Energy Cyber-Physical Systems: Research Challenges and Opportunities

Report from NSF Workshop held December 15-16, 2013 in Arlington, Virginia

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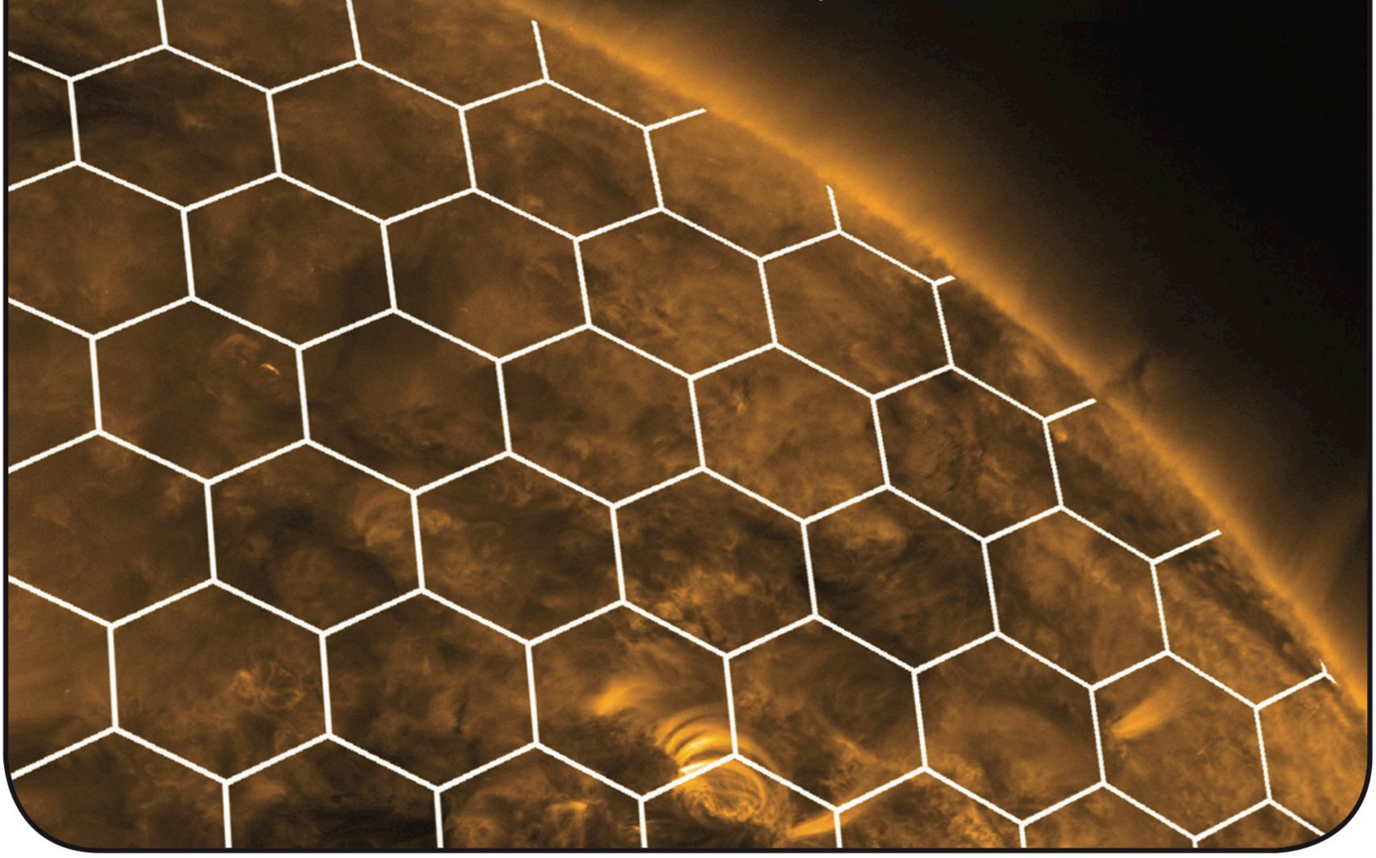

Energy Cyber-Physical Systems

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Preface

The NSF CISE Program asked the academic community to participate in an NSF Workshop on Energy Cyber Physical Systems, which was held at the Water View Conference center in Arlington, Virginia on December 16-17, 2013. With over 100 participants and as many written contributions, and with day and a half of intensive discussions, the community identified many research challenges and opportunities related to energy CPS. This report is prepared per NSF's request and summarizes key discussions from the Workshop. NSF formed a smaller group of Workshop participants listed on the cover of the report to create a summary report. The report was also posted for comments by all interested Workshop participants, and the feedback is incorporated. The report has extracted the key points from the Workshop discussions that were organized by the energy application domains, and as such, does not follow the sequence of discussions that were presented at the Workshop but does incorporate the key discussion points. To augment the report's impact, several written workshop contributions that have been recognized as particularly insightful are added to report as appendices..

