects of resilience to be individually defined, quantified and engineered. For example,

- Some initiating failures or an initial attack may be followed by widespread propagation of outages and/or misinformation leading to blackout, which is followed by a recovery process of restoring functionality, followed by evolution of the system as operators and designers and learning technology respond to the previous blackouts, near misses, or precursors. The performance of each of these stages contributes strongly to the overall resilience and progress in ensuring resilience in all of these both separately and in combination is needed.
- Taxonomy and analysis of attacks/failures is highly challenging.
    - It is desirable to be able to detect malicious attacks and distinguish them from naturally occurring faults.
    - There are also a variety of propagating failure mechanisms, recovery efforts, and responses to blackouts over the long term – categorization of these failures is especially complex when there are several interacting subsystems, as is the case with the cyber-physical grid,
- Moreover, the grid is complex, with many interacting subsystems, and resilience metrics may need to be developed either using specific mechanisms for specific subsystems, or more broadly analyze methods that are needed due to combinations and interactions of subsystems. It seems that resilience should be addressed both bottom-up and top-down.

Methods for grid cyber-physical resilience can and must draw on other subjects (e.g. grid engineering, detailed and high level modeling, data analytics, controls and protection, fault tolerance modeling and control, robust controls, optimization, high performance computing, wide area monitoring, machine learning, complex systems theory, networks, large scale simulation, multi-agents, statistical physics, system architecture, discrete event modeling, signal processing, numerical analysis, game theory, reliability, statistics, hybrid systems, symbolic execution tools).

5.2. Challenges

There are multiple overall challenges in addressing resilience:

- *Complexity.* There are already a gigantic number of cyber-physical failure paths, and adding more interconnections to an already complicated cyber-physical grid could greatly increase the possible interactions. It is highly challenging to catalog even a higher risk subset of the failure paths. Many of the failure paths are unusual, and common failure paths are often already removed by engineering, and this leaves rare and unusual interactions as the "normal accident".

Good design can provide some decoupling in time or space scales or between subsystems. There are also a huge number of attack and initiating failure scenarios. The challenge is not simply the number of failure paths and attacks, but also their diversity. The required level of redundancy in functional paths is not clear, but there are economic limits to the feasibility of massive redundancy so that additional approaches need to be developed. There is a need for graceful degradation of complicated high performance systems into adequate but more robust and simpler control systems.

- *Methods for Contingency analysis:* There is a challenge to integrate measurements, information, algorithms communications and models. For example, "what if" contingency analysis cannot rely only on models of the physical system but must also consider the impact of failures in the cyber components. Large quantities of observed or computed data need to be converted into actionable information that provably enhances resilience. Grid operators require margins to the various sorts of grid failure to be computed and recommendations of effective mitigations if the margin becomes too small. Examples of advice are generator re-dispatch, real-time islanding, or load shedding that provably solves the problem in a large majority of cases.
- *Modeling for resilience:* Cyber-physical modeling appropriate to study resilience even in the present grid with its physics, controls, protection, information and computing systems is a challenge. The emerging smart grid and its interactions with the present grid cyber-physics and with other networked infrastructures is even more challenging. The modeling ranges over time and space scales and the cyber and physical networks and subsystems are heterogeneous and multi-layered. Hybrid, stochastic, nonlinear, and large-scale phenomena abound. It is difficult to model human operators, investment decisions, and economics. The varieties of malicious attacks are poorly characterized, as are the impacts and costs of system and infrastructure failures.
- *Uncertainties:* There are statistical and related challenges in dealing with the uncertainty of attacks, failures, and the subsequent events. These challenges are particularly acute for rare but extreme events involving long complicated series of cascading events leading to catastrophic infrastructure failure. It would be desirable to better predict the initial portions of high-risk cascades in real time so that they can be mitigated.
- *Implementation of resiliency strategies:* Feasibility of implementation is a major challenge and constraint. Cost and benefits must be estimated and who pays must be determined. For example, physical hardening of power grid components is expensive and this must be balanced against the benefits. Except for isolated microgrids, solutions must integrate with the current grid and interact well with the extensive existing cyber-physics. Practical grid enhancements towards resilience may have to coordinate with other objectives in order to be built.
- *Broader interdependencies:* Resilience strategies must also take into consideration the interdependencies between the ECPS and other infrastructures, such as first-responder (emergency response) systems and mass-communication media (for broadcasting emergency information to the population). Moreover, strategies should conform to regulatory policies or otherwise initiate modification of existing policies and practices.

