Towards a Pervasive Computing Enabled Modeling Environment for Integrated Coevolving Energy Systems

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***Abstract*—We present elements of a pervasive computing enabled modeling environment for integrated national energy systems (CI-MINES) to support policy and decision making as it pertains to co-evolving socio-energy systems. Decision support systems built using CI-MINES will provide public policy makers as well as private stakeholders entirely new ways to design and architect next-generation energy systems. When complete, CI-MINES can be used to evaluate the relative merits of competing conceptual architectures for interactive energy grids and markets before substantial investment is made in realizing them. It will also help evaluate new ways to invest in renewable energy sources and assess the reliability and security of the emerging grid architectures. CI-MINES is based on recent computational advances for modeling extremely large, complex, multi-scale socio-technical systems.**

I. INTRODUCTION

The US needs to develop a coordinated program to architect and build the next generation power grid or Smart Grid, harness renewable energy sources and reduce its carbon footprint while expanding generation and distribution capacities (see [3] for additional details). It is envisaged that a Smart Grid will allow household appliances to communicate with utility services through home computers and mobile devices, adjust consumption based on real time prices, and be able to sell electricity back into the grid generated from renewable sources, or stored in through their plug-in electric vehicles. This requires consumers to act as suppliers at times and the grid to be able to handle two-way flows.

These kinds of challenges can be best understood and addressed through an integrated energy systems environment which represents all aspects of a “Smart Grid”— this includes the communications system, real time demand side management, regulation, monitoring, micro-grid, distributed generation, cyber-security etc. In this paper, the term Smart Grid is often used as a short hand for the “integrated energy systems”.

The advancement of technology has caused consumers to add more electronic devices to their homes, such as microwaves, computers, smartphones, HD TVs, etc. and this has resulted in additional challenges for the grid. These devices are much more sensitive to voltage fluctuations than traditional appliances. Further, urbanization and globalization have created population centers in remote places which are located far from the generation sources. This requires transmission infrastructure to be able to carry power to long distances. In the West coast, frequent oscillations occur in the power due to this factor. If the oscillations are severe it can cause automatic shutdown of power to protect equipment as was the case in 1996 blackout [1].

Adding monitoring, control and communication to the electrical delivery system can optimize the electrical usage, improve the reliability of the old grid through distributed intelligence, consumers’ engagement in demand responsiveness, and adoption of more renewable sources of energy. Studies have shown that consumers can be incentivized to be more energy efficient if they were made aware of the social norms and given peer comparison feedback [10], [34]. Experiments have been undertaken where the utility companies have mailed the energy bill to the households along with a report that compares the current usage with the prior months usage and with the peers usage. It also provides the usage rank to the household compared to the average and the most efficient homes in the neighborhood. Households that receive such a report show a consistent and sustained reduction in their energy usage. These studies suggest that policy makers can impose mandatory peer reporting and other similar instruments to cut costs and improve carbon savings. This is particularly important since the utility companies do not have the incentive to nudge consumers to reduce energy consumption [35].

A better management of energy demand especially during the peak periods will save billions of dollars as the utilities will not need to build, maintain and operate peaking plants that are brought on line only during emergencies or satisfy extreme levels of demand. Advanced metering infrastructure (AMI) allow two-way communication between the utilities and the consumers or their appliances. It provides time stamped energy consumption data which can help with grid management, smoothing out the load curve and more actionable saving options to the consumers [4], [25]. The existing automatic meter reading (AMR) only allows one-way communications but is cheaper than the AMI.

A comprehensive national energy plan is being developed to implement this vision [3]. The plan recognizes that energy system modernization poses evolving scientific, policy and design challenges that test the limits of current understanding. At the same time, a revolution in networked information technology is proliferating digital devices that, by ubiquitous and varied measurement and interaction with the end users and the underlying energy system, will provide context-rich information and services to producers, distributors and consumers in the energy system. Collectively such networked devices will provide a rich and individualized pervasive computing environment, by measuring and interacting with the end users, their activities and the underlying energy system [32], [33].

