Research Statement

I build intelligent and adaptive *signal and information processing* systems to *manage*, *monitor*, *control* and *simulate* sustainable social scale network (cyber-physical) systems. My main application area is advancing the design, optimization, planning and data-driven modeling of electric power systems by creating novel sensing and control platforms, robust data processing algorithms and dynamical statistical decision methods. I have combined statistical models based on currently *underused data* with *novel sensing platforms* and state of the art algorithms along with *theoretical guarantees* to propose solutions that have increased efficiency and reliability, while decreasing operations costs. I am excited by the prospect of integrating modern systems models with real-world data sources in research that requires carefully applied statistics and stochastic modeling along with new theoretical insights. My work has resulted in more than 40 patents (21 issued), several awards, publications and commercial products. It has been supported by NSF, California Energy Commission, IBM Research, Adobe, E-On, China State Grid Corporation, Precourt Energy Efficiency Center, Tomkat Center for Sustainable Energy and the Powell Foundation Fellowship. I believe strongly in the importance of effective interdisciplinary and collaborative research, having worked with researchers of various fields , industry practitioners (e.g. PG&E, SGCC) and policy makers (e.g. CAISO, EPRI) in many problems.

Power systems are undergoing a dramatic change. The increasing deployment of renewable generation has led to challenges in the form of increased supply-side uncertainty at multiple time scales and changes in power flow patterns. Opportunities to control this variability arise in the form of storage and demand-side coordination utilizing load control technologies and financial incentives. In fact, the edge of the power network is undergoing a transformation with the adoption of a wide set of power electronic systems and communication technologies. Yet, we lack a principled approach to design, monitor and operate this new system. In particular, existing approaches fail to utilize data at different time and resource resolutions generated by these new technologies, and often result in solutions that don't run on practical embedded system and control platforms. The consequence is that theoretically sound approaches do not work well in practice. Often, practical solutions require development of new models and theoretical approaches, resulting in improved algorithms.

I founded and direct the Stanford Sustainable Systems Lab to address these challenges. We build data-driven end-to-end solutions to monitor and control power systems, in particular power distribution networks following the approach outlined in Fig. 1. We focus on three aspects of system design: processing and integration of data to characterize network and consumer behavior, stochastic control and optimization algorithms and implementation of prototype solutions in embedded system platforms. I have also led the establishment of the Smart Grid Group, consisting of 8 faculty and 5 affiliate companies to bridge the gap in providing access to data and opportunities for practical experiments.

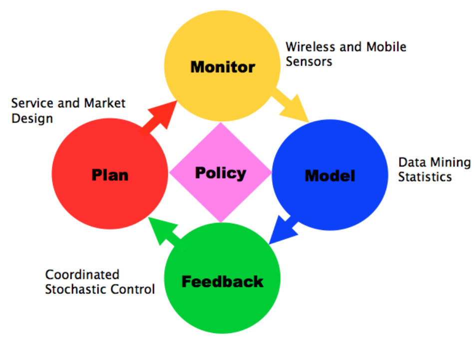

Figure 1: Designing and operating large complex energy networks.

Some of the important contributions of our group to research in energy systems are:

- Complete characterization of Stochastic Dispatch problem in a power network, including practical algorithms.
- First large scale smart meter based study of demand side management potential utilizing data from 300,000+ customers.
- Customer targeting and segmentation algorithms based on smart meter data, adopted by oPower, PG&E, LAPWD.
- Behavior driven consumption models, utilized at oPower, C3 Energy, PG&E and SCE.
- Development of the open source VISDOM system for demand side management based on smart meter data, adopted by SGCC, PG&E, LBNL.
- Complete characterization of Cornout games with stochastic resources introducing the notion of right sized aggregations and validation with data.
- Complete characterization of the forecasting scaling problem producing the first data-set unbiased methodology to evaluate forecasting algorithms.
- Proof of concept of a low cost non-contact voltage sensor for distribution network voltages with metering level accuracy, including the first optimal placement and detection algorithm for outages.
- Approximation algorithms for various classes of deferrable and curtailable load scheduling, under evaluation at AutoGrid.
- First smart meter data driven rate design algorithms reported in the literature.

