1   Project Description

Contents

1.1   Introduction

Development of the "Smart Grid", a modernized power infrastructure, is one of the key technological challenges facing the United States at the dawn of the 21st century. According to the Department of Energy (DoE) , the smart grid should: (1) Enable active participation by consumers by providing choices and incentives to modify electricity purchasing patterns and behavior; (2) Accommodate all generation and storage options, including wind and solar power. (3) Enable new products, services, and markets through a flexible market providing cost-benefit trade-offs to consumers and market participants; (4) Provide reliable power that is relatively interruption-free; (5) Optimize asset utilization and maximize operational efficiency; (6) Provide the ability to self-heal by anticipating and responding to system disturbances; (7) Resist attacks on physical infrastructure by natural disasters and attacks on cyber-structure by malware and hackers [Nat08].

Supporting "all generation options" implies the need to support distributed, small scale, intermittent generation such as residential solar. Supporting "all storage options" implies the need to support distributed, small scale, intermittent storage such as electric vehicle batteries. Once energy generation and storage can be just as decentralized as energy consumption, the utility of microgrids as a building block for the DoE Smart Grid becomes clear. Microgrids are semi-autonomous, self-regulating electrical systems below the subsystem level that can involve small-scale storage and generation as well as consumption.

1.1.1   Vision

Our vision for a sustainable energy pathway begins with the creation of a functional, semi-autonomous, self-regulating microgrid that creates a positive energy future for the University of Hawaii at Manoa campus. This campus currently faces severe energy challenges: while energy consumption per square foot is among the lowest across campuses in the nation (at approximately 65K BTU per square foot), the cost of energy

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Section 1.1.1 must provide a concise description of the "vision" for our proposed sustainable energy pathway that focuses on energy transmission, distribution, efficiency, and use. We must show in our vision: a combination of scientific knowledge and technical innovation; a recognition of environmental, societal, and economic imperatives; and a promotion of education and workforce development. We need a transformative approach to SEP, not incremental advances or deployment of existing technologies.

per square foot is among the highest in the nation (approximately $4.50 per square foot), as is the cost of energy per student FTE (approximately $1,300 per student FTE).

Making matters more complicated, an aggressive retrofitting of mechanical systems at the University over the past 10 years has largely exhausted the traditional avenue to energy cost reduction. In addition, because the State of Hawaii depends on fossil fuels for almost 90% of its energy, it is possible, if not probable, that the cost of energy in Hawaii, already the highest in the nation, will rise substantially in the next 20 years. The current high cost of energy and the probability of it rising even higher, combined with the exhaustion of traditional approaches to energy cost reduction, has led David Hafner, an Assistant Vice Chancellor at the University of Hawaii to state, *"the cost of energy represents an* existential *threat to the University of Hawaii as a Research I university"* [Haf11].

We present this background to emphasize that our choice to focus on a sustainable energy pathway for the University of Hawaii at Manoa campus is not because it would be "nice to have", it is because the status quo is quite literally unsustainable. To retain its current quality of campus life, the University of Hawaii must find a way to generate a substantial fraction of campus power, reduce the cost per kilowatt of electricity purchased from the utility, and create a "climate of energy conservation" among campus members that minimizes overall demand.

Our vision involves the transformation of the campus from one which passively delegates to the utility all responsibility for its energy needs, to one which owns and operates a smart, sustainable microgrid involving up to 5 MW of solar generation, short term, small scale storage, automated demand response for the major on-campus HVAC systems, and consumer facing information technology to engage campus members in support of the microgrid and its goals. This vision requires innovation in transmission, distribution, efficiency, and use. Our research and development plan involves five interrelated research components, summarized as follows:

1. *Sensors and monitoring.* A responsive microgrid requires the ability to assess its current state and estimate its future state. To enable these capabilities, this component will design and install a network of strategically located power and environmental sensors into the UH campus as well as into the neighboring vicinity. This raw data will be collected and stored in a server for use in modeling and analysis.

2. *Modeling and analysis.* This component takes the raw power and environmental data and applies stochastic modeling techniques to gain insight into both the current and near-future state of the grid. This component provides the information necessary for control and optimization.

3. *Control and optimization.* This component uses models and analyses to support voltage and frequency regulation, peak shaving and peak shifting. By maintaining quality of service while reducing load and ramp, the University microgrid will reduce the cost per kWh of supplemental energy bought from the utility.

4. *Social, economic, privacy, security, and policy implications.* It is explicitly not our goal to create a grid that operates transparently and invisibly from its users. Indeed, we believe that part of the problems with our current electrical infrastructure results from lack of public awareness concerning the problems of reliable, sufficient, and sustainable energy production. This component investigates the information technology necessary to inform campus members about the microgrid in an actionable form that lets them actively participate in achieving its goals. In so doing, we must confront and address the privacy and security issues that result, both with respect to the security of the grid itself and the ways grid data could be used to inappropriately monitor campus member behaviors.

5. *Education and workforce development.* All of the PIs on this project are also active participants in the Center for Renewable Energy and Island Sustainability (REIS), a project with a central focus on

workforce development in renewable energy. As a natural result, our vision includes the development of curriculum materials about microgrid design, implementation, and evaluation, and students with real-world experience in development of the microgrid. Our participation in REIS helps ensure that workforce development will span multiple disciplines including computer science, engineering, economics, urban planning, law, biology, and other disciplines.

Our vision begins, but does not end, with addressing the energy challenges facing the University of Hawaii at Manoa campus. First, the creation of a functional microgrid for the UH Manoa campus will create technology, data, and workforce training essential for the development of similar microgrids for other educational, government, and military "campuses" across the Hawaiian islands. Replication of the approach will yield important insights into the transformation of a single centralized, top-down grid into multiple, decentralized, federated microgrids.

Second, while the mainland US does not yet feel the level of energy pressure faced by Hawaii, we believe these pressures will rise across the country in coming years as the price of oil rises or if a commitment to sustainable energy pathways is made. We believe the science and engineering produced by this research will provide significant aid to microgrid development outside Hawaii, and thus provide a important building block in service of the Department of Energy's goal of a nationwide Smart Grid.