5.3. Metrics

The various aspects of resilience all require quantification with metrics so that resilience may be monitored, assessed, and actions taken. All of these metrics must quantify the "distance to failure" or "risk of failure" in some manner or other. For example, the integration into the grid of a new system, algorithm or technology could be assessed with resilience metrics to ensure that resilience is maintained or enhanced. Some metrics will depend on historical data and other metrics will be evaluated from the system state. Metrics should help to quantify risk and/or cost so that suitable investments in resilience can be made.

Examples of metrics include:

- Fraction of components surviving a given attack or overload
- Time to recover a given fraction of network functionality
- Time to move to a set of normal operating state
- Number of violations during transients
- Probability distribution of blackout size
- Degree of criticality in complex system self-organization
- Cost of blackouts or failure of any linked infrastructure
- Average amount of propagation of cascading failures

5.4. Future research needs

In summary, maintaining and improving cyber-physical system resilience at minimum cost as the electricity network transforms must address challenges of complexity, contingency analysis, modeling, uncertainty, and implementation. To monitor and maintain resilience, the various aspects of resilience must be quantified with practical metrics that give actionable information based on a deeper and interdisciplinary understanding of resilience of cyber-physical networked infrastructures.

6. Performance

6.1. Background

This section discusses two broad research issues regarding the performance of Energy Cyber Physical Systems:

- What criteria should be used to assess the performance of energy CPS?
- What resources do we need to develop to assess the performance of energy CPS before deployment?

6.2. Performance criteria

The performance criteria that a CPS should meet can be grouped in three categories as illustrated in the Figure 2.

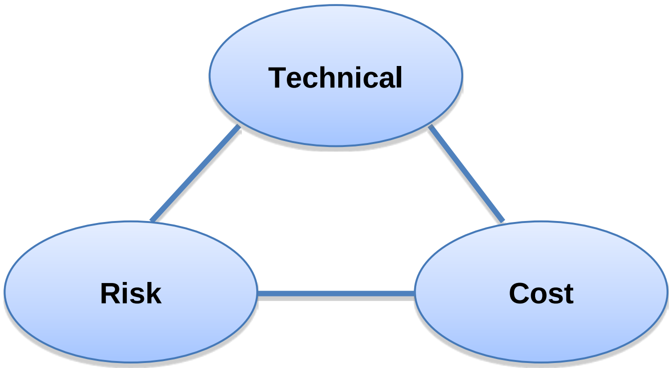

Figure 2. Interrelated performance criteria

Performance criteria for CPS enhancements include (but are not limited to): increases in the transmission capacity, quality of the information provided in support of decision-making, savings in operational cost or deferred investments, enhanced flexibility (i.e. ability to adapt to different situations and to provide differentiated services). The contributions towards national goals such as energy independence and security, mitigating climate change, and a clean environment should also be assessed.

Risk criteria can be deterministic or probabilistic and aim to measure the margin between an operating point and the physical system's stability limits, the robustness of the overall system to fault and failures, as well as its resilience to natural disasters, to large exogenous changes, to physical or cyber-attacks, and its ability to postpone obsolescence. In addition, the public acceptability of the technology should be considered at all stages of development.

Finally, bearing in mind the vast amounts of money involved in the operation and development of Energy CPS, it is essential to consider the operational, investment, and lifetime costs of the CPS, as well as who pays the costs, and the distribution of the benefits.

