1 Vision Statement

Development of the "Smart Grid", a modernized power infrastructure, is a key sustainability challenge facing the United States. According to the Department of Energy, 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 [40].

The very first goal, enable active participation by consumers, involves a fundamental paradigm shift. Electrical utilities traditionally focus on achieving the opposite goal: enabling *passive* consumers whose participation to plugging in appliances and paying a monthly bill. The historical success of utilities at reliably providing high quality power at low cost has led to multiple generations of consumers who know almost nothing about how their homes and workplaces are powered.

Initial efforts to enable active participation have focused on providing consumers with energy consumption data, and have achieved only limited success with respect to participation, savings, and long-term adoption [15, 20, 22]. Feedback on consumption can facilitate one-time positive behaviors, such as installing new insulation or purchasing energy efficient appliances. While helpful, such behaviors do not constitute active participation. Time-of-use pricing is another approach to active participation, but the typical result is installation of controllers and a "set it and forget it" behavior. Unfortunately, feedback on consumption can even facilitate negative behaviors, such as when consumers install grid-tied solar panels and then consume more electricity because it now appears to be "free". In all of these cases, consumer participation is ultimately personal and short-term.

We believe that an exclusive focus on consumption is not sufficient to produce *active participation*—in other words, sustained awareness and engagement at both personal and community levels. In this project, we propose a complementary focus to help overcome the barrier to active participation. In Hawaii, our nation-leading adoption of distributed, intermittent renewables such as rooftop photovoltaics has created the potential for significant negative impact on power quality, with attendant impact on consumer electronics reliability and overall grid stability [42, 35]. Unfortunately, attempts by Hawaii's major electrical utility to address this problem by restricting PV installation have resulted in media and government scrutiny and significant consumer backlash [52, 56, 17, 13, 12]. As rooftop PV is now cheaper than utility-supplied energy in 42 of America's 50 largest cities [32], the issues we face now in Hawaii may soon appear in many other metropolitan areas. For all these reasons, Hawaii is well-suited as a testbed for determining if consumer-oriented power *quality* feedback can lead not only to active participation in the Smart Grid on an individual level but, more importantly, to the social, political, and economic changes necessary for a reliable grid based on clean energy.

To investigate this question, we initiated the Open Power Quality (OPQ) research project [30], which involves the design and implementation of a low-cost, open source hardware device called OPQBox which monitors power quality within a household and sends data via the Internet to our software service called OPQHub. Together, they enable consumers to monitor their own power quality as well as participate in a crowdsourced perspective on power quality across the grid. OPQ produces open data allowing individuals and the community at large to learn: (a) whether a household is experiencing degraded power quality; (b) whether the observed problem is isolated to a single house or more widespread in the grid; (c) whether the problem is intermittent, frequent, unpredictable, or regularly occurring; and (d) whether the problem is severe enough to warrant calls to the utility and/or purchase of residential UPS systems to protect power quality-sensitive appliances such as computers.

At first glance, adding a focus on power quality might seem even less likely to produce active engagement by consumers. For one thing, consumers have a direct economic interest in consumption since it appears on their monthly bill, while power quality does not appear to have a visible cost. For another thing, power quality seems like a low-level technical issue that should be entrusted to the utility to monitor and maintain.

We disagree with both of these assertions. First, consumers do have a direct economic interest in power quality. Over the past 20 years, consumers have significantly increased use of electronics creating non-linear loads (i.e. PV inverters, power supplies, photocopiers, computers, laser printers, battery chargers). Such nonlinear loads reduce power quality by injecting harmonics, which have been shown to reduce appliance efficiency, cause overheating, and increase power and air conditioning cost [42]. Ironically, these electronic devices are simultaneously more sensitive to power quality problems. A study by the National Power Laboratory indicates that the average computer site is subject to almost 100 potentially harmful power quality events per year [16].