1.1.2 Integration

This project is designed to explore the challenges and opportunities of microgrid development from multiple perspectives and multiple disciplines.

From a scientific perspective, our sustainable energy pathway will produce opportunities for the development of new analytic methods. As further discussed in Section **??**, this research is expected to result in the development of new analytic methods based upon belief propogation networks and Markov models. It will also support the development of controlled and semi-controlled experiments to understand both the physical issues underlying a semi-autonomous, self-regulating microgrid (as discussed in Section **??**), as well as the social issues (as discussed in Section **??**).

From an engineering perspective, the challenges and opportunities are obvious and manifest. The microgrid requires the specification, acquisition, and/or fabrication of hardware and software components for sensing and regulation of electrical and environmental data. These components must be integrated into the current electrical and physical infrastructure of the University of Hawaii campus in a manner compliant with all state and federal regulations. Finally, the microgrid must interact with the centralized grid provided by the utility, both accepting control signals from that grid as well as providing status information back to the utility.

The scientific and engineering challenges will not be faced in isolation but form a natural, complementary, and synergistic pair of viewpoints. For example, the development of analytic methods will be guided by the control and optimization goals. Conversely, resolution of engineering challenges such as the optimal placement of sensors will be guided by controlled experimental procedures that are intended to produce methods for sensor placement useful outside of the University of Hawaii context.

1.1.3 Collaboration (Management Plan)

Section 1.1.2 must summarize how we will approach the research from an interdisciplinary perspective that integrates science and engineering with a synergistic, systems approach.

Section 1.1.3 must discuss the roles, qualifications, and synergy of the multi-disciplinary team, the leadership structure, and the integration of the proposed activities among team members. International or industrial collaborations can strengthen the proposal.

	Inside microgrid / UH	**Outside microgrid / UH**
Science / Engineering	Kavcic, Kuh, Johnson, Hafner	Fuji, Fripp
Environment / Policy	Hafner, Meder, Kuh	Mikulina, Meder, Johnson

Figure 1: Team members and focal areas

This team consists of four principal investigators (Professors Aleksandar Kavcic, Philip Johnson, Anthony Kuh, and Matthias Fripp from the University of Hawaii) along with four collaborators (Dora Nakafuji, Hawaiian Electric Company; David Hafner and Stephen Meder, Associate Vice Chancellors for the University of Hawaii; and Jeff Mikulina, Blue Planet Foundation). Each of the four collaborators have supplied a letter indicating their support for the project and interest in participation.

Team members were carefully chosen to provide a broad, interdisciplinary, and complementary set of skills. Professors Kuh, Kavcic, and Fripp are from the Department of Electrical Engineering and have expertise in sensing, modeling, and power systems. Professor Johnson is from the Department of Information and Computer Sciences and has expertise in software engineering and consumer-facing interfaces to the Smart Grid. Dr. Dora Nakafuji is Director of Renewable Energy at Hawaiian Electric Company and has expertise in utility-side systems. David Hafner is an Assistant Vice Chancellor and head of Facilities Management at the University of Hawaii and has expertise in UH power systems and requirements. Stephen Meder is also an Assistant Vice Chancellor and head of sustainability initiatives at the University of Hawaii. Finally, Jeff Mikulina is the Executive Director of Blue Planet Foundation, a Hawaii-based environmental advocacy group which has played a major role in renewable energy policy development in Hawaii.

For a summary of the basic roles and responsibilities of these team members, it is useful to think of the project as consisting of two dimensions. The first dimension, domain of inquiry, comprises two basic areas: science/engineering and social/environmental/policy. The second dimension, domain of application, also has two basic areas: internal to the proposed microgrid (i.e. the University of Hawaii campus) and external to the proposed microgrid (i.e. the surrounding environment).

Figure 1 illustrates these two dimensions and the focal points for the team members in a simple table. As the table shows, at least one PI and at least one collaborator is associated with each of the four areas in the table.

The project will be led by Dr. Kuh who will manage the work, ensure coordination among the investigators, and track milestones. The entire team will meet monthly by conference call to discuss research and education progress, with smaller meetings in focus areas occuring more frequently. A yearly summit meeting will provide an opportunity to assess overall progress and adjust milestones if necessary.

At the University of Hawaii, the PIs will hold weekly meetings with graduate students. Typically, a student or faculty member will present their research results which will be critiqued by the whole group. The meetings will ensure that work is collaborative and will give all investigators and students an opportunity to see the different phases of the research project. Dr. Nakafuji recently became an adjunct Professor at the University of Hawaii and will join our meeting at regular intervals.

The PIs will serve as leaders for the five research components. Professor Kuh will lead sensors and monitoring, Professor Kavcic will lead modeling and analysis, Professor Fripp will lead control and optimization, Professor Johnson will lead social, economic, privacy, security, and policy implications, and Professor Kuh will (also) lead education and workforce development.

All PIs will work together on recruiting, retention, and outreach efforts. Special attention will be given to recruiting of underrepresented students with assistance from NHSEMP and SWE.

1.2 Pathway to Smart, Sustainable Microgrids

Our pathway to smart, sustainable microgrids involves the development of a testbed consisting of the UH Manoa campus. This section goes into detail on the five research components introduced above.

1.2.1 Sensing, monitoring, and data gathering

We will consider a complex micro-grid with a high penetration of distributed renewable energy generation. Theoretical studies will be considered along with extensive simulations in conjunction with working on a real test-bed, the University of Hawaii at Manoa (UHM) micro-grid. The UHM micro-grid test-bed will provide validation on simulation and theoretical studies.