It must be stressed that these improvements should be measured against current practice rather than against other enhancements that have been proposed but not deployed by industry. It is necessary for new methods to integrate with or complement the existing energy grid CPS systems.

6.3. Modeling and Simulation for Performance Assessment

Considering their scale, it is essential to develop tools that can assess more accurately the expected performance of new and enhanced energy CPS. In particular, this will require continuing work on the development of models and tools to simulate their behavior. Major issues include:

- Ensuring the scalability of the simulations
- Developing tools that can model simultaneously the cyber and physical domains
- Determining the model detail needed for the purpose of each tool.
- Developing tools that can realistically model system operation for the purpose of system planning
- Enhancing the ability of simulation tools to operate at multiple timescales
- Enhancing the ability of simulation tools to model hybrid systems
- Further develop simulation and optimization techniques that model the stochastic nature of physical systems, computing systems, and communication systems
- Developing techniques for optimizing the balance between the technical, risk and cost criteria discussed in the previous section.

6.4. Test Cases and Validation with Real Data and Test-beds

A particularly critical issue is the availability of realistic test cases and data sets. Academic research in Energy CPS tends to rely on standard test systems that are incomplete and do not reflect actual industrial practices. Realistic data sets would enable good ideas to be refined and erroneous ideas to be rejected. The unavailability of test cases and data means that new techniques are currently not tested in a sufficiently rigorous manner, which delays or prevents their adoption by industry.

Some aspects of Energy CPS also need to be demonstrated or validated using physical test-beds. Good quality test-beds should be scalable to a practical size, should support testing of hardware in the loop, should have an open design so they are easily useable by the wider research community and should be cross-validated against the behavior of actual systems. Since it is impossible to represent all aspects of the CPS grid in a single test-bed, the aspect of the CPS grid to be tested must be properly defined so that the test-bed can be designed to properly represent and validate that particular aspect.

It was recognized that an Energy CPS testbed can help address many questions as the complexity of the system increases. At the same time research questions arise in developing such testbeds in the first place. The following list created based on the discussions captures both types of questions:

- Issues related to temporal multi-scale in control and operations.
- Issues related to synchronization
- Data management and information architectures for Energy CPS
- Testbed instrumentation of experiment data capturing and management
- Management of complex testbeds including safety, privacy, etc. New CPS architectures and models, where the system architecture is the unit under test.
- Aspects of system composability given CPS heterogeneity.

- Aspects of “openness” and future-proof features of energy CPS designs.
- Need to create a repository of existing energy CPS models
- Federated energy CPS testbeds.
- Relevance and application of open architectures and open source systems.
- Capturing rare events in the CPS system.

7. Education

7.1. Background

The modern energy industry is becoming increasingly complex, as it integrates traditional knowledge domains in the energy industry with those of communications, computing, and information technologies. The Center for Energy Workforce Development (CEWD) has published a document [5] describing the various levels of competency, ranging from fundamental educational content to industry-specific skills, that enable the creation of career pathways that prepare students for careers in the energy industry. However, the CEWD document does not address the union of the different and diverse technological elements that are essential to successful implementation of cyber-physical energy systems. These technological elements are summarized by the US Department of Energy (DOE) as follows [6].

- Integrated communications, connecting components to open architecture for real-time information and control, allowing every part of the grid to both 'talk' and 'listen'
- Sensing and measurement technologies, to support faster and more accurate response such as remote monitoring, time-of-use pricing and demand-side management
- Advanced components, to apply the latest research in superconductivity, storage, power electronics and diagnostics
- Advanced control methods, to monitor essential components, enabling rapid diagnosis and precise solutions appropriate to any event
- Improved interfaces and decision support, to amplify human decision-making, transforming grid operators and managers quite literally into visionaries when it comes to seeing into their systems

The workshop discussions touch upon the priority areas within the ambit of instructional approaches that will effectively prepare the emerging workforce of industry-workers, researchers and educators for tackling the complex challenges of implementing the next generation of energy integration and delivery solutions.