Second, utilities rarely have equipment in place to monitor power quality at the household level, nor are there regulatory requirements on utilities to monitor or report power quality. The finest granularity reporting required in the U.S. is called MAIFI, which tracks the number of occurrences of *outages* lasting three to five minutes. Various groups have called MAIFI inadequate to measure the presence and consumer cost of non-outage power quality events related to voltage, frequency, and harmonic distortion [43, 34, 19]. Making matters worse, Moreno-Munoz cites an estimate that more than 30% of the power being drawn from utilities is headed for sensitive equipment, and that this percentage is rising [39].

To summarize: consumers require better power quality than ever before, and at the same time are installing both consumer electronics and distributed generation that can have a negative impact on the performance, cost, reliability, and lifespan of their own electrical appliances. Utilities are not required to monitor and report power quality events, and as we will see in Section 2.1, current utility-scale equipment is too expensive for wide-spread deployment. As a result, active participation by consumers (via power quality monitoring) may not be simply a desirable goal for the Smart Grid, it may in fact be a necessary prerequisite for achieving the other goals of the Smart Grid.

Our project proposes a mixture of "incremental" and "transformational" computational science research and development goals. On the incremental side, our 2014 pilot study [28] demonstrated the basic technical feasibility of our hardware and software. In this project, we will incrementally enhance the capabilities of the computational properties of our hardware and software to provide better reliability, safety, accuracy, and scalability.

Our project also proposes several transformational goals. First, our project explores the challenges involved in transforming power quality from a *technical* issue into a *social* issue. If successful, the approach could be adapted to other sustainability resource challenges (i.e. food, waste, and water) in which crowd-sourced monitoring and data analysis could facilitate new computational approaches to efficiency, conservation, and production.

Second, our hardware and software has the effect of making power quality data available as part of the Internet of Things (IoT) [49]. This has tremendous computational implications, both positive and negative. On the positive side, integration with the IoT allows local, consumer-based response to local power quality problems. As a simple example, detection of poor power quality (or impending poor power quality such as occurs with voltage collapse) within a household could signal power-sensitive IoT devices within the household to disconnect themselves temporarily from the grid. On the negative side, addition of power quality data to the IoT has cybersecurity implications: for example, hackers could potentially exploit public power quality data to induce grid disruption.

Third, our project will produce novel and valuable open source datasets regarding end-user power quality at the community level. When combined with other contemporaneous data (such as grid topography, solar insolation, PV generation sources, and consumption), the project creates a data testbed supporting computational science endeavors involving grid prediction, reliability, and renewable energy integration.

We pursue these goals through the following activities. First, we will manufacture and distribute 150 of our second generation OPQBoxes to volunteer households in three Oahu neighborhoods, producing power quality data to be stored in our public cloud-based OPQHub service over a period of six months. Through pre and post test questionnaires along with analysis of data collected by our devices, we will assess the extent to which crowdsourced power quality data influences household member attitudes toward the electrical utility and public policy regarding the grid, as well as behaviors including: interaction with neighbors regarding power quality; calls to the utility; unplugging of sensitive consumer electronics during periods shown to correlate with power quality events (such as thunderstorms); and installation of residential UPS systems in response to household power quality events. We will compare this data with a control group of households who do not receive the monitoring devices.

Second, we will combine the power quality dataset collected above with environmental data (temperature, humidity, wind speed and direction, lightning, and insolation), household consumption data (as available through an opt-in procedure), and household generation through photovoltaics (again, as available through an opt-in procedure). We will perform exploratory analysis on the resulting dataset to determine how sampling rates, synchronization, precision, and history impact on detection, monitoring, prediction and diagnosis of power problems.

Third, we will explore the cyberprivacy and cybersecurity issues associated with open power quality data in the context of the Internet of Things. Our goal is to provide evidence-based recommendations for how to better secure the grid to prevent disruptions based upon such data, as well as how to better secure the IoT.

To be successful, our approach requires a combination of software and hardware engineering, human-computer interaction, data analytics, and social science experimentation. Philip Johnson is a Professor of Computer Science, has a research background in software engineering, and led the NSF-sponsored Kukui Cup project [26] to investigate the application of gamification techniques to improve energy literacy and behavioral change. Matthias Fripp is an Assistant Professor of Electrical Engineering, has a research background in power systems, and leads the Switch project [23] that supports deployment of renewable and conventional energy resources in large power systems. Daniele Spirandelli is an Assistant Professor in the Department of Urban and Regional Planning, has a research background in environmental planning and climate change, and leads projects to better understand the feedback systems between environmental change and human behavior.