Advances in technologies for computing, communication and power electronics provide entirely new ways to re-architect energy systems - from generation to transmission, distribution, control and protection. Modern communication networks will provide novel ways of measuring, controlling and disseminating information about energy systems and provide pathways for social, economic, and control networks to interact with the power networks [36]. Consumers can be active participants, adapting their behavior to time-dependent price information [24]; operators can monitor and control the grid in near real time to control cascading failures or to manage distributed generation facilities [27]. Economic decisions can be made on shorter time scales. Economics, social constraints and communication technologies will thus play a critical role in this redesign [29], [31]. Unfortunately, the resulting complex, coupled system designs will exceed the analytical capabilities of current models. Making rational infrastructure investment decisions will require models that go far beyond current capabilities that often represent each of these individual components. The next generation tools will have to allow analyst to undertake not just static analysis but fully dynamic analysis of the interdependent networks that will constitute the Smart Grid. Figure 1 gives an overview of the interaction among the various human, social, informational and infrastructural layers.

Although the power network and, the monitoring and control networks, are strongly coupled, they are typically studied and modeled separately. As a result, questions about interdependent dynamics, e.g. cascading impacts and unintended consequences across multiple networks are often poorly represented. From design, R&D directions and policy perspectives, this is problematic because designs for a national Smart Grid will have to incorporate and exploit comprehensive understanding of interdependent networks and processes. Technologies - including distributed generation, micro-grids and market regulatory mechanisms - will lead to market inefficiencies, suboptimal incentive structures for renewable energy and unintended gaps in reliability and security if integrated system-level analysis is not properly supported. Furthermore, the coupled networks co-evolve (as illustrated in Figure 1), and changes in one network affect how other networks operate; this is further complicated by changes in user behavior. In other words, next-generation energy systems networks cannot be effectively designed, analyzed and controlled in isolation from the social, economic, sensing and control contexts in which they operate.

Here, we propose CI-Mines as a pervasive computing enabled modeling environment for studying and supporting policy and decision making in integrated national energy systems. CI-Mines can be applied to address a variety of practical issues related to Smart Grid, e.g. enabling active participation by consumers through demand response programs, enabling new policy instruments to incentivize efficient consumption and production, optimization of electrical assets and operations etc. It can help policy makers adapt to evolving market designs and market forces e.g. understanding price responsiveness as green cars and environment friendly vehicles create significant challenges for sustainable energy infrastructure as well as two way flow of electricity on the grid.

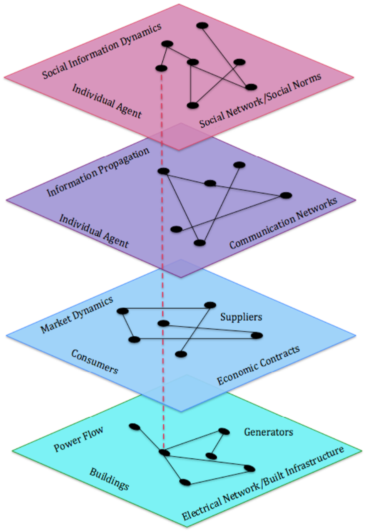

Fig. 1: Schematic diagram representing the multi-layer interaction of human, social and integrated energy networks. Individual behaviors, networks, policies and dynamics co-evolve leading to complicated inter-dependencies.

II. CI-Mines

We describe our ongoing efforts to develop CI-Mines: Pervasive computing enabled modeling environment for Integrated National Energy Systems. CI-Mines will fill an important technology gap in design and analysis of the next generation integrated national energy systems. It will support public and private stakeholders as they respond to the national goal of building resilient and sustainable energy systems. Several components of CI-Mines have already been developed.

A. Conceptual and System Architecture

A conceptual architecture of CI-Mines is shown in Figure 2, and is intended to model co-evolving networks depicted in Figure 1. It consists of four inter-related modules: (i) Data collection, (ii) Data integration and query processing, (iii) Model formation and network dynamics (Mines) and (iv) Model driven decision support. The first module collects data on humans, buildings, behavior, socio-demographics, social norms, usage history etc. This module pulls together data from various human as well as electronic sensors. In addition to electronic sensors including PMUs, SCADA systems and next generation metering system, we are creating an infrastructure wherein crowd sourced information can also be accessed seamlessly. The second module is tasked with integrating data collected by the first module and processes them using centralized as well as distributed methods. The third module synthesizes coupled networked representations of (i) infrastructure networks, including electricity grid, SCADA networks and (ii) various social and economic networks that are coupled to the infrastructure networks. The last module comprises of various dynamic models that can be used to reason about the dynamical evolution of the co-evolving socio-energy network.