The report writing team recognized the conclusions made in the previous report on the similar subject from a Workshop held in 2009, so this report may be considered a complement to the 2009 report.

Acknowledgement

Many have impacted the creation of this report with their written contributions, reviews and editorial suggestions. Particular thanks go to the following individuals:

The writing team: Mladen Kezunovic, Coordinator, and other members, Anuradha Annaswamy, Ian Dobson, Santiago Grijalva, Daniel Kirschen, Joydeep Mitra, Le Xie

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

Executive Summary

The report first recognizes the limitations and constraints of the legacy energy CPS, 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 approach with centralized generation, redundant long-range transmission paths, and radial distribution, to a new concept with distributed generation, variable renewable resources, extended transmission and meshed distribution, with the addition of energy storage and micro grids, has been pointed as the main challenge and focus for the Energy CPS research. This transition in the power system design has a profound impact on how the energy CPS may be implemented in the future because the power system physical infrastructure has been transformed, the control approaches are more decentralized, and the targets for operating the system are placing more emphasis on the role of loads that may contain generation and storage. The additional need for improved cyber physical security across both the transmission/distribution network and large number of customs devices adds complexity to the CPS design considering the new megascale of the CPS integration. The report objective has been defined to summarize the Workshop discussions that provided further insight into the research needs, barriers, and future directions leading to the report goal of being a comprehensive inventory of the energy CPS emerging research targets.

Next, the report focuses on the Architecture needs and requirements for the future Energy CPS. It is clearly articulated that 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 energy CPS designs that are scalable and flexible based on the prevailing computational requirements will need to be invented. The range of actors that will play active role in controlling various aspects of the enhanced power grid will be extend to include, besides utility personnel, also 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 energy CPS.

The report then focuses on the core difference of the next generation energy CPS requirements that are driven by control and protection of the future electricity grid. It is emphasized that new control loops will be established, both localized and system-wide, which imposes new spatial-temporal dynamics of the power grid, and in turn the energy CPS. It has been widely recognized that the variability of the renewable generation requires fresh look at the role of the flexible load in compensating for the variability by controlling differently its own consumption, as well as newly added on-site generation and energy storage. The mentioned changes in the physical system requirements for control and protection have also a direct impact on the whole sale and retail electricity market, and hence tighter interaction has to be a property of the future energy CPS design. This becomes particularly challenging when recognizing a huge expansion of the localized CPS computational, communication and data management needs at the distributed generation and customer sites known as micro grids. The need to research a CPS layered control and protection architecture that allows predictive, adaptive and corrective actions is widely acknowledged.

The subsequent concern is the power system resiliency, and its impact on the energy CPS design requirements. Complexity, methods for contingency analysis, modeling for resilience, uncertainties and implementation of resilience strategies are identified as the research challenges. Additionally, the broader interdependencies between critical infrastructures for energy, transportation, gas and water management are mentioned by the Workshop participant and further explored by the writing team. The key to the achievement of the mentioned design goals is to establish metrics that will allow comparison, testing and verification of the future CPS solutions. The metric itself, due to its complexity and innovative ways of addressing SPC performance assessment is considered an important research effort.

The previous observation have led to a conclusion that the performance criteria for the future energy CPS will have to be studied to make sure the research community fully understands what the future expectations of the fundamental research are. The role of modeling and simulation tools and the need to enhance them as the research needs expand has been recognized. This has led to an articulated need for large scale testbeds implementation to evaluate future energy CPS solutions. It was outlined that besides the technical criteria, the assessment of risks and associated cost need to be the performance requirements of the future CPS solutions. Hence, research into the novel modeling, simulation, testing and verification of integrated CPS is needed.

While the education needs for the next generation researchers and users of the energy CPS has been discussed, it has not be 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 the academic setting but also training for the industry and outreach efforts to educate the public. The innovative research how to convey fundamentals of energy CPS design is judged as necessary to be able to change the legacy thinking that was developed over the last 50 years.

Once the team has summarized the Workshop discussions it was recognized that the policy and regulation issues may have a profound impact on the future solutions, so several aspect of this problem were mentioned 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, and societal benefits should be pursued by the legislative bodies that are guiding research policies and appropriating research funds.

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

The writing team wanted to make sure that some notable Workshop written contributions are fully recognized as the guidance for the future research, so the team selected 21 written contributions to be included as an Appendix to this report.

As a summary, the discussion as the Workshop and the team effort on the report creation clearly indicate that the energy CPS has grown out of the traditional paradigm and needs to be brought to the next, yet unexplored level through both the innovative fundamental research and demonstration of plausible solutions. To achieve that, the following broad research directions are recommended:

- Explore further the physical laws of the energy domain to be able to match the fundamental properties of the cyber solution for a tightly integrated CPS, which is needed if the energy CPS is to be effective and responsive to the future control needs
- Recognize shortcoming of existing solutions and understand the new barriers to be able to define future energy CPS requirements, which are facing fundamentally new performance expectations including enhanced robustness and cyber-physical security
- Further the fundamental understanding of the hybrid control systems where the continuous dynamics are affected by structural (topology) changes, which will be a prevailing property of the energy CPS going forward
- Focus on development of fundamentally new evaluation metric and testbeds that will allow verification of the new solutions, which is a part of the fundamental understanding how the new solutions may perform in practical settings in the future
- Devise an educational and training program that will allow both academic and industrial stakeholders to bridge the knowledge gap, which is a serious impediment when transitioning from the legacy to totally new and innovative energy CPS concepts

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1. Introduction

Since the beginning of the electricity 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 a control based on Supervisory Control and Data Acquisition (SCADA) systems.
2) During the 1990'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 sustainability concerns and strategic objectives, 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 can be 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 major part of the sustainability targets. This goal is strategic and imposed by our desire to move into 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. This encompasses advanced sensing, communication, estimation optimization, planning, etc. This goal 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 architecture 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 Energy CPS, much like the information technology revolution that occurred in the past decades.

This section provides a background of the issues surrounding Energy Cyber Physical Systems (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 ECPSs. 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 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 to perform various planning and 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 is a distributed automation function that has the purpose of detecting faults and immediately issuing 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
- 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 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 not suffice
- The load was usually considered a passive element of the system and the main task was to plan the 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 high power power electronics
- The regulatory and policy framework protected the customer interests through State regulatory commissions and power system operation performance through FERC and NERC.

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 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 the 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 in 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 coordination of control 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 prevailing conditions based on statistical properties
- The trained workforce that can innovate, evaluate and implement solutions in a complicated disciplinary and multidisciplinary CPS environment is lacking.

1.3. Future needs and requirements

The following future needs were identified by workshop participants.

- *Sustainability*. This universal need poses the question of how to select the best ECPS solution in the future
- *Reliability*. While some major improvements in reliability were achieved over the years, reliability cannot be properly quantified so that reliability can be optimized subject to cost. Deterministic reliability 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 large scale cascading blackouts or natural disasters 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 wholesale and retail markets 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
- *Low 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*. The change in the customer role from passive to active could be facilitated by microgrids, as well as distributed generation and energy storage

1.4. Objectives and Goal of this report

The objective of the report is to summarize discussions from the ECPS Workshop held on December 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 Composing 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 system must be integrative and flexible. Such a design will need to integrate legacy infrastructure and all 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, future design of electric energy systems will need to integrate seamlessly (1) physics-based modeling of new energy resources; and (2) data-driven modeling of new 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 to be translated in electric energy systems.

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

The design of cyber-physical energy system should accommodate not only today's legacy infrastructure, but also drastically 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 customers' participation?
- How do we control energy exchange scheduling across multiple layers with quantifiable performances?
- How do we standardize the design process to enable Plug and Play?
- 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 to design the mechanism and policy 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?

Such a design paradigm needs to draw 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 cyber elements of communications, computation and control. In this category are infrastructures such as electric power grids and gas networks.

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

E-CPSs have been designed in order to meet the objective of producing, transporting and delivering energy. This design followed a set of given assumptions and requirements and considered technological limitations at the time of their incremental design. 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 continued to evolve becoming larger and 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 management, cause unprecedented changes to the foundational elements on which electricity systems have been developed and the manner in which they are currently operated and managed. The 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 the Table, paradigm shifts are occurring in the electricity supply system. The significance of 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, and how these requirements map to achieving objectives by design.

3.3. High Level Needs

As sensing and communication systems are deployed across the grid, the traditional consumer becomes more aware of its energy consumption patterns and behavior and recognizes the opportunities to make some decisions regarding its 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
Professional Carriers	• 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 gridwise perspective, and presents challenges from emerging topics, the most dominant of which includes Markets, Demand Response+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 methods, 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. Quite often, wholesale markets function using bilateral agreements, between a willing buyer and a willing seller to exchange electricity or rights to generating capacity under mutually agreeable terms for a specified period of time. Wholesale markets are typically organized as auctions that are run by independent system operators (ISO). They 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. 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 reserve 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 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 the trend in more accurate forecast models for entities, such as the weather and demand, over decreasing horizons, market models at multiple time-scales that incorporate the varying forecast models and their modeling errors need to be developed.
- Also needed are dynamic market mechanisms that represent wind energy, with its uncertainties, in market bidding, model the impact of intermittency and uncertainty in renewables 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 "behind the meter" 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 and disaggregate flexible demand from retail level to wholesale level and vice versa.
- 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

- 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

- 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.
- Theories and designs for distributed SOC that are robust to communication network errors and failures as well as delays and losses. Algorithm synthesis must be carried out from a control perspective that accommodates communication network properties, including performance margins and redundant functionality.
- 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

Energy CPS are 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

- A redesign of primary, secondary, and tertiary layer that integrates renewable energy as a dispatchable source while providing 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. The complexity of decision-making is shown in Figure 1.