Sensing for Future Distribution Systems. The foundation for improved network operations and planning is the availability of dense measurements of environmental and grid state variables. Deployment costs have limited the ability to measure variables such as wind speeds and distribution system voltage and current phasors. I address these issues by building novel wireless sensing systems:

Non-contact fault detection and state estimation. We have proposed and validated a novel non-contact voltage measurement for systems of up to 10kV obtaining measurement accuracies beyond 0.1% and negligible phase distortion [35]. This system can be combined with accurate PMU hardware to provide state-of-the art performance in phasor measurements at very low cost (20% of existing solutions) without interference from transformers at the feeders.

Autonomous UAV based renewables analytics. The main limitation for accurate wind power forecasts has been the lack of short-term to real-time measurements due to high installation costs. We have designed an autonomous wind speed, direction and temperature autonomous mobile sensor based on a custom quadcopter system. The system is able to recharge itself and fly for 45 min to an hour [28] . Wind speed measurements are collected by a self-orienting measurement system. Sensors can be deployed to collect data at targeted areas and the information utilized by real-time prediction models. The system is being tested in partnership with a local sailing company to predict wind speeds in the San Francisco Bay Area. Based on this data, the performance of renewable systems can also be characterized. A key performance metric is understanding sustained increase or decrease in power output, i.e. ramps. We proposed the first systematic and fast consistent algorithm to detect ramps at multiple scales and produced empirical distributions of ramp duration, rate and frequency for thousands of sites in California[36]. Additionally in on going work, we utilize a simple non-parametric pattern based method combined with Gaussian Processes to predict wind and solar power outputs [19] that improves existing practice significantly.

VISDOM (Visualization and Insight for Demand Operations and Management). Real-time sensing of supply and demand from the electricity network enables a dramatically improved understanding of the variability and flexibility potential from smart grids. In our work, we built a platform for demand-side data analytics that builds statistical models from individual consumer time-series data and is used for various goals:

Consumer targeting and Segmentation. The millions of small and medium loads in the power system offer an enormous opportunity to extract demand side flexibility. However, identifying and enrolling customers that yield the best outcomes for programs that elicit demand-side flexibility has been a challenge. Typically, observed energy yields are only 10% to 20%.Existing approaches fail due to prohibitive monitoring costs and incorrect assumptions about consumer behavior. Widespread deployment of smart meters and other sensors provide 15 min to an hour resolution data on individual consumers. These data can be utilized to estimate and enhance the opportunity to extract demand-side flexibility. In particular, different *features* computed from these data can reveal consumption patterns of individuals and businesses, including behavioral patterns. We have built VISDOM, an open-source software platform that integrates multiple sources of data, including smart meters, census information and weather information and enables the characterization of different types of demand flexibility by utilizing carefully designed features. These features are utilized to build a pattern based characterization of consumer behavior and predict the amount and reliability of demand-response from a collection of consumers. VISDOM has been applied at PG&E to data from 350,000 homes and 400,000 businesses to provide the first smart meter data driven characterization of their customers. VISDOM revealed that only about 15% of households followed existing models for load consumption [12]. We have also designed segmentation [13] and targeting algorithms [14] to identify and enroll the best customers for each program resulting in yields of 60% or higher. We utilize the prior algorithms to provide the first purely data-driven characterization of different types of demand-flexibility potential in residential loads, including storage, pricing, demand response and load scheduling [29]. In on-going work we are utilizing these features to estimate pricing response models for electricity customers to static and dynamic pricing. Experiments are being conducted at Pacific Gas & Electric to target thermal demand response, storage and time-of-use pricing programs.