B. System Architecture and Associated Cyber-Environment

Figure 3 gives an overview of CI-MINES. An initial version of the system called *Simfrastructure* has been developed and being used for reasoning about other socially coupled systems [23]. Simfrastructure is a powerful middleware that allows diverse computing systems, models and databases to interact seamlessly. The CI we are developing consists of mechanisms to allow end users access to very large, complex models over the web, a data management environment to support analysis and data and a visual analytics environment to support decision-making and consequence analysis. Just as the advent of search engines, such as Google, radically altered research and analysis of technical subjects across the board, Simfrastructure is designed with the goal of making computational, modeling and data resources seamless, invisible, and indispensable in routine analytical efforts. When extended, Simfrastructure will be able to connect: (i) MINES, (ii) web-based graphical user-interfaces for interacting with MINES, (iii) tools and environments for visual analytics and decision support and (iv) environments for collecting and integrating diverse data sets that MINES hopes to use. In other words, Simfrastructure can be viewed as a pervasive cyber-environment that supports MINES-based analysis and reasoning.

C. MINES

Mines is the modeling component of CI-MINES. It comprises of three elements: (i) a set of models for synthesizing and modifying networks, (ii) models and tools for representing individual and organization behavior and (iii) dynamical models that tie (i) and (ii) and allow us to represent the dynamical outcomes. As opposed to mean field analytical models, the models developed here are network based and algorithmic in nature.

Synthesizing co-evolving socio-energy networks. A key element of our modeling environment is the resolution and scale of systems that can be analyzed. Our models use representations of individual people and explicit interaction between these individuals and infrastructures. The methods for modeling extremely large coupled complex networks are based on technical advances in interaction based computing, and high performance algorithm design and implementation. These advances allow us to study large coupled networks that are dynamic and unstructured. For instance, a model representing Chicago would involve 10 million customers, commercial locations, electrical infrastructure and associated market components.

We have developed such models in the past for urban transport planning, public health epidemiology, telecommunication systems, e.g., the *TRANSIMS* and *Simdemics* modeling environments [13], [18], [20], [22], [23], [28]. Our initial work on energy systems can be found in [6]–[9], [26]. The basic idea is described below.

We first create a synthetic representation of each household in a region from the US Census data; this is done by integrating a variety of databases from commercial and public sources into a common architecture for data exchange that preserves the confidentiality of the original data sets, and yet produces realistic attributes and demographics for the synthetic individuals. Joint demographic distributions are reconstructed from the marginal distributions available in typical census data together with joint distributions in Public Use Microdata Samples (PUMS) using an iterative proportional fitting technique. A census of this synthetic population yields results that are statistically indistinguishable from the original census data, if they are both aggregated to the *block group level* [19], [30].

Next, each synthetic person in a household is assigned a set of activities to perform during the day, along with the times when the activities begin and end, as derived from the activity or time-use survey data from the National Household Travel Survey (NHTS), and American Time Use Survey (ATUS). This step ensures that each synthetic household is matched with one of the survey households, using a decision tree based on demographics such as the number of people in the household, number of children of various ages, household income, etc. For each person and each activity performed by this person, a preliminary assignment of a location is made based on observed land-use patterns, building capacity, tax data, etc. [11], [19]. This completes the location assignment step for each person and for each of their activities.

Synthetic individuals placed within a realistic urban context can be composed with other aggregated as well as high resolution data sets. For instance, in the case of telecommunication systems, these synthetic individuals can endowed with demand for telecommunication resources [21], [22]. In case of epidemics, they can be endowed with disease specific characteristics. Synthetic individuals provide a natural way to compose aggregated information and also to develop a spatial model [28].

Building on our earlier work, MINES will endow synthetic individuals with realistic spatio-temporal energy demand patterns. On the spatial scale it will be at the level of buildings, and at the temporal scale, at the level of an hour or a few minutes. The novelty lies in combining survey based, commercial, behavioral, census and activity data to generate realistic location specific demand profiles. Spatial and temporal aggregation at the level of communities of firms is possible and is currently being investigated. As people move from location to location to support a variety of activities during the day, the energy demand profile of the buildings change