7.2. Focal Aspects

In view of the expanding scope of cyber-physical systems, it was deemed necessary to seek community input regarding the role of education and the needs in this area. The challenges identified, the areas of research proposed, and the impacts desired are reported below.

7.2.1 Inclusion

It was recognized that all stakeholders—industry, academia, government, and consumers—are in need of education in order to enable successful growth of cyber-physical energy systems. On the one hand, engineers and students need to comprehend, model, develop and deploy these complex systems; on the other, consumers as well as policy-makers need a better understanding of matters related to both technology and utilization, as well as their role in emerging programs, such as demand response, that involve customer engagement.

Challenges and needs discussed by workshop participants concerned the identification of CPS training that the industry needs, and the identification of entities that will drive this education and training.

7.2.2 Contents and delivery

The discussions concerning contents of ECPS education touched upon a wide range of topics ranging from power system concepts (such as circuit theory, energy conversion, stability, control, protection) to sensors, networks, communication, computing, cyber-security and markets. It was mentioned that development and evolution of contents must be cognizant of ongoing and future ECPS needs.

Challenges discussed by workshop participants include the design and development of curriculum that (a) allows specialization while ensuring breadth within programs (such as electrical engineering, or electrical and computer engineering), and (b) adequately covers the “interface” between the different sub-areas in an integrative manner, rather than merely including a mixture of traditional courses.

Other topics in pedagogical research that were proposed by the participants include (i) cyber security in power engineering education, (ii) development of a body of knowledge identifying core and advanced skills for ECPS, and (iii) curricula for ECPS, including degree and certificate programs.

7.2.3 Instruction tools

Some of the challenges discussed, as reported above, necessitate the design and development of more complex instruction tools than are extant today. It should address a large and diverse constituency encompassing students, researchers, industry practitioners, policy-makers, and consumers.

The desired outcome of the above research is that the educational models and products developed should better educate future ECPS researchers and practitioners. Appropriate vehicles for dissemination of the growing body of knowledge, and suitable tools for assessment of participation and impact are also part of the emerging need.

The role test-beds as instructional, research and training tools was discussed, and design of appropriate test-beds was identified as a research need.

7.3. Future Needs

Future needs in the domain of pedagogical research, as identified by the workshop participants, fundamentally consist of managing the profusion of knowledge in the rapidly emerging field of cyber-physical energy systems. Specifically, the workshop participants identified the following needs:

(1) Identification of training needs for each of the stakeholder segments;
(2) Curricular design that effectively integrates the different sub-areas while also allowing for depth of knowledge within sub-areas and strong emphasis on cross-disciplinary training for CPS researchers;
(3) Instructional tools that effectively educate future researchers and practitioners, as well as tools for assessing participation and impact of these pedagogical instruments.

8. Policy and Regulation

8.1. Background

In understanding the role of regulation, it is perhaps useful to get an overview of the jurisdictional structure in the U.S. in the context of energy policy. The U.S. Congress determines energy policies, the Environmental Protection Agency determines environmental policy, and the Department of Energy funds and executes energy policies promulgated by federal law [7]. The Federal Trade Commission determines consumer protection policy. Transmission and interstate commerce fall within federal jurisdiction and are regulated by the federal government through the Federal Energy Regulatory Commission (FERC). Both the federal and state governments have jurisdiction over the sale of electricity to consumers. Economic regulation of the distribution segment is a state responsibility and is typically performed by Public Utility Commissions. Independent system operators (ISOs) and regional transmission operators (RTOs) regulated by FERC operate each of the Western, Eastern and Texas Interconnects. FERC does not have jurisdiction over the States of Alaska and Hawaii because of the isolated nature of their grids. The North American Electric Reliability Corporation (NERC) is authorized by the Federal Power Act to ensure the reliability of the bulk power system by establishing and enforcing reliability standards, monitoring the system, providing forecasts, and offering education, training, and certification programs (including those for transmission operators, reliability coordinators, balancing authorities, and system operators). Some NERC members have formed regional organizations with similar missions (ISOs and RTOs).