Today's modern electrical grid system relies on a vast web of distribution networks (D) and transmission corridors (T) to deliver power to customers. Tremendous control, visibility and communication resources and standards exist to support the "T" portion. The "D" portion has received much less attention and poses one of the weakest links to enabling wide adoption of more distributed resources. The "D" portion tends to be more disperse, less automated and non-standard across the nation. Making matters worse, the utility operators have limited or no visibility to the distributed resources emerging on their systems. The influx of customer-sited PV systems and emerging plug-in-hybrid vehicle technologies deployed at the distribution level have accelerated the need to accurately model impacts of these distributed generation (DG) resources on the electric system. On the UHM micro-grid test-bed this requires design and installation of appropriate sensing equipment to monitor environmental resource data, electrical grid data, and building energy usage. This is closely tied to other aspects of the project including modeling and analysis, optimization and control, and the economic and social implications.

This research considers both theoretical and practical aspects of gathering data from sensor and monitors. Multiple data types will be gathered requiring construction of sensor networks and data fusion from the multiple sensor networks. A key is to deploy enough monitors and sensors so that important information can be gathered and processed. Information that is needed are events that can will impact the operation of the grid. This includes detecting ramps that occur with solar energy due to changing weather conditions (from cloudy to sunny or vice versa) and faults that can occur on the electrical grid. With sufficient sensor networks deployed intelligent control and optimization strategies can be made to reduce energy usage in buildings subject to economic considerations and energy requirements made on labs, classrooms, and offices in the building. In this subsection we discuss the data types, data collection, building sensor networks, and gathering information from the data (sensor fusion, compression, and data mining).

Data types. To accurately model and analyze the micro-grid along with designing optimization and control strategies for the grid several sets of data need to be monitored. We also need to consider measuring data both spatially and temporally. The data that we consider in this proposal are environmental resource data, electrical grid data, building energy usage, and data gathered from users of energy on the micro-grid. This data will be gathered from our test-bed, the UHM micro-grid.

Environmental resource data is monitored so that we can better forecast the energy generation of distributed renewable energy sources such as solar PV panels. Here we build and deploy sensor boxes that measure solar irradiation, wind speed and direction, temperature, and humidity. These sensors and monitors will be placed on rooftops of UHM buildings with key considerations being how fast we sample data, how many sensors do we deploy, and where do we place sensors.

Electrical grid data will also be gathered from existing utility meters. Additional meters will be placed at key locations on buses and electrical lines. Currents, voltages, complex power, and energy usage will be measured. Again key considerations are how fast we sample data, where to deploy meters, and what sensors and monitors do we use that are already deployed on the grid.

We would like to get better information about load data and this can be done by deploying sensors and monitors in buildings. Here we can monitor energy usage by deploying sensors to measure energy usage in rooms from air conditioning, electrical equipment, and lighting. *(Philip, perhaps you can help here, WattDepot).*

Data is gathered from different sources to understand how energy is generated and consumed on the micro-grid. This requires understanding user behavior. Recently, an energy dorm competition was held, the Kukui cup where the goal was for student in the dorm to use knowledge about energy consumption to reduce energy usage. Numerous survey results were conducted to understand student behavior as it related to energy consumption. This will continue with our proposal. (Philip, perhaps you can add here too).

Data collection. There are several issues to be considered when getting data from sensors, monitors, and meters. How much information is to be gathered, how do we collect this data, and how do we organize this data. The first issue is discussed here with the other two issues discussed in subsequent subsections.

Where do we place the sensors? There has been substantial research on the sensor placement problem from researchers studying sensor networks with applications for environmental monitoring [DCI02, DC03], monitoring the electrical grid with PMUs [JA06, XA04], and biomedical monitoring. Tools from signal processing, statistics, and machine learning are used. The problem is often framed as an optimization problem of minimizing some error criterion or maximizing some information criterion. Once space has been discretized it can be formulated as placing m sensors among $n > m$ possible locations. Optimal algorithms are computationally infeasible for large m and n, but greedy algorithms that run in polynomial time of m and n often give good approximations to optimal algorithms [LNI11, KSG08]. Some key aspects of the optimization include properties of submodularity and monotonicity [NWF78]. We study these algorithms as it applies to our algorithm for both static and dynamic cases. A state space model can be used to model the dynamics of different parameters with a linear state space model given by

$$x(k+1) = Ax(k) + Bu(k)$$

$$y(k) = C(x(k) + v(k))$$

where $x(k)$ is the state of the system (e.g. on the electrical grid, current phasor at n different nodes). A goal is to determine the best C matrix which is a binary 0/1 matrix with at most one 1 in any column and exactly one 1 in every row.

We must also determine how often to sample data. The sensor placement problem and sampling problem depend on the information we need to control and optimize the micro-grid. This depends on the modeling and analysis of the micro-grid and also what events we are trying to detect. Other factors that come into play are the economics associated with placing sensors, monitors, and meters. A goal is to place and sample sensors so that they give the most useful information. With limited resources we would consider placing sensors on the grid and to monitor the environment along an electrical line where there is significant renewable generation and hence intermittent generation. This will give us a better understanding of effects of renewable energy generation, how we can model this, and designing control and optimization algorithms that can mitigate intermittency subject to available resources; batteries and demand response.

Sensor network Implementation. We will create two sensor networks at the micro-grid level. One sensor network will consist of environmental resource data collected from student built self powered energy boxes that measure solar irradiance, wind speed and direction, temperature, and humidity. There will also be other environmental sensors such as solar resource locational monitors (e.g. LM2 monitors). A goal is to monitor environmental resource data both spatially and temporally on the UHM campus. Most of these sensors will be placed on top of UHM buildings. This will aid in understanding energy produced by distributed PV

sources placed around the campus. Wireless networks will be used to gather this data to a central server and storage system.

A second sensor network will monitor the electrical grid. This will consist of sampling existing HECO utility meters and deploying demand side load monitors (e.g. AMI and PMI type devices) and PMI field device data concentrators. These sensors will be connected together via a wireless network and again sent to a central server and storage system.

(Also need a discussion of building sensor networks: Philip)

Information gathering. We have a Smart Energy Laboratory in 493 Holmes to collect the data from different sensor networks. This will be stored in a data server and storage system. Data will be gathered from sensor networks monitoring environmental resource data, electrical grid data, and sensor netqworks in buildings monitoring energy usage. This data will be time stamped. In addition there will be data collected from students, staff, and faculty on campus about their energy usage. A goal in the data collection is to perform sensor fusion so that information can be obtained to assist in detecting key events that happen on the micro-grid (e.g ramps in energy produced by distributed solar PV and faults that occur on the electrical grid).