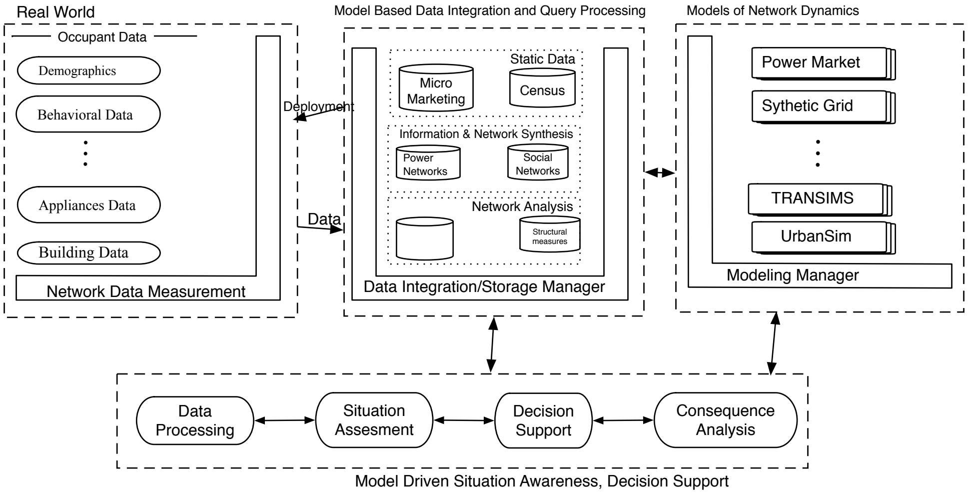

Fig. 2: Conceptual Systems Architecture of CI-MINES for information fusion, model execution and data processing.

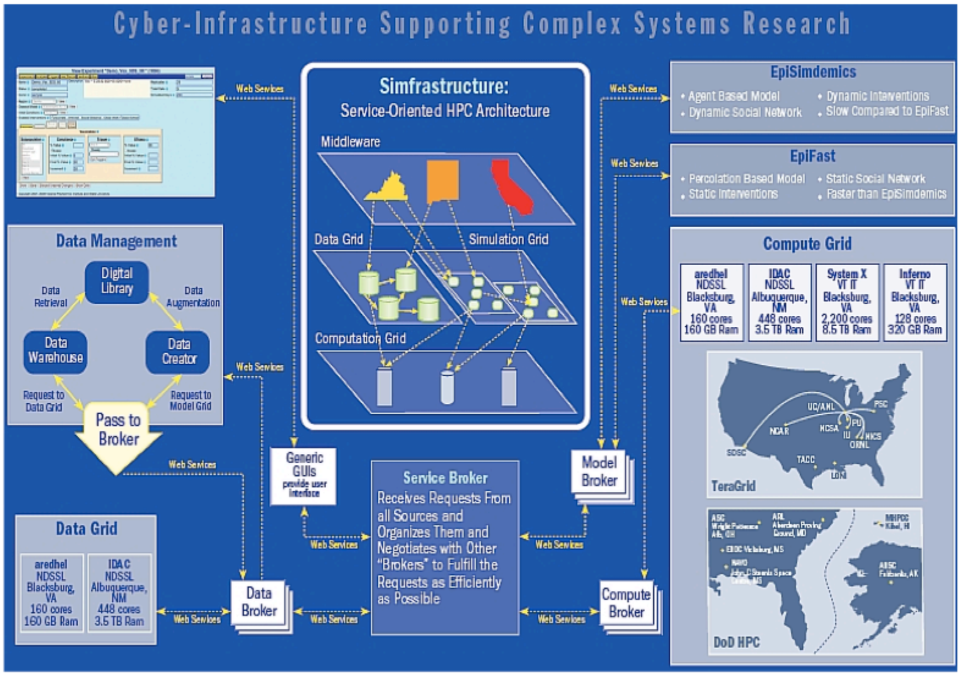

Fig. 3: A schematic diagram of Simfrastructure (adapted from from [23]). Simfrastructure serves as the middleware for CI-MINES.

dynamically. Realistic models of people mobility, specifics of the locations, demographics of the people present at the location etc. are needed to generate spatio-temporal demand profiles. An aspect that is missing in [21] are models for behavioral adaptation along with means of simulating the dynamical outcomes of these adaptations. We are currently investigating this as a part of a DOE funded project [2].

The electrical infrastructure elements such as the substations, transmission lines, the distribution system, load bearing nodes, generators etc. need to be represented in detail and placed in a common geographic coordinate system. This detailed system will provide an end-to-end model of the people and the electrical infrastructure. This type of model enables one to study the effect of behavioral changes in the agents, as caused by changes in demographics, social environment, supply, economic factors, technological factors and public policy, on the spatial and temporal distribution of the energy usage. Note that realistic and implementable policies require individual level, demographic based representations.