Within this structure, most cost-based and incentive regulation models are primarily aimed at achieving cost-efficiency and are not designed to promote innovative investments or high levels of R&D. Regulatory models are generally intended to keep investment and operational costs under control and to minimize network tariffs while meeting the required levels of stability, reliability, and power quality. The reliability rules tend to be deterministic and procedure based rather than risk based and outcome based. While traditional models incentivize the reduction of costs, significant redesign is necessary to incentivize and promote the development and adoption of new technologies.

In the course of the workshop, participants provided input regarding the ways in which regulation and public policy could facilitate the deployment and operation of ECPS. Most of the opportunities discussed lie in market mechanisms and rate structures that involve renewable generation and demand response. It was recognized that in order to increase participation these mechanisms should benefit participants by providing them with incentives, and by mitigating their risks.

8.2. Incentives, Risks, and Benefits

The course of the electric utility industry is often altered by regulation and public policy. Recent experience with deregulation has shown that implementation with inadequate understanding of the industry sector and related technological issues can produce negative effects. Regulatory bodies and the electric industry should work closely to enable the critical pathways that lead to national benefits via strategic targets. This is reflected in the Figure 3, which was published by the Electric Power Research Institute (EPRI) in a 2003 report [8] based on stakeholder input on the future of electricity markets.