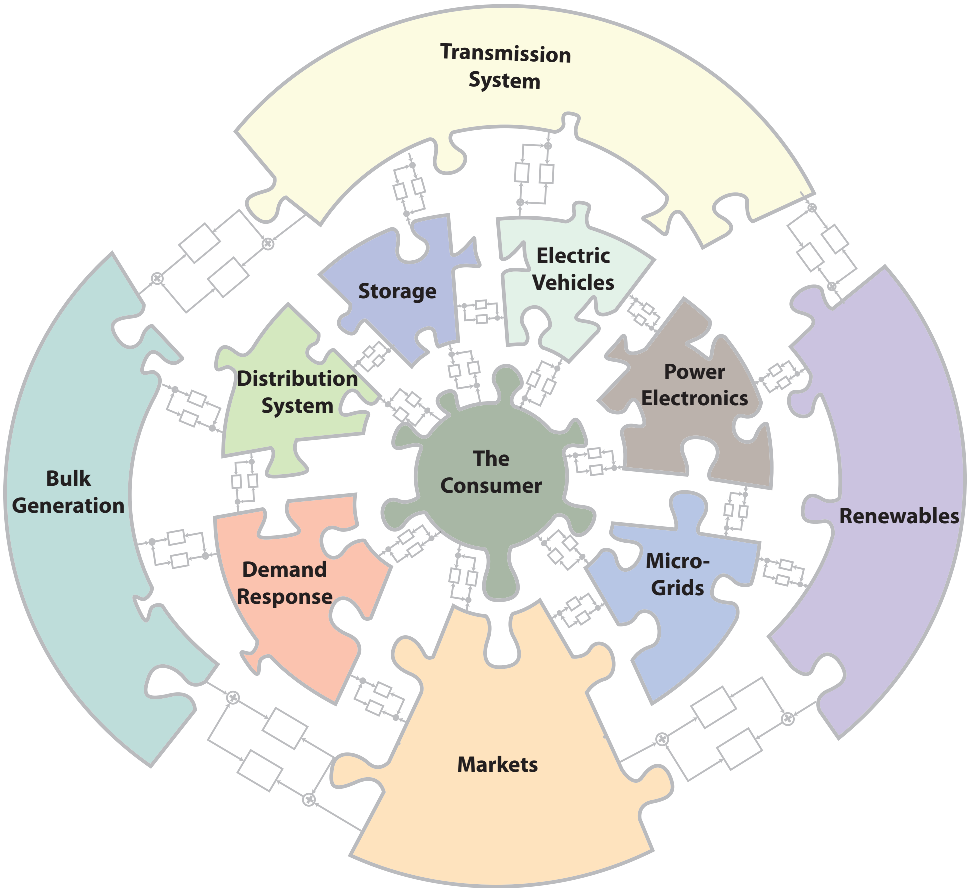

Figure 1: Control of Smart Grids – New Opportunities in an Energy CPS [4]

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 complicated, 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.

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 on measurements only but also requires information from cyber-physical models. 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

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).

5.4. 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 reliance 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.

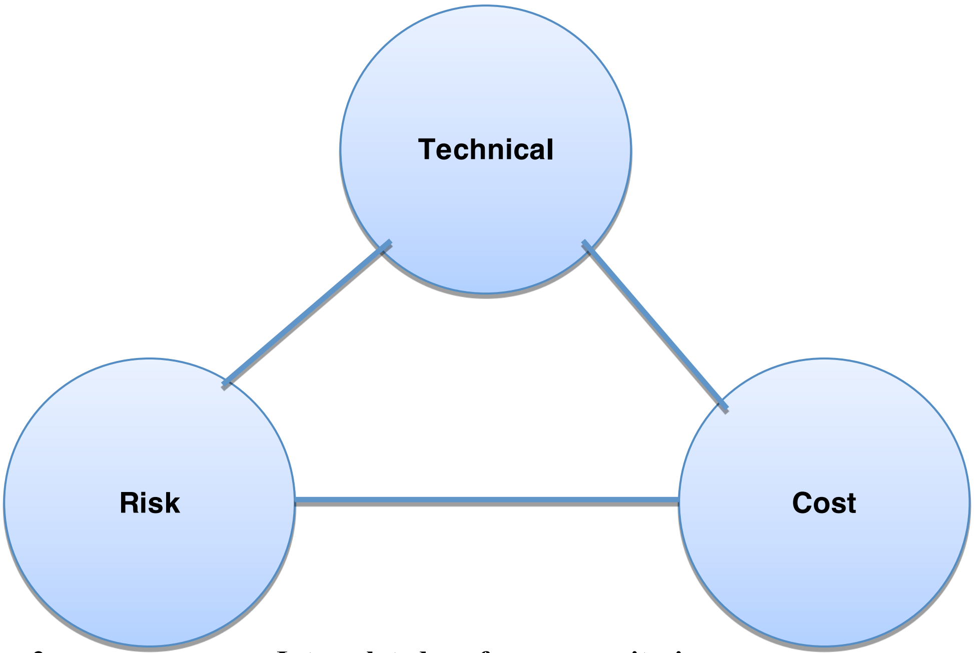

Figure 2. Interrelated performance criteria

Technical criteria should measure by how much enhancing the CPS improves performance over the existing system. Technical criteria for CPS enhancements therefore 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 reliability 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 operational 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. 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 stochastic simulation and optimization techniques
- Developing techniques for optimizing the balance between the technical, risk and cost criteria discussed in the previous section.

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 testbed, 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.

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.

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 crossdisciplinary training for CPS researchers.
(3) Instructional tools that effectively education future researchers and practitioners, as well as tools for assessing participation and impact of these pedagogical instruments.

8. Policies and Regulation

8.1. Background

In understanding the role of regulation, it is perhaps useful to get an overview of the jurisdicational structure in the US in the context of energy policy. The US 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.

8.2. Needs

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.

Workshop participants in several sessions indicated that there was 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.

Participants also felt there was 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.

8.3. 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.

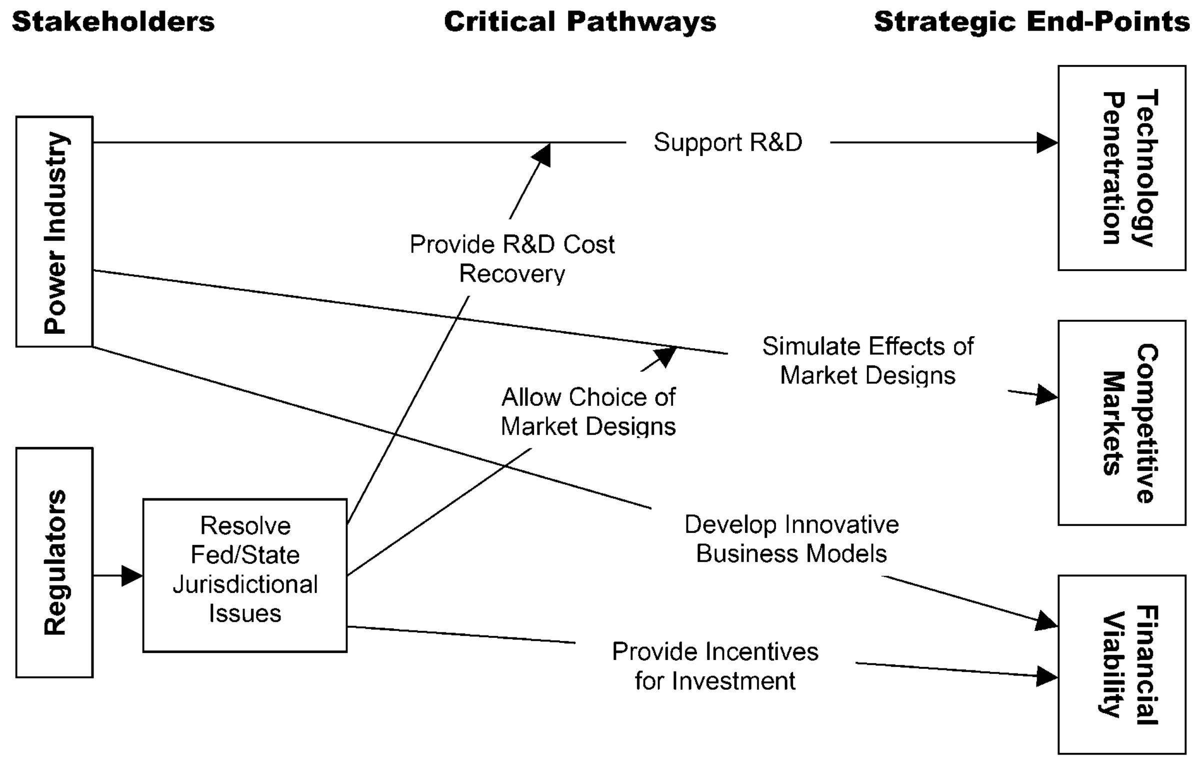

Figure 3. EPRI's view of the need for future interactions [8]

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.

8.4. 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) Innovation in market design and rate structures that incentivize customer participation in integration of renewable generation, demand response programs, and permitting use of plug-in electric/hybrid vehicles in grid-support/ancillary service mechanisms.
(2) 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 better definition of the purpose and responsibilities of such control.

9. Other Interdependent Energy CPS Infrastructures

9.1. Background

As the 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 layered interdependency concept is lustrated with an example in Figure 4. The details of the interdependencies for the electricity and gas layers are discussed next.

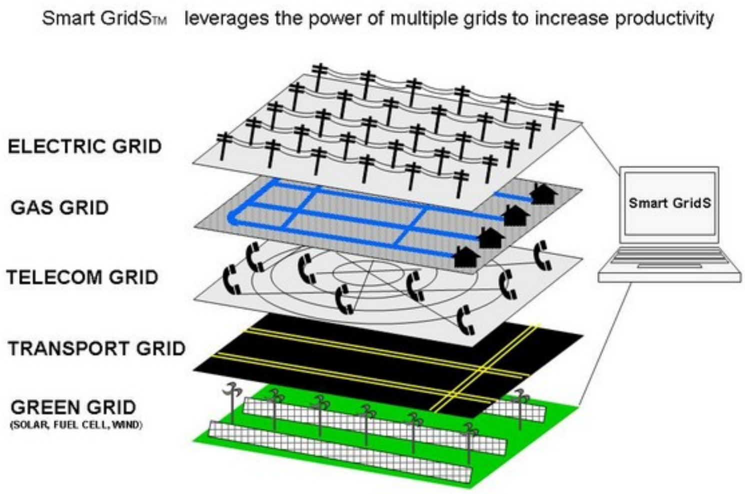

Figure 4. An example of the infrastructure interdependencies

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 and of concern. The most common instance in places such as Northeastern US, is during cold snaps, when the demand for electricity and NG increase 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. Coordination between the two infrastructures is therefore essential for reliable power generation. 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. Yet another example of the need for coordination occurs in the context of markets. 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. Economies of scale are much larger in electric power transmission projects, as opposed to NG transmission. Retrofitting a line to increase transmission capacity is prohibitively expensive. It is more economical to install the required capacity of a transmission line initially than to retrofit the line later. Increased capacity can be obtained with relative ease in the latter case by raising the pressure at NG pipelines. 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 a 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 various discussions from the Workshop, feedback from the writing team and special reviewers, as well as NSF staff, the following are some key global priorities regarding future research:

- Explore further the physical laws of the energy domain to be able to match the fundamental properties of the cyber solution for a tightly integrated CPS, which is needed if the energy CPS is to be effective and responsive to the future control needs
- Recognize shortcoming of existing solutions and understand the new barriers to be able to define future energy CPS requirements, which are facing fundamentally new performance expectations including enhanced robustness and cyber-physical security
- Further the fundamental understanding of the hybrid control systems where the continuous dynamics are affected by structural (topology) changes, which will be a prevailing property of the energy CPS going forward
- Focus on development of fundamentally new evaluation metric and testbeds that will allow verification of the new solutions, which is a part of the fundamental understanding how the new solutions may perform in practical settings in the future
- Devise an educational and training program that will allow both academic and industrial stakeholders to bridge the knowledge gap, which is a serious impediment when transitioning from the legacy to totally new and innovative energy CPS concepts

11. References

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12. Appendices

1. Program:

2013 National Workshop on Energy Cyber-Physical Systems

Arlington, VA ✱ December 16-17, 2013

Monday, December 16

7:00 a.m. – 8:00 a.m.	**Registration and Continental Breakfast (Riverview Foyer)**
8:00 a.m. – 8:05 a.m.	**Opening Remarks and Introductions - *Keith Marzullo (NSF)* (Riverview)**
8:05 a.m. – 8:20 a.m.	**Workshop Goals and Objectives - David Corman (NSF) (Riverview)**
8:20 a.m. – 8:50 a.m.	**"Lay of the Land-Overview" - Mladen Kezunovic (Texas A&M) (Riverview)**

8:50 a.m. – 10:35 a.m. SESSION 1: Control, Modeling, Design, Interdependencies, Uncertainties

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8:50 a.m. – 9:20 a.m.	**Invited Talks (Plenary) (Riverview)** *Sudip Mazumder (UIC)* *Santiago Grijalva (NREL)*
9:20 a.m. – 10:35 a.m.	**Breakout Sessions Parallel** **1. Control Architectures, Design (Riverview)** *Ben Hodges (Texas) - Moderator* *Anurag Srivastava (Washington State) – Reporter* **2. Interdependencies, Modeling (Archimedes)** *Alex Stankovic (Tufts) – Moderator* *Steve Chiu (Idaho State) – Reporter* **3. Uncertainties, Risk Analysis (Brennan)** *Branko Kosovic (NCAR) - Moderator* *Aranya Chakrabortty (NCSU) – Reporter*
10:20 a.m. – 10:35 a.m.	**Summary: Report Outs (Plenary) (Riverview)**
10:35 a.m. – 10:50 a.m.	**Coffee Break – WCC Atrium – 2nd Level (Riverview Foyer)**

10:50 a.m. – 12:35 p.m. SESSION II: Transmission and Distribution, Big Data, Computational Challenges, Data Analytics, Integration of Renewables, Markets

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10:50 a.m. – 11:20 a.m. **Invited Talks (Plenary) (Riverview)**

Ian Dobson (Iowa State)
Vijay Vittal (Arizona State)

11:20 a.m. – 12:20 p.m. **Breakout Sessions (Parallel)**

1. Transmission (Big Data, Data Analytics, Computational Challenges) (Riverview)
Maija Ilic (Carnegie Mellon University) - Moderator
Ganesh K. Venayagamoorthy (Clemson) - Reporter

2. Distribution (Big Data, Data Analytics, Computational Challenges) (Archimedes)
Ian Dobson (Iowa State University) - Moderator
Ning Lu (North Carolina State University) - Reporter

3. Integration of Renewables, Market (Brennan)
Joydeep Mitra (Michigan State University) – Moderator
Sid Suryanarayanan (Colorado State) – Reporter

12:20 p.m. – 12:35 p.m. **Summary: Report Outs (Plenary) (Riverview)**

12:35 p.m. – 1:35 p.m. **Lunch (Riverview Foyer)**

1:35 p.m. – 3:20 p.m. SESSION III: Flexible Load, Microgrids, Demand Side, Buildings, Storage, Embedded Systems, EVs

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1:35 p.m. – 2:05 p.m. **Invited Talks (Plenary) (Riverview)**
Sairaj Dhople (Minnesota)
Tariq Samad (Honeywell)

2:05 p.m. – 3:05 p.m. **Breakout Sessions (Parallel)**

1. Demand Side Management, Buildings, EVs (Riverview)
Eli Bozorgzadeh (UC-Irvine) – Moderator
Le Xie (Texas A&M) – Reporter

2. Flexible Loads, Embedded Systems (Archimedes)
Bernard Lesieutre (Wisconsin) – Moderator
Ting Zhu (Binghamton) – Reporter

3. Microgrids, Energy Storage (Brennan)
Daniel Kirschen (Washington) – Moderator
Marilyn Wolf (GA Tech) – Reporter

3:05 p.m. – 3:20 p.m. **Summary Report Outs (Plenary) (Riverview)**

3:20 p.m. – 3:35 p.m. **Coffee Break – WCC Atrium 2nd Level (Riverview Foyer)**

3:35 p.m. – 5:20 p.m.	**SESSION IV: Cyber-Physical Security, Privacy, and Resiliency**

3:35 p.m. – 4:05 p.m. **Invited Talks (Plenary) (Riverview)**
Anuradha Annaswamy (MIT)
Dhananjay Phatak (Maryland)

4:05 p.m. – 5:05 p.m. **Breakout Sessions (Parallel)**

1. Cyber-Physical Security (Riverview)
William Sanders (UIUC) – Moderator
Shane Clark (BBN) – Reporter

2. Privacy, Metadata (Archimedes)
Joseph Januszewski (WDT) - Moderator
DhananjayPhatak (Maryland) - Reporter

3. Microgrids, Energy Storage (Brennan)
Anuradha Annaswamy (MIT) - Moderator
Lalitha Sankar (Arizona State) – Reporter

5:05 p.m. – 5:20 p.m. **Summary Report Outs (Plenary) (Riverview)**

5:20 p.m. – 5:50 p.m. **All Issues: Brainstorming (Plenary) (Riverview)**
5:50 p.m. – 6:00 p.m. **NSF Feedback (Riverview)**

Tuesday, December 17

7:00 a.m. – 8:00 a.m. **Registration and Continental Breakfast (Riverview Foyer)**

8:00 a.m. – 8:15 p.m. **Highlights of Day 1 Discussions (Rivervew)**

8:15 a.m. – 10:00 a.m.	**SESSION V: Education, Test beds**

8:15 a.m. – 8:45 a.m. *Philip Brisk (UC-Riverside)*
Jin Wang (The Ohio State)

8:45 a.m. – 9:45 a.m. **Breakout Sessions (Parallel)**

1. Education (Riverview)
Peter Sauer (UIUC) - Moderator
Steve Chiu (Idaho State) - Reporter

2. Test beds (Archimedes)
Manimaran Govindarasu (Iowa State) - Moderator
Natasha Balac (UC-San Diego) - Reporter

9:45 a.m. – 10:00 a.m. **Summary Report Outs (Plenary) (Riverview)**

10:00 a.m. – 10:15 a.m. **Coffee Break (Riverview Foyer)**

10:15 a.m. – 11:15 a.m. **All Issues: Brainstorming (Plenary)**
Mladen Kezunovic (Texas A&M) (Riverview)

11:15 a.m. – 12:15 p.m. **Straw Man: Report Outline (Plenary) - David Corman (NSF) (Riverview)**

12:15 p.m. **Workshop Adjourned**

12:15 p.m. – 12:30 p.m.	**Working Lunch: Report Drafting – Mladen Kezunovic (Texas A&M) (Riverview)**
2:30 p.m. – 3:00 p.m.	**Plan for Report Completion**

2. Workshop Attendees, Organizers, and Sponsors

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Mladen Kezunovic (*Texas A&M University)*

Program Committee

Helen Gill *(National Science Foundation – Retired)*

Santiago Grijalva *(National Renewable Energy Laboratory)*

Marija Illic *(Carnegie Mellon University)*

Frankie King *(Vanderbilt University)*

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Bill Sanders *(University of Illinois at Urbana-Champaign)*

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Marilyn Wolf *(Georgia Institute of Technology)*

Sponsors

Ted Baker *(National Science Foundation)*

David Corman *(National Science Foundation)*

Tho Nguyen *(National Science Foundation)*

Workshop Attendees

Mohammad Abdullah Al Faruque (*University of California, Irvine)*

Anuradha Annaswamy *(Massachusetts Institute of Technology)*

Kishan Baheti *(National Science Foundation)*

Theodore Baker *(National Science Foundation)*

Natasha Balac *(University of California at San Diego)*

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Benjamin Beckmann (*GE Global Research)*

Rick Blum *(Lehigh University)*

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Nilanjan Chakraborty *(Carnegie Mellon University)*

Lijun Chen (*University of Colorado at Boulder)*

Steve Chiu *(Idaho State University)*

Shane Clark *(BBN Technologies)*

David Corman *(National Science Foundation)*

Ayse Coskun *(Boston University)*

Eduardo Cotilla-Sanchez *(Oregon State University)*

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Ian Dobson *(Iowa State University)*

Yaser Fallah (West Virginia University)

Helen Gill *(National Science Foundation – Retired)*

Manimaran Govindarasu (*Iowa State University)*

Santiago Grijalva *(National Renewable Energy Laboratory)*

Shuo Han *(University of Pennsylvania)*

Ben Hodges *(University of Texas at Austin)*

Alefiya Hussain *(University of Southern California)*

Marija Ilic *(Carnegie Mellon University)*

Chuanyi Ji *(Georgia Institute of Technology)*

Amy Karns *(Vanderbilt University)*

Rajesh Kavasseri *(North Dakota State University)*

George Kesidis *(Pennsylvania State University)*

Mladen Kezunovic *(Texas A&M University)*

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Wei Yu *(Towson University)*

Hongwei Zhang *(Wayne State University)*

Wei Zhang *(The Ohio State University)*

Ting Zhu *(Binghamton University)*

3. Acronyms and Definitions

AGC – Automatic Generation Control
CEWD – Center for Energy Workforce Development
CHP – Combined Heat and Power Partnership is an EPA voluntary program that seeks to reduce the environmental impact of electricity generation
CISE – Directorate for Computer and Information Science & Engineering
CPS – Cyber-Physical Systems
DAM – Day-ahead market
DG cluster – Density grid cluster
DOE – U.S. Department of Energy
ECPS or E-CPS – Energy Cyber-Physical Systems
EMS – Energy Management System
EPRI – Electric Power Research Institute
EV – Electric vehicle
FACTS – Flexible Ac Transmission System
FERC – Federal Energy Regulatory Commission
ICI – Interdependent critical infrastructure
ICT – Information and communication technologies
ISO – Independent system operators
NERC – North American Electric Reliability Corporation
NG – Natural gas
NSF – National Science Foundation
PV – Personal vehicle
QoS – Quality of Service
R&D – Research and development
RTM – Real-time market
RTO – Regional transmission operator
SCADA – Supervisory Control and Data Acquisition
SOC – Secure operating center