Mathematically, such a system can be viewed as composition of graph dynamical systems [13], [14], [16], which we have studied extensively for applications, such as epidemics in social networks. Key issues in integrated energy systems, such as system dynamics and vulnerabilities, can be related to fundamental dynamical questions in graph dynamical systems, such as reachability, fixed points and predecessor existence.

D. *Computational Challenges*

Developing scalable CI-MINES is computationally challenging. The size and scope of the co-evolving networks, simulating dynamics on such systems, managing large amounts of data and developing pervasive distributed computing systems all present certain generic as well as application specific challenges. We refer the reader to [13], [23] for discussion on this topic. Application specific challenges are numerous and we highlight three diverse problems. The first challenge is developing behavioral adaptation models that can represent how users are likely to adapt (current energy systems provide very little insights into this) when presented with *meaningful* choices. A related challenge is to develop models of electrical grid. As the grid operations and ownership is private, it is becoming increasingly harder to obtain data about the grid. Security concerns complicate the matters further. Both these are data challenges: availability of data, both numeric and procedural. The second challenge is to develop scalable models that can be efficiently mapped on high performance computing architectures. AC power flow codes are known to be computationally expensive, DC codes can be computed reasonably fast in isolation and often adequate. More importantly though, power flow models have to be coupled with demand and user behavior models as well as economic models. Our early work [7] was largely suitable for single processor machine; we have recently developed generic scaling methods that we believe provide a way forward. A final challenge pertains to validation, verification and uncertainty quantification pertaining to these systems. Classical notions of predictive validation are simply not appropriate when dealing with complex systems such as integrated energy systems. The issue is not confined to energy systems per se but any socially-coupled system.

III. APPLICATIONS AND RESEARCH AREAS

Some of the components of CI-MINES are already in place, while others are being developed or adapted for the energy application.

A. *Case Study*

We outline the following case study to illustrate the utility of CI-MINES. The conventional transmission grid and large sized plants such as hydro and nuclear, usually are responsible for supplying a large fraction of the power in a region. Any disruption to these plants and hence a steady supply of power, whether deliberately caused by terrorists or inadvertently caused by the system can be very detrimental to the society. Due to the increase in the reliability needs of the consumers and the desire to use renewable energy, distributed generation seems an attractive supplement to the utility-supplied power. Distributed power generation occurs at a small scale, dispersed form, close to the load or point of consumption and does not need to be carried over long distances through a vast transmission grid which includes thousands of miles of high voltage lines.

The user can design a micro grid that connects small generators and uses renewable energy sources for fueling. The consumers can have the option to draw electricity from either the local micro grid or the centralized conventional grid. The local grid offers cheap green energy, and reduces dependence on the central transmission system. This is especially important during the peak hours of the day. In addition it improves the ability to smooth out the load curve which keeps expensive peaking power plants from having to come on line. The envisioned modeling environment outlined above can help analyze the various aspects of such a case study and help design new policy instruments to improve the efficiency and robustness of our electrical infrastructure.

B. *Synthetic Grid*

Recent work in Network Science has demonstrated the importance of studying dynamical phenomena of interest on realistic networks. In the past, constituent elements of the electrical network were available for research. This has changed radically in the recent years - the primary motivations for this change are security, privacy and proprietary concerns. The structure of the network has a profound impact on the dynamical process e.g. its ability to transfer current, its vulnerability and reliability in the event of failures, and the market power that gets created due to strategic locations on the network [26]. As the power industry undergoes further deregulation and sees an influx of new players due to federal and global energy initiatives, explicit data pertaining to the network and its constituent elements are unlikely to be available.

We suggest that emerging technological gap can be filled by developing methods and underlying theory that will yield first principles based models of the national electrical network. By first principles we imply that the generative processes are not based on simple random graph models that, although, mathematically appealing, fall well short of generating realistic networks. We can build on earlier work we have done in this area in other socio-technical networks [15].

The starting point of our work is based on two important observations: (i) no single database is likely to contain all the information that allows us to construct an exact representation of the current power network; however, a large number of data sets and expert knowledge are available so as to be able to develop models that yield representations of power networks that are statistically similar to real power networks and (ii) synthetic network constructions require not just simple data fusion and integration techniques but also require one to appeal to social, behavioral, economic and technical theories for filling missing data in a consistent manner. This dynamical system based generation and synthesis of such networks is both necessary and possible.

The synthetic electrical grid can help understand the global properties of the underlying network that must be analyzed in order to understand the local behavior [8]. For instance, knowing whether the grid is one large connected component is useful in determining the feasibility of transferring power between any two nodes on the network [5], [7], [15], [17], [26].