Demand characterization, forecasting and baselining. Demand forecasting and baselining are central to the operations of distribution network solutions. Existing approaches focus on point-estimates that minimize Mean Squared Error and are applied to megawatt sized systems. Moreover, despite several models for characterizing different types of demand consumption little is understood about the influence of behavior and the temporal variability of the response. These limitations have resulted in inaccurate estimates and a poor probabilistic characterization of the system. We have designed a series of algorithms to provide full probability distributions as estimates, building upon ideas in Gaussian Processes and hierarchical statistical models. [2] provides a segmentation based estimate of load duration curves showing that 20% of customers are responsible for 60% of cost. [4] proposes modeling the sensitivity of consumption to external driving factors (e.g temperature) while accounting for occupancy resulting in a stimulus driven Hidden Markov Model (SHMM). his led to the first probabilistic estimates of heating and cooling consumption for a large area [1] and methods that can infer various household characteristics [3]. We uncovered a novel *scaling law* for load forecasting accuracy as a function of the *size* of the load, demonstrating that predicting 500 homes is as accurate as whole feeders while individual homes are hard to forecast [37]. We are currently developing baselining algorithms for estimating the impact of demand-response and energy efficiency systems based on the observed scaling law in partnership with State Grid Corporation and E-on.

Customer response prediction. Estimating program impact at an individual consumer level has been a difficult task. Causal estimates have been provided utilizing experiment design by assigning customers to control and treatment groups. Causal response estimators then are able to measure the *average treatment effect* across the population. Predictive estimates of individual customers rely on predictors that don't capture behavior correctly and end up with large errors. Currently, there is no satisfactory method to determine savings in the population of different programs such as demand response or peak pricing. Instead we propose a different approach: smart-meter measurements from a customer prior to program participation are utilized to build a baseline; the difference between actual consumption and baseline is the treatment effect. We then utilize features from prior to program participation to drive savings estimates. Currently we are investigating the performance of this method in existing programs in a joint project with LBNL.

Rate and demand response compensation design. Retail distribution system rates have always been designed based on aggregate information for large groups of customers. The availability of smart meter data has enabled the opportunity to observed individual consumer behaviors and its uncertainty in more detail. In particular the need to balance between the increase in forecasting accuracy and the loss in pattern consumption resolution due to aggregation. [22] proposes a customized pricing plan for consumers that balances this tradeoff. It enables wholesale cost reduction of about 30% to service these customers.

Energy efficiency. Modeling and ranking the efficiency of energy utilization in buildings is central to achieve energy efficiency goals. Typical methods have relied on average per square ft. estimates of consumption. Instead we propose a data-driven ranking methodology that relies on a two dimensional evaluation: each building has a level of service (LOS) and consumption. They can then be profiled [9] and ranked [10] following this information. An experiment was conducted at a Microsoft campus to evaluate the methods in practice.

VADER: Visualization and Analytics for Distributed Energy Resources. In its current state, the distribution system is incapable of handling small to moderate amounts of PV penetration. This is because it was initially designed for handling passive loads that, at the level of a substation, have low variability and are forecastable with high accuracy. It has been an open loop system with little monitoring and control. With the addition of PV energy sources, the overall scenario will change dramatically due to (1) two way power flow on network and (2) high aggregate variability. Additionally, changes on the consumption side lead to a number of smart loads, Electric Vehicles (EVs) and Demand Response.These fundamental changes in the characteristic of the generation and consumption of power will lead to a number of practical engineering problems that must be overcome to allow increased penetration of Distributed PV. Solving the specific engineering challenges which come at any moderate level of PV penetration requires closed loop integration of data from (1) PV sources, (2) customer load data from smart meters, (3) EV charging data, and (4) local and line mounted precision instruments. These data are not traditionally used by utilities in operations since they are non-SCADA and the current grid does not require such level of control. To integrate this data and provide real time intelligence from these non-SCADA data, we propose VADER (Visualization and Analytics of Distributed Energy Resources) platform. VADER is a unified data analytics platform that enables the integration of massive and heterogeneous data streams for granular real-time monitoring, visualization and control of Distributed Energy Resources (DER) in distribution networks. Some of the initial contributions in this area are