Tools are needed to organize and fuse the raw data from sensor networks. This includes using filtering, sensor fusion, source coding, compressed sensing, and machine learning to process the data to extract useful information from the data. Once this is done models can be created of the micro-grid to analyze and simulate the behavior of the grid. Then control and optimization algorithms can be tested on simulation networks to deal with events such as ramping and faults. Software packages such as Powerworld, matlab, and PScad will be used along with visualization tools such as TREX designed by Referentia.

1.2.2 Modeling and analysis

Given appropriate data, the next step is to apply analytic techniques to create real-time and historical information useful for control and optimization of the microgrid.

Two important contributions of this part of the research will be: (1) analytic techniques that enable us to adequately characterize the current state of the microgrid without a cost-prohibitive deployment of sensing equipment, and (2) analytic techniques that enable short-term prediction of various useful attributes of the micro-grid (such as future (potentially peak) load and ramp) and the surrounding environment (insolation, wind speed and direction, etc.)

It should be noted that there is an interdependence between the "sensing and monitoring" subproject and the "modeling and analysis" subproject: we will "tune" the installation of sensing equipment in order to obtain acceptable quality of analytic outcomes for the next step, control and optimization. Furthermore, the chosen models and analytical tools cannot only be good descriptors of the underlying physical processes, but also need to be matched to the signal processing (detection and estimation) methods, or else the signal processing methods will not be of much use.

Belief Propagation. Through or previously funded NSF project (ECCS-1029081), we have already established that the factor-graph approach is well-suited to modeling the electrical connections of a microgrid. Figure 2 shows a schematic view of a factor-graph associated with a fictitious microgrid. The nodes in the mocrogrid are divided into three layers: 1) the observation layer (sensors, measurement equipment), 2) the behavior layer (collection of network nodes, loads and microgenerators) and 3) the communication layer. We demonstrated that, with only a few well placed sensors in the grid, we are able to track slowly evolving behaviors of the grid as well as with more elaborate exact maximum-likelihood estimators [HKKN10, HKKY11, HKKN11]. This is mainly because the electrical grid is typically a *tree* graph, where correlations among renewable sources create rare loops with large diameters.
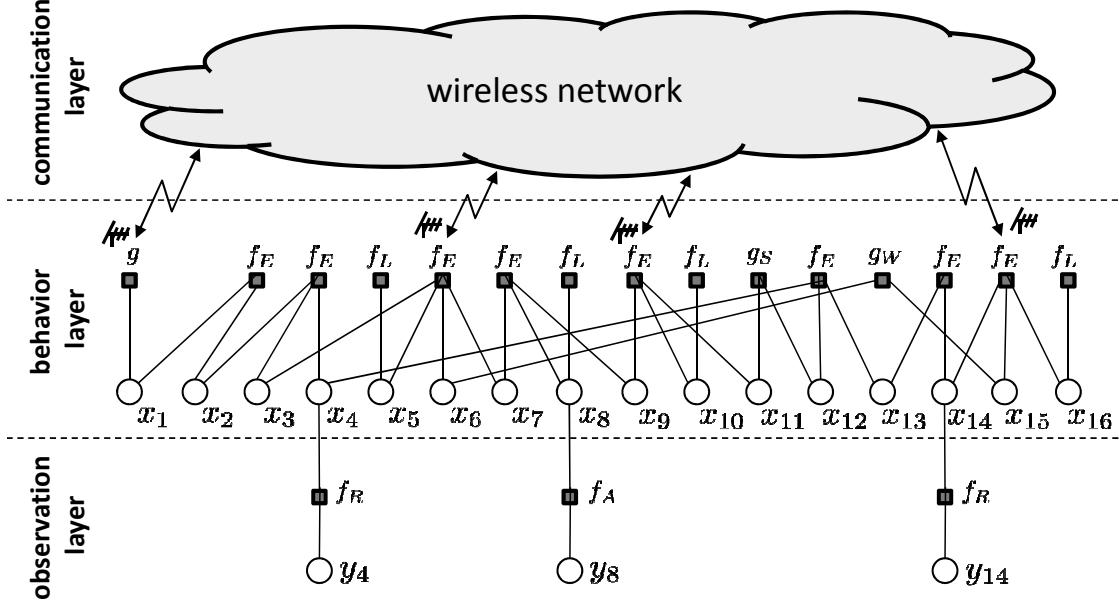
Figure 2: Factor graph - an abstraction of the microgrid. The factor graph consists of the behavior layer and the observation layer. The communication layer provides additional global communication features. In this figure, the state variables are denoted by x_i and available observations (sparse measurements) are denoted by y_i. The belief-propagation algorithm is a monitoring algorithm that works by passing only *local* messages along the solid edges of the graph, yet achieves *global* monitoring.

In this research, we plan to use belief propagation as a tool that would also enable 1) tracking the grid in transitional modes (e.g., if a large number of users and/or renewable microgenerators enter and/or drop from the microgrid abruptly) and 2) short-term future prediction of the grid behavior at node-levels. To this end, we will develop the necessary modeling and prediction tools.

Modeling demand. Often, the demand in grid networks is described using historical *histograms*. However, historical histogram patterns do not reveal the true spatiotemporal character of the demand. It is obvious that spatial and temporal correlations will need to be exploited in order to arrive at a model that would be useful for spatiotemporal demand prediction, i.e., prediction that can predict the demand, say, 5 minutes in advance at any given set of spatial location locations in the microgrid. Furthermore, in order to utilize the belief-propagation tool, we will seek to model the demand among various nodes in the microgrid as a spatiotemporal Markov process with as few loops as possible (because it is the loops that adversely affect belief propagation [WLK95, KFL01, LDH$^+$07]). We note that simple Gauss-Markov process modeling will likely not suffice because Gaussian processes are well-suited only for tracking slow changes. Yet, demand in campus environment can be spatially and temporally bursty (because of correlation to class-times tarts, lab-clusters, weather/heat conditions and distributed renewable microgenerators). For this reason, we plan leverage our experience in modeling Gauss-Markov processes [KM00] and finite-state machines [YKT05, VKAL08] to develop a comprehensive double-layer Gauss-Markov/finite-state spatiotemporal demand model. We will extrapolate, calibrate and test the model using measurement data from sensors distributed around the campus.