C. *Individual Models of Demand Behavior*

Efficient and stable markets require active participation from both the consumers and suppliers. Demand and supply models are crucial for modeling the market interactions and understanding market mechanisms. Realistic modeling of consumer demand requires a combination of statistical modeling and behavioral modeling that allows consumers to adapt to changing market conditions.

The individual-based demand and supply models will be of broad value in developing scale-up plans for elements of Smart Grid infrastructure under small-scale tests, and in studies of grid resilience during crisis conditions. They are different than classical statistical models developed in economics that usually assume perfect information and rational agents. Recent research in behavioral economics is aimed at closing the gap between real and ideal world.

In the context of power systems, such individual-based models are important and necessary for a number of reasons. For instance, issues such as responsiveness to prices, distributed demand generation, willingness to purchase green energy etc. cannot be studied without disaggregated modeling. To understand the demand behavior of different end-users, e.g. rich, poor, residential, industrial, risk averse, risk neutral etc., it is necessary to develop an individual based system that can accommodate individuals' demographics as well as their behavioral characteristics.

PDE and ODE based models inform the policy makers as to how an average consumer will behave under various circumstances. Although very useful in several application, they are not suitable when one needs to represent and study individual heterogeneity and scale. Individuals, groups and organizations that make the consumer and supplier energy landscape have a wide spectrum of demographic features and behavioral attributes. Furthermore, behavioral adaptation is extremely important to understand when developing new energy systems. For example, the demand response to real time prices will differ across people depending upon their socio-economic and behavioral attributes. Individuals with higher income are less likely to be price elastic as compared to the lower income strata. Industrial locations are likely to consume more electricity per capita than the residential locations. Understanding and modeling demand responsiveness in a disaggregated way will increase the efficiency of the markets, reduce price volatility and allocate scarce electricity resources more efficiently [6], [9], [25].

The disaggregated demand profiles, at the scale of individuals, groups and geographically spread entities (e.g. company) can be used to demonstrate how active consumer participation can improve the efficiency of the market; how appropriate incentives can be built to use green energy; and how energy sustainability and security can be improved through behavioral changes. Our preliminary results on the subject have been reported in [7], [29], [33]. We are currently extending these models and modeling methodologies to represent multi-scale (time, space and organization) systems and also to represent behavioral adaptations. As an example it would be desirable to model demands for electricity for recharging batteries in the next generation electric cars. Prediction in such situations is not really feasible, nor the sole goal. Rather an important goal is adaptation - can the models help consumers and suppliers adapt to the changing landscape in an effective manner.

D. Market and its Interplay with the Transmission Grid

A detailed representation of the market and its coupling with the electrical grid is needed to study the issues that lie at the intersection of the market and the electrical infrastructure. This coupling will enable the economic contracts to be checked for physical feasibility on the grid. One of the goals of CI-MINES is to use advances in computation to study the market, its participants and its interaction with the electrical infrastructure.

The micro level behavior of the market participants coevolves with the physical constraints posed by the grid. As an example, our previous work has shown that binding transmission constraints can create non-competitive conditions in the market. The electrical constraints and the network topology can create isolated geographic markets where generators can have local monopoly and hence can exert market power. This work was based on a quantifiable, flow-based definition of the locational market power which accounts for the electrical network topology [7], [26]. Issues such as locational market power cannot be studied in isolation in the market environment or in the power systems model; an end-to-end modeling environment such as CI-MINES is needed. In addition it allows one to study cascading failures in inter-dependent societal infrastructures and networks [12].

A variety of trading rules, that can accommodate game-theoretical behavioral strategies for bidding, can be designed and implemented. The models can be used to validate particular Smart Grid investment strategies, and help corporate planners understand the sensitivities of the market outcomes to changes in market structure, bidding strategies, market clearing algorithms, and regulatory policies [7]. Grid reliability can be studied by load flow analysis as both one way and two-way flows will be supported on the grid.

IV. SUMMARY AND CONCLUSIONS

The study of next generation integrated energy systems requires detailed representation and analysis of the power grid and power flow, as well as the social, economic, sensing and control contexts in which they operate. These different aspects are typically studied in isolation, and are computationally extremely challenging; further, models and data are not well understood or easily available. We propose CI-MINES as the first integrated framework for studying and supporting policy and decision making in integrated energy systems.

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