To help maximize its benefits, the OPQ project is "triple open source": the hardware schematics are available under the CERN Open Hardware License, the software and firmware are available under the GNU Public License Version 3, while the power quality data will be available under the Open Data Commons Open Database License. Our goal is to create a developer and user community around an ecosystem of hardware, software, and data that maximizes forward progress in understanding the relationship between household power quality, grid dynamics, and consumer engagement.

2 Background and significance

The OPQ research project involves the development of three basic components: the OPQBox power quality monitoring hardware, the OPQHub service for crowdsourced power quality data, and analytics to make the collected data useful.

2.1 Power quality monitoring hardware

Starting at the high end, a phasor measurement unit (PMU) captures measurements of voltage or current at a rate of 30-60 Hz, and uses GPS to ensure that the timestamps recorded between different PMUs are accurate to approximately 1 microsecond [53]. As of 2014, there were approximately 1100 installed PMUs in the North American power grid. The cost of a single PMU hardware device and its installation on a transmission line can reach $150,000. The PMU user community consists of utilities who install and maintain PMUs at substations or generation plants in order to assess grid stability.

The Wide-Area Frequency Monitoring Network (FNET) is a project by researchers at Virginia Tech based upon a GPS-synchronized single-phase "frequency disturbance recorder" (FDR) that can be installed at ordinary 120V outlets [54]. Currently, FNET gathers frequency and voltage data from approximately 80 FDRs installed across North America. By monitoring changes, FNET can detect generator trips (which cause a decline in frequency) and load shedding (which cause an increase in frequency). Because the geographical location of each FDR is known, and because the timestamps are synchronized to less than a microsecond, FNET can be used to triangulate both the original size and location of such events. The FNET user community is a consortium consisting of utilities, power companies, and government groups who pay $10,000 per year to gain real-time access to the data.

Industrial manufacturing companies form a different user community for power quality monitoring. These companies are not concerned with overall grid quality but only with the quality of the power received at their buildings. For example, devices such as PQube [33] connect to AC power and can collect a variety of power data including voltage, frequency, THD (total harmonic distortion), and reactive power (VAR). PQube data is highly accurate and each device comes with an NIST calibration certificate. A single PQube device can cost over $5,000. Companies such as Fluke, PowerSight, and Tektronix also sell devices for measuring power quality problems in industrial or laboratory settings, for prices generally starting around $1,000.

A partnership consisting of the California Institute for Energy and the Environment, Power Standards Lab, Lawrence Berkeley National Lab, and UC Berkeley are extending PQubes with custom hardware to create "micro" PMUs [46, 47]. The goal is to manufacture PMUs at a low enough price point to justify their installation below the transmission level, and thus provide utilities with additional data that improves their situational awareness and faster service restoration.

Residential consumers form a relatively unexplored user community for power quality monitoring. One of the few commercial products for this user community is the AC Scout [44]. This device plugs into 120V power outlets and can monitor voltage and frequency. The AC Scout is designed only to monitor a single household, and is designed to write entries to a log file when pre-defined thresholds for voltage and frequency are exceeded. The log file can be off-loaded from the device to a computer via a USB cable or sent via email if the ethernet cable connection to the Internet is provided. Since data from one AC Scout is not intended for comparison with others, there is no attempt at synchronization.

Device	Cost	Measurements	Synchronization	Communication
PMU	$100,000	frequency, voltage, current	GPS	Secure LAN
FDR	$2,500	frequency, voltage	GPS	Internet
PQube	$5,000+	frequency, voltage, THD, VARs	(none)	(none)
mPMU	$5,000+	frequency, voltage, THD, VARs	GPS	Custom network
AC Scout	$200+	frequency, voltage	(none)	(none)
OPQ	$60	frequency, voltage, THD	NTP	HTTP/SSE

Figure 1: *Comparison of hardware devices for power quality monitoring*

Figure 1 summarizes how our OPQ hardware compares to other devices. First, we