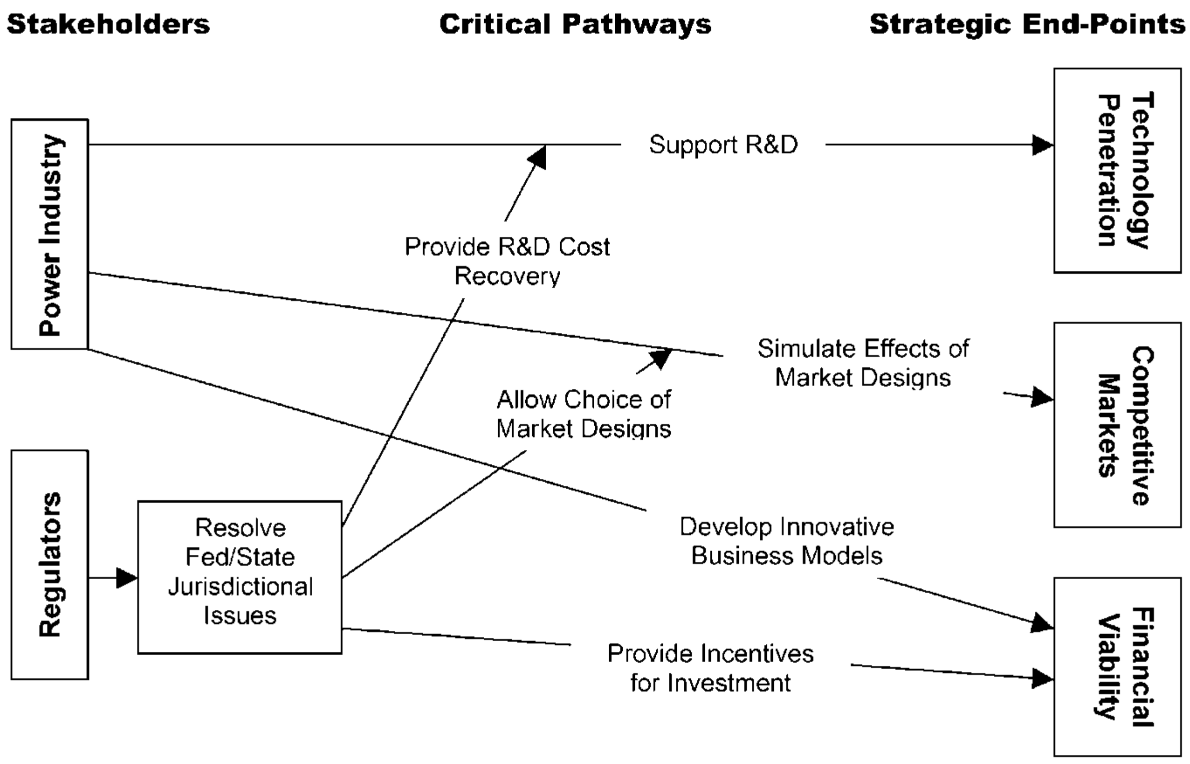

Figure 3. EPRI's view of the need for future interactions [8]

The risks arising from poor regulation are several. Some of these are:

1. Technological: If regulation mandates adoption of technology without adequate infrastructure, it results in poor implementation or stranded asset costs. Instances of such stranded asset costs have been encountered in the aftermath of deregulation and in the deployment of smart meters. Both the details and the general thrust of regulations and standards can either enable or block innovation and deployment in new technologies and business opportunities. Examples include interconnection standards, and allocating the responsibilities and costs for reliability.
2. Financial: If regulation does not adequately foster investment in research and development, innovation and adoption of new technology suffer, resulting in stagnation of the industry. The electric industry has been plagued over the last four decades by an inadequate structure for R&D cost recovery and a lack of investor confidence.

The potential benefits of good regulation, with input from stakeholders and consumers, lie in the opportunity to overcome the risks and challenges discussed above. Good regulation will restore investor confidence and financial viability of the electric industry, promote development and penetration of technology, and increase product value for end-users.

8.3. Future Research Directions

Research has already shown [7] that regulation comprising customer incentives and disincentives alone (e.g., time of use pricing, feed-in tariffs, etc.) are not sufficient, and that more comprehensive and far-reaching regulatory innovation is essential to create an environment that is conducive to the development and adoption of technology. The specific areas of need identified by workshop participants are:

1. There is a need for research and innovation in market design and rate structures that incentivize customer participation in (i) integration of renewable generation, (ii) demand response programs, and (iii) permitting use of plug-in electric/hybrid vehicles in grid-support/ancillary service mechanisms.
2. There is a need for innovation in policy that encourages load shaving (of flexible loads). Further, there is need for (a) research on and development of clear policy on who should control the various devices (such as embedded systems) that manage or schedule connected flexible loads, and (b) better definition of the purpose of such control.

9. Other Interdependent Energy CPS Infrastructures

9.1. Background

As critical infrastructures develop further it becomes clear that the energy infrastructures such as gas and electricity are heavily dependent on other related infrastructures such as transportation, water and telecommunications. Such a layered interdependency concept is illustrated with an example in Figure 4. The details of the interdependencies for the electricity and gas layers are discussed next.

Image courtesy DOE

Figure 4. An example of the infrastructure interdependencies

9.2. Example of interdependencies: electricity and natural gas infrastructures

Yet another critical infrastructure that is energy-centric, complex, poised for a huge cyber-enabled transformation, and is highly interconnected with the power grid, is that of natural gas (NG). Similar to the electric infrastructure, the NG infrastructure consists of transmission (pipelines), producers (wells), storage, and consumers. NG marketers facilitate movement of NG by coordinating the sale of gas quantity and pipeline capacity contracts. Pipelines use compressors along the line to create the flow of NG from the injection point on the line to the consumer of the NG. One of the fastest growing consumers of NG is the electricity sector for use by NG-fired generation, and as such, NG-fired generators link both the NG and electricity networks. In many regions in the US, NG currently fuels a large portion of the electricity generation portfolio, which is increasing even further with growing penetration of renewable energy. The inevitable features of intermittency and uncertainty in the renewables is necessitating increased dependence on NG fired generators which are capable of fast, on-demand response for power balance. As a result, tighter coordination and information sharing between electric grid operators and NG suppliers is a necessary component for a reliable and resilient interdependent critical infrastructure (ICI) of electricity and NG.