Network Topology Reconstruction. Learning the topology and the network parameters of a radial or a potentially cyclic distribution network is a non traditional system identification challenge. Voltage and power measurements from smart meters embedded local and global information but the least squares recovery problem is non-convex and challenging. We propose a graphical modeling approach that describes the probabilistic relationship among voltage measurements. Utilizing power flow analysis, we demonstrate that a a mutual information-based identification algorithm can learn tree and partially meshed network topology from measurements. The approach is validated in a networks with sizes varying from 113 to 3000 buses with reconstruction errors less than 3%, that substantially improves the current state of the art.

Sensor Placement. Designing monitoring deployments for future distribution networks has remained an open problem. Most methods are combinatorial and model-based, seldom capturing how the sensor data is utilized in applications. We have formulated joint placement and detection problems to decide where to deploy these sensors in the network, and how to optimally detect outages [41] and determine network topology by fusing the information with smart meter data. In the near future we expect the system can provide a real-time voltage map of each node in a feeder to design improved reactive power support systems.

REMATCH. Planning systems for distribution networks and micro grids utilize transmission planning principles. The total feeder load is assumed to be known and a deterministic optimization is utilized to add a combination of distributed generation and network support devices to meet this load to a specified loss of load probability. The presence of demand-side management opportunities (deferrable loads, demand response, energy efficiency, pricing), storage and a more ample set of network devices requires a more scalable approach. REMATCH is a planning system based on assuming electricity to be generated or consumed as a collection of contingent (probabilistic) discrete hourly blocks. The goal of planning is then to provide a matching between supply and demand blocks under every contingency scenario given a constraint on cost and/or loss of load probability. Opportunities to store or defer supply or demand are represented as a collection of matching edges. The planning horizon is represented as a scenario tree, where assumptions can be made explicit on the evolution of costs and uncertainty. REMATCH enables the scalable deployment of distribution network solutions, inclusion of a variety of demand side management programs and storage. Because the solution is a matching, it can be also deployed progressively. In ongoing work, we have shown that a REMATCH designed network can be operated in a decentralized and distributed way utilizing contingent trades between devices resulting in optimal stochastic power balancing [26]. Currently, we are implementing a software for REMATCH and connecting it to the GridSpice Network Simulator to simulate obtained matched networks.

Powernet: Embedded Systems and Controls for Power Coordination. We organize the network control into three layers: a resource aggregation, a stochastic power balancing and network coordination. We design data-driven algorithms for power management at the distribution system level in various time-scales. The methods we propose form an architecture that organizes the distribution system into clusters of resources. Each cluster engages with consumers in its domain relying on service markets, achieves local power balance and provides basic control functionality. In current work we explored centralized coordination within clusters and in future work we will investigate intra-cluster coordination.

Stochastic power balancing. The system operator needs to dispatch various types of generators to compensate the randomness in supply when integrating wind and solar into the grid. Existing deterministic practice absorbs the additional uncertainty with spinning reserves, resulting in an integration cost of about \$8 to \$11 per MWh. Reduction in cost requires proper utilization of statistical information about renewables when purchasing power in existing sequential markets. In [33] we designed Risk Limiting Dispatch, an integrated stochastic control framework for these problems relying on closed form solutions for dispatch decisions under different power system objective functions and market structures. Integration costs are reduced to \$2 to \$3 per MWh without requiring substantial market and system software changes [32]. The methodology has been generalized to include network constraints [40], storage [27, 25], electric vehicles and approximation algorithms for deferrable loads [21]. New theoretical approaches to approximate constrained dynamic programs in the context of power systems have been developed as part of this work. We have also considered the impacts of these strategies on markets [38]. We are currently investigating how to incorporate integral task constraints in these contexts. More recently, we have started to investigate how to solve 0-1 dynamic programs that can be utilized to control a broader set of loads