Modeling renewable sources. Much like the loads (demand) are spatially and temporally distributed, so are the renewable micro-generators. The UH campus already has several clusters of photovoltaic (PV) generators and two small wind turbines (typically used for experimental purposes) dispersed around campus. Therefore, we will need to model their energy outputs using spatiotemporal Markov processes (with as few loops as possible) that are capable of modeling both slowly varying effects as well as (spatially and temporally) localized bursts. Again, we will utilize a layered Gauss-Markov/finite-state modeling approach to capture both effects. However, unlike modeling demand, here we will need to heavily correlate the model to weather conditions (night/day, cloud-cover, wind speed and direction). We will extrapolate, calibrate and test the model using weather measurement data from irradiance sensors, wind velocity sensors and cloud cameras distributed around the campus.

Prediction. It is a well-known fact that the Kalman predictor is the optimal predictor of spatial and temporal Gaussian processes [Kal60, KB61, Kai68]. When the Gaussian process further possesses a Markov structure (i.e., a Gauss-Markov process), the Kalman predictor is computationally less intensive [KFL01, LDH$^+$07]. In our case, we will likely have a two-layer spatial and temporal Gauss-Markov/finite-state process to track. The optimal tracker of this process would be a spatiotemporal combination of a Kalman predictor [Kal60, KB61] and a forward recursion of the Baum-Welch algorithm [BP66, BCJR74]. However, this approach will likely be too computationally intensive to be practical. Therefore, we will ignore the loops in the model, and implement the predictor using belief propagation derived for a tree-like double-layer (Gauss-Markov/finite-state) graph, but applied to the exact loopy microgrid graph.

We envision that the developed prediction tool will be used to indicate where and how the control mechanisms (e.g., peak-shaving, gray-outs, etc.) should be applied. However, we must consider the sensitivity of certain locations when applying control. For example, it would be detrimental to shut off the air conditioner in a sensitive climate controlled laboratory, or in computer server clusters that must remain cool. For this reason, it is desirable to have a prediction method that will account for these sensitivities. It is well-known that any prediction method suffers form uncertainly, misdetection and false alarms. Grossly false estimation or prediction of the state of certain sensitive nodes may adversely affect the stability of the network or sensitive campus locations. This can be minimized in two possible ways. Firstly, we may choose to place sensors in the vicinities of highly sensitive nodes, and thus minimize the risk of misprediction. Secondly, we may choose to dampen the belief-propagation algorithm to prevent wild belief swings in the vicinities of highly sensitive nodes. This amounts to placing weights (or other types of constraints) on beliefs corresponding to highly sensitive nodes. We shall term this approach *sensitivity weighted* belief-propagation. To our knowledge, no such approach has been attempted in smart-grid networks, although similar strategies are available in the communications and error-control coding literature [WP99, JN06, VFK07].

Analysis. The final piece of the modeling and analysis effort is the actual analysis of the proposed models and tracking methods. In tracking mode, we will utilize statistical signal processing techniques to analyze the performance of the trackers. For example, under under stationarity conditions, we can easily bound the performance of maximum-likelihood estimators of Gausian processes. We will extend these techniques, and combine them with bounding techniques typical for finite-state processes [HKMM09], to develop bounds for tracking the layered Gauss-Markov/finite-state process in under certain stationarity assumptions.

Under extremely non-stationary conditions, however, it will be extremely difficult to come up with analytical tools that will be able to bound the performance of the estimator/tracker. Indeed, in the signal processing literature, response to extreme non-stationarities are typically demonstrated by simulations [Yan95, Tan05]. For this reason, it is actually very important to design a good model that will not only be useful for designing the detector, but also for designing the simulator. The usefulness of this approach will be extremely important when determining the response to *rare events*. Rare events are events that are rarely (or

never observed) in practice until they happen in reality (e.g., black-outs, shut-downs, catastrophic failures). The only way to understand how such events would affect the system is through simulations. We will conduct analysis studies of these rare, extremely non-stationary events through the means of simulations using the developed process models.

1.2.3   Control and optimization

The primary goals of a smart, sustainable microgrid are to use electrical energy as efficiently as possible, maximize the amount of energy coming from renewable resources, and minimize the overall cost of energy while retaining acceptable levels of reliability and quality. The optimization and control module of this project will study how well these goals can be met by scheduling electricity production and consumption using data and forecasts from the modeling and analysis module.

Some of the important capabilities of the microgrid control system will include: peak shaving/shifting, ramp-rate management, lowered overall consumption and voltage and frequency regulation (*** drop the last two, since we don't discuss them further? ***). The initial approach will focus on cooling loads, which make up most of (*** are the largest component of? ***) UHM's electricity demand. Later in the project we will develop optimal control strategies for other time-shiftable loads, such as water heating, energy-intensive scientific research, and eventually electric vehicles. The control effort will also manage UHM's many individual backup generators as a coordinated asset, making them available for peak shaving and ramp rate management. All these efforts will improve the demand profile presented to the electric utility and reduce the campus's electricity bills.

This research will study power control techniques at several levels of user interaction, from direct automation through voluntary user responses to campus alerts. Direct automation will be used for systems that run in the background with no direct effect on users. For example, electricity demand for chillers and water heaters can be deferred several minutes or hours by adjusting their temperature setpoints slightly. However, chillers can defer electricity consumption even longer if users participate by raising the setpoint of in-building thermostats or by accepting automatic adjustments to these thermostats. Some other loads may best be managed by community awareness techniques that show microgrid participants how to help achieve cost savings and more efficient usage of renewable resources, e.g., by reducing lighting or deferring energy-intensive batch processes during critical power periods. The user-facing elements of this project will build on knowledge gained in the campus's successful Kukui Cup competition to reduce student energy use, (*** as well as collaboration with smart metering researchers in Oxford University's Lower Carbon Futures group?***). We will also conduct new research on effective design of user interfaces for shared management of the microgrid.

In addition to developing the software and hardware systems required for control and optimization, we will measure the effectiveness of these control strategies in a real world setting. This will serve two purposes: First, it will provide valuable information on the magnitude and duration of energy time-shifting (real or virtual storage) available from a wide variety of building energy systems, as well as estimates of how this capability changes over time as user interest increases or decreases. Second, this information will be used to fine-tune the optimization and control algorithms, to more precisely achieve the desired level of load control.

The microgrid optimization system will use a multi-period stochastic linear optimization model to choose how to control loads and backup generators in order to minimize the total cost of providing power to the campus. The objective function of this model will use a broad definition of the total cost of power, including the time-varying cost of electricity, utility charges based on the peak load and ramp-rate for the year, the cost of operating backup generators as peak- or ramp-shaving units, and the "costs" of load control itself – inconveniencing users or depleting their interest in future load control measures. During each optimization cycle, the model will consider several alternative scenarios, each defined by specific values for

future loads, renewable power production and electricity costs, over periods ranging from the next few minutes to the next 24 hours, as well as forecasts of the year's peak load and ramps. Scenarios will be generated that cover the forecasted values for each of these future parameters, as well as the uncertainty range of these forecasts. The optimizer will choose a control strategy that minimizes the expected cost of power over all these scenarios.

We will also explore tradeoffs between efficiency and peak-management when many pieces of equipment are operated at part load. For example, UHM's smart grid and smart chiller water distribution system will allow the campus to run many generators or chillers at once, giving a strong peak-shaving or ramp-shaving capability. However, running many chillers or generators at once could increase total power consumption, since these machines are less efficient when they are run at part load.

1.2.4 Social, economic, privacy, security, and policy implications

As discussed in the introduction to this proposal, one of the key properties of a smart grid according to the Department of Energy is to "enable active participation by consumers". We believe that this is especially important for a microgrid, and that it would be naive to assume that a smart, sustainable microgrid could be implemented transparently and invisibly to its users. Many people are used to virtually unlimited, low-cost, and reliable electrical energy produced in an unsustainable, environmentally harmful manner and do not yet understand why this cannot continue.

Thus, an important part of this project is to develop information that can not only be used to control the grid, but also be used to inform the inhabitants of the microgrid about its current state in a useful, actionable form. We believe this is important not only to obtain support from consumers for the costs and complexity associated with development of a smart, sustainable microgrid, but also to enable them to become active participants in management of the grid. By actively participating, efficiencies not possible with chiller management alone can be realized. In addition, it will create the data necessary for broader policy decisions by local government that can make future smart, sustainable microgrids easier to develop and deploy.

Privacy and security issues. Enabling active participation by consumers is made difficult by the fact that the collection, analysis, and usage of power and environmental data within a micro-grid creates significant new security and privacy considerations. The canonical security concern is the possibility of unauthorized agents infiltrating the microgrid network and becoming capable of injecting control signals into the microgrid leading to power and/or equipment failure. The canonical privacy concern is the possibility of unauthorized agents infiltrating the microgrid network and using its data to gain insight into the behaviors of campus members and organizations, enabling them to better plan and execute robberies or other illegal activities.

Smart grid security and privacy issues can be organized into categories corresponding to primary grid componets: the PCS system, smart meters, power system state estimation, smart grid communication protocol, and smart grid simulation for security analysis.

The most common PCS system is SCADA. Traditional PCS systems were designed with no outside network connection, so they did not typically have any security built in. Adding security to PCS systems is complicated due to their real-time, low latency (sub-second), and high availability requirements [VC09].

Smart meters provide fine-grained, near-real time information about power use within a building or other component of the campus. Security issues include tampering with the smart meter readings to effectively "steal" power. Privacy issues include using the fine-grained data to infer the behaviors of occupants. Berthier, Sanders, and Khurana have proposed a comprehensive set of security tools for smart meters [BSK10].

Maintaining the integrity of the grid requires power system state estimation, and yields a security risk of attackers injecting false data into the model to create system instability or for financial gain [XMS10].

Allocating the processing overhead necessary to distinguish false from real data is problematic due to the high-availability and low-latency (sub-second) requirements for this component. Some research has been done on how many compromised sources are required to carry out an unobservable attack [KJTT10].

Network communication and their associated protocols is the backbone of the smart grid, and the security and privacy issues are diverse and dependent upon the nature of the protocols and the types of information that are being communicated. A particularly difficult issue is the need to interface with legacy systems which were not designed with support for security. Khurana et. al. have proposed a set of design guidelines for smart grid protocols to reduce the number of vulnerabilities [KBY+10].

Finally, smart grids cannot be taken down for testing, and so simulation systems are used for testing instead. While traditional grid simulation systems are focused on availability and stability concerns, smart grids will require these systems to support security and privacy assessment as well. Kundar et al have begun work on a framework that provides initial progress toward smart grid security analysis through simulation [KFL+10].

A contribution of this research project will be the evaluation of these techniques in the context of microgrid design and implementation and insights into enhanced privacy and security based upon our experiences.

Social and policy issues. To investigate social and policy issues, we plan to build upon the Kukui Cup project experiences at the University of Hawaii. The Kukui Cup is an advanced energy challenge that involves real-time feedback, incentives, education, and game mechanics to investigate how to obtain sustained, positive changes in energy behaviors. [Bre11, BLX+11].

More to come.

Economic issues. The final area of investigation for this research component is the economic implications of the microgrid. Our principal focus in this area will be to determine how effectively the microgrid can serve to decrease the overall cost of energy supplied by the local utility. Currently, the University electrical rates for a given month are primarily a function of two variables: the peak demand by the University during that month, and the peak rate of increase in demand (ramp) during the month [Haf11].

If the microgrid design is effective, then we should be able to lower peak demand in the following ways: (1) by integrating solar generation (which reduces demand from the utility); (2) though automated demand response (which, when combined with adequate prediction, should enable the system to shut down chillers in advance of periods of high load, reducing peak requirements), and (3) through customer-facing user interfaces, which could inform campus members of periods of high loads and enable those with discretionary power loads to shift them in time to periods of lighter overall demand.

We will also be able to evaluate the ability of our prediction algorithms to reduce the rate of increase in demand.

By the conclusion of the project, we will be able to produce comprehensive cost-benefit analyses of the investment required to create the sustainable, smart microgrid and the economic benefits that accrued from its implementation and use. We will provide an accounting for the savings from generation, automated demand-response, and user behavioral change.

1.2.5 Education and workforce development

The Hawaii Clean Energy Initiative (HECI) is a Memorandum of Understanding (MOU) between the state of Hawaii and the Department of Energy signed in 2008 that set goals for Hawaii so that by 2030 70% of our energy will come from clean energy sources (30% from energy efficiency and 40% from renewable energy sources). Through the Renewable Energy and Island Sustainability (REIS) goup we have developed curriculum and courses in energy and sustainability to help train this workforce that will be needed to

achieve these goals. Much as HCEI will rely more on local energy sources the REIS group is working to have Hawaii more reliant on locally trained experts in energy and sustainability.

This proposal will work on further development of courses in the smart grid and renewable energy areas with a focus on systems, software, and policy issues. We will create graduate level courses in the smart grid area and also help develop courses on energy in social sciences. In addition we are working through local funding agencies to develop a short twenty hour course on smart grids and integration of renewable sources that will be available to UHM students and faculty and also the external community. This course will be broken up into five four hour segments: grid overview, policies and standards, tools and capabilities, communications and networking and security, and integration of sources.

A major component of education and training is conducting research while using the Smart Campus Energy Lab (SCEL) and working on the UHM micro-grid test-bed. Both graduate and undergraduate students will be working on research projects in conjunction with HECO engineers and UHM facility people. There will be a close integration between the different research areas and also between education in the classroom where concepts are learned, analysis where models, algorithms, optimization, and control methods are formulated, software and hardware simulation studies, and test-beds where analysis and simulations are confirmed.

Integration of members of under-represented minorities   This project will collaborate with the Native Hawaiian Science and Engineering Mentorship Program (NHSEMP) to broaden the participation of under-represented groups. NHSEMP is a successful program housed at the University of Hawaii funded (in part) by the National Science Foundation Louis Stokes Alliance for Minority Participation Program and the U.S. Department of Education Native Hawaiian Education Program. The program is already very successful in attracting members of the Pacific Islander minority into the undergraduate engineering program. Our next goal is to achieve a smooth transition of the most talented minority students into the best graduate programs nationwide. For example, we are already implementing an REU exchange program with our collaborators (at MIT) in conjunction with a joint project between MIT and University of Hawaii [NSF Grants ECCS-0725555 and ECCS-0725649]. Throughout 2008 and 2009, MIT hosted Hawaiian minority undergraduates from Professor Kavcic's group. Their video-documented experiences can be viewed at **http://www2.hawaii.edu/˜thanhvu/Videos.html**. We are also presently in the process of selecting qualified minority undergraduates to send to Pittsburgh, PA to participate in our joint project with Carnegie Mellon University [NSF Grants ECCS- ECCS-1029081]. We will continue to draw representatives of underrepresented into our research program in conjunction with this project. UH minority undergraduates will spend their semesters working as researchers with at University of Hawaii and their summer/winter breaks as interns/researchers at HECO or visiting our research partners on the mainland.

1.3   Project plan

Figure 3 illustrates the project timeline, organized by the five research components. The four years of this project are broken down into four phases: a six month "ramp up" phase at the start of the project, followed by two eighteen month phases in which we iteratively develop and evaluate the microgrid, followed by a six month "ramp down" phase in which we focus on documentation, evaluation, and other activities necessary to allow maximal external use of the knowledge and skills gained during this project.

The goal of the initial six month ramp up phase is to complete all of the startup activities necessary to ensure a successful Phase I implementation of the microgrid. For all research components, this involves hiring of personnel and initial meetings to review literature and become familiar with relevant issues and technologies. For the sensing and monitoring component, the ramp up period also involves the development of a simple server based upon historical data that can provide simulated data about building loads, environmental data, and grid state. This simulated data will be relatively imprecise given the short time available

Research Components & Tasks	2012-Q3,Q4	2013-Q1,Q2	2013-Q3,Q4	2014-Q1,Q2	2014-Q3,Q4	2015-Q1,Q2	2015-Q3,Q4	2016-Q1,Q2
Sensing and monitoring								
Ramp up: Simulator development	X							
Phase I: Env, Building, Grid sensors		X	X	X				
Phase I: Data storage & Network Dev.		X						
Phase II: Env, Building, Grid sensors					X	X	X	
Phase II: Data storage & Network Dev.					X			
Ramp down: final eval and documentation								X
Modeling and analysis								
Ramp up: Belief Propogation Simulator	X							
Phase I: Demand & Renewables models		X	X					
Phase I: Prediction algorithms		X						
Phase II: Demand & Renewables model					X	X		
Phase II: Prediction algorithms					X			
Ramp down: analysis theory								X
Control and Optimization								
Ramp up: Identify and group loads	X							
Phase I: control unit installation		X	X	X				
Phase I: optimization software V1		X						
Phase II: control unit installation					X	X	X	
Phase II: optimization software V2					X			
Ramp down: documentation								X
Social, Economic, Privacy, Security, Policy								
Ramp up: baseline data	X							
Phase I: Consumer UI development		X	X	X				
Phase I: Consumer UI evaluation		X						
Phase I: Consumer UI development					X	X	X	
Phase I: Consumer UI evaluation					X			
Ramp down: final evaluation								X
Education & Workforce Development								
Ramp up: curriculum design	X							
Phase I: courses and workshops		X	X	X				
Phase I: curriculum evaluation		X						
Phase II: courses and workshops					X	X	X	
Phase II: curriculum evaluation					X			
Ramp down: final evaluation								X

Figure 3: Work breakdown structure.

for implementation, but its goal is to simply enable other research components to make progress prior to complete installation of sensors. The modeling and analysis component will also create a simulator during the ramp up phase, in this case for a belief propogation network appropriate to the microgrid. The control and optimization component will research historical loads and assess control unit types and applicability. The social, economic, privacy, security, and policy (SEPSP) research component will obtain baseline data regarding energy use, attitudes, and concerns among the university stakeholders. Finally, the education and workforce development research component will work on curriculum during the ramp up phase.

After ramp up, the project begins two eighteen month cycles of microgrid design, implementation, and evaluation. We designed the project so that by the end of year two of this four year project, we will have created a functional microgrid, though not complete or optimal. By the end of Phase I, the sensors and monitoring research component will have installed an initial set of environmental, grid, and building sensors and this data will be provided for use in modeling, analysis, control, and optimization. Based upon Phase I experiences, the sensors and monitoring research component will install additional sensors or modify existing ones to improve the quality of grid performance in Phase II.

A similar iterative approach is employed in the other research components. During Phase I, the modeling and analysis research component will create models of both energy demand and renewable resource production and build an initial predication algorithm using the data provided by Phase I sensors and monitoring. The strengths and weaknesses of these initial models and the data they are based upon will be evaluated at

the end of Phase I and used to construct more robust and performant models and prediction algorithms in Phase II. Similarly, the control and optimization research component will implement initial control mechanisms during Phase I, and the results will be used to generate Phase II requirements for the modeling and analysis and sensors and monitoring research components.

The SEPSP research component during Phase I and II is similarly iterative, but here the focus is on creating and evaluating user interfaces that result in active participation by campus members in the management of the grid. Finally, the education and workforce development components will focus during Phase I on more general curriculum while the micro grid is still under initial construction. During Phase II, the curriculum can be refocused to incorporate "live" analysis of the running microgrid and its operational state.

The project plan provides for a six month "ramp down" period at the conclusion of the four years. The goal during this period is to ensure that we have create curriculum, publications, software, hardware, and documentation of maximal utility to others wishing to engage in microgrid development either in Hawaii or on the mainland. In addition, the final six months serves as a "buffer" period in the event that Phase I or Phase II takes longer than expected.

1.4   Results from prior NSF research

The PIs for this project have had the following NSF-supported projects during the past five years:

1. P. Johnson, *Human centered information integration for the Smart Grid*, NSF Grant IIS-1017126, 8/15/10 - 8/14/13, $381,467. The objective of this research is to design information technology and associated experimental methods to help understand what information, provided in what ways and at what times, enables consumers to make positive, sustained changes to their energy consumption behaviors. Selected publications include [BJ10, BLJ11, BLX$^+$11, Bre11, LXBJ12].

2. P. Johnson, *Supporting development of highly dependable software through continuous, automated, in-process, and individualized software measurement validation*, NSF Grant CCF02-34568, 9/01/02 - 8/31/07, $638,000. The objective of this research was to design, implement, and validate software measures within a development infrastructure that supports the development of highly dependable software systems. Selected publications for this project include [JP05, Pau04, JKP$^+$05, JKA$^+$04, JKA$^+$03, Joh03, KJ04, FJG$^+$04, JKP$^+$05, BZS$^+$07, HNB$^+$06, JK07, Joh07, KJE09].

3. A. Kavcic, *Energy-Efficient Communication with Optimized ECC Decoders: Connecting Algorithms and Implementations*, NSF Grant ECCS-0725649, 09/01/07 - 08/31/10, $120,000. This was a joint project with MIT. The PI was responsible for reshaping Reed-Solomon soft decoding algorithms for VLSI implementation. Selected publications for this project include [BK10, BKMP10, LKF08, LFK08, LKF10b, LKF10a].

4. A. Kavcic *Channels with Memory – Universal-Compression-Based Modeling Principles for Computing and Optimizing Information Rates* NSF Grant CCF-1018984, 08/01/10 - 07/31/13, $462,000. The aim of the project is to utilize compression-based modeling principles to compute information rates of long-memory channels whose memory is so long that conventional channel modeling principles fail. The following publications are available to date [LK11, YPK11a, HKM11, LK12, YKP11, YPK11b].

5. A. Kavcic *Collaborative Research: Factor-Graph Approach to Monitoring and Failure Assessment in Smart-Grid Networks* NSF Grant ECCS-1029081, 10/01/10 - 09/30/13, $225,000. This is a joint project between the University of Hawaii and Carnegie Mellon University. University of Hawaii is responsible for developing the factor-graph framework for belief propagation monitoring, while Carnegie Mellon is responsible for devising micro-grid control algorithms. Publications to date include [HKKN10, HKKY11, HKKN11].

6. A. Kavcic *Collaborative Research: Cross-Layer and Unified Signal Processing System Design for Ultra-High-Capacity Next-Generation Magnetic Storage* NSF Grant ECCS-1128705, 09/01/11 - 08/31/14, $165,000. The aim of the project is to formulate a unified signal processing and coding framework that will integrate the magnetic and solid state memories into a single device. The project started only very recently and there are no results to report to date.

7. A. Kuh, *Incremental and Distributed Learning in Nonstationary Environments with Applications to Wind Forecasting*, NSF Grant ECCS-098344, 9/01/09 - 8/31/11, $150,251. The objective of this research is to design novel nonlinear kernel online and distributed learning algorithms for applications including wind forecasting. Selected publications for this project include [KMCK10, KK10].

8. A. Kuh, *US-Japan Joint Seminar Information Theory*, NSF Grant 0508025 $35,750. Funds used to support graduate students for conferences and for visit to Japan.

Professors Johnson, Kavcic, and Kuh also had NSF support dating back more than 5 years.

1.5 Conclusions

Summarize the expected contributions of the proposed research and how we meet the requirements of this solicitation.

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