That the electricity and NG infrastructures are highly interdependent is easy to see. The most common instance in places such as Northeastern US, is during cold snaps, when the demand for electricity and NG increases simultaneously for heating requirements. NG price hikes due to pipeline constraints increase marginal costs of NG-fired generation, which in turn leads to dramatic increases in market prices for electricity. This interdependence is increased further with more emphasis on NG-fired generation in general as coal plants retire due to environmental regulations. These underscore the fact that with proper coordination, these interdependencies can be highly beneficial. Any interruption or pressure loss in critical NG pipeline systems may lead to a loss of multiple NG-fired electric generators, thereby reducing the supplied power and therefore jeopardizing the power system security. A tightly coordinated set of infrastructures can result in a reliable and efficient power generation. Yet another example of the need for coordination occurs in the context of markets [9]. In deregulated electricity markets, the supply of electricity is organized through a day-ahead and real-time market, which requires accurate information on generator availability and prices as well as consumer demand. With increased reliance on NG, information on fuel availability to NG-fired generators is of increasing concern. This is complicated by the structure of the NG sector, which has separate markets for buying NG quantities and buying NG transportation or capacity and lacks flexible market mechanisms for a proper allocation of both gas quantity and transportation.

There are significant operational, contracting, planning, and regulatory differences between the two infrastructures that may impede the necessary coordination between them. The underlying physics, that of the path of an electron from generation to the consumer versus the path of fuel from production wells to the end user, are different, with the former moving at the speed of light, and the latter significantly below the speed of sound. Storage is highly expensive, and therefore scant in the former, while simple and necessary in NG. Control of individual constituents is near to impossible in the electric sector (ex. power flows in transmission segments) in relation to the NG sector (ex. NG flows in pipelines). Most importantly, the levels of instrumentation, monitoring, automation, and cyber-centric operation in the overall NG infrastructure are significantly less developed compared to the electric infrastructure.

Despite the compelling need for the two infrastructures to coordinate their planning as well as operation, minimal interactions currently exist between the two. The NG and electricity markets have evolved, by and large, separately and as such have serious inconsistencies. Additionally, there is a lack of information transparency between NG pipeline constraints and electricity transmission constraints which can lead to unexpected withdrawal of NG from pipelines by generators who are required for electricity system security. Most importantly, NG usage for electricity generation has low priority on the NG market, and therefore any increased interdependencies between the two, which is inevitable in the face of increasing penetration of renewables, poses serious security concerns to the electricity infrastructure.

In order to ensure resilient, reliable, affordable, and green power, a cyber-physical approach for analyzing and designing a NG-infrastructure that is tightly and synergistically coordinated with the electrical infrastructure is essential. Modeling tools for analyzing the combined electricity-gas infrastructures are needed. Architectures that promote diagnostic and prognostic resiliency methods for these combined infrastructures need to be developed. Market mechanisms that facilitate a combined planning and operation of these infrastructures need to be investigated. Distributed, dynamic, and hierarchical control methodologies for facilitating appropriate decision making in these infrastructures need to be developed.

10. Conclusions

Taking into account the discussions from the Workshop, feedback from the writing team and special reviewers, as well as NSF staff, the following are some key overall priorities for future research:

- Explore further the physical laws of energy systems and synergy with CPS design, which is needed if the ECPS is to be effective and responsive to future societal needs.
- Recognize the shortcomings of traditional approaches and develop fundamentally new approaches that will meet new expectations for the performance of ECPS, including enhanced robustness and cyber-physical security.
- Advance the fundamental understanding of hybrid control systems where the continuous dynamics are affected by structural (topology) changes.
- Focus on development of fundamentally new evaluation metrics and testbeds to support the validation of new solutions.
- Devise an educational and training program that will allow both academic and industrial specialists to make the transition from legacy systems to new paradigms for ECPS.

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