Resource aggregation. Eliciting flexibility requires adapting mechanism design frameworks to environments with significant supply and demand side uncertainty and engaging large numbers of agents. Aggregation of consumers and producers increases forecasting accuracy and reduces variability. My work identifies appropriate data-driven mechanism designs to enable effective aggregation. On the supply side, we propose differentiating power according to its reliability and design trading [42, 8] and contract mechanisms for this purpose[7]. More recently, we have developed a scaling theory for resource aggregation in Cournot games and shown that suppliers with uncertainty should be aggregated to a maximum size to balance the reduction in forecast uncertainty with loss of efficiency due to market power from aggregation [39]. On the demand side, we focus on designing data-driven systems to compensate consumers for their flexibility, utilizing fair demand-response compensation [20], real-time pricing and slotted scheduling of power consumption.

Plug & Play Network Coordination. While power balancing and market operations address the slowest time-scales of power management, in the fast time scale various services are required, including frequency and voltage regulation. The typical approach relies on complex control designs that satisfy constraints imposed by generators and loads to achieve stabilization and performance. The profile of loads in distribution networks has shifted significantly with an increased presence of constant power loads behind power converters. We have demonstrated instability even in small networks with three or four elements, when the control follows traditional coordination-free mechanisms. Instead, we propose utilizing power electronics to design an interface system for network elements. The interface ensures that every element is presented as a passive device to the whole network, providing simple and direct stability guarantees. Furthermore, a very simple communication system enables implementation of coordination. We are currently prototyping a DC network version of this device, to utilize in simplifying power distribution and control in data centers.

Data-driven monitoring and control of transportation networks

The availability and utilization of real-time information about system performance and state has been the major limiting factor towards more efficient operation and maintenance of transportation and roadway systems. In my research I have addressed this challenged by designing and deploying various layers of a sensor data-driven approach to these networks, ranging from fundamentally new wireless sensing modalities to data processing and control schemes utilizing these sensors. I have built multiple systems that combine these ideas to deliver real-time monitoring and control solutions for infrastructure networks:

Real-time traffic monitoring. Traffic data for arterial roads (e.g. El Camino Real) is lacking due to the inaccuracy and cost of existing solutions. I built a novel wireless sensor network based on magnetometers to provide urban street block travel time and emissions measurements[15, 16]. The system utilizes insights from traffic dynamics to build a simple and efficient statistical procedure that matches the magnetic signature of the vehicle as it moves. The system reduces deployment costs by more than 80% while preserving privacy and being twice as accurate as existing alternatives. The platform is deployed in 100+ locations and commercialized by Sensys Networks, Inc. Additionally, I built a system to cleanse and integrate data from 30,000 existing sensors reporting highway traffic conditions, including new bad data detection methods [34], sensor fixing program recommendations [30], distributed estimation [31] and sensor placement methods [11].

Real-time pavement monitoring. Roadway pavements are costly ($750k to $2MM) and difficult to monitor. The major driver of damage to roadways is the load of the traffic that travels on it. To profile this damage we built a wireless accelerometer sensor network that is embedded in the road and is able to classify vehicles [5] and provide their axle by axle loads. The system relies on a novel displacement estimation algorithm that combines insights from a layered-elastic partial differential equation model and nonparametric statistics to overcome classical performance issues [6]. The system has been deployed in Sunol, CA at a cost of $100k. The same platform enables *wireless structural health monitoring* using novel statistical algorithms for damage progression and occurrence [17, 18].

Real-time parking management. A parking space has a differentiated value according to its location, occupancy of the lot and the profile of the driver. The transportation literature has not adressed how to price parking when such real-time information is available. We are designing algorithms that utilize such information and provide real-time network pricing inspired by e-commerce revenue management [24, 23]. We have also built and deployed a wireless individual spot monitoring system at Stanford University. Smart phone apps that implement the pricing algorithms as well as novel ideas such as load balancing across parking lots by utilizing driver behavioral traits are explored in our testbed at Stanford University and using data from the SF Park project. Real-time parking management can provide downtown congestion relief of more than 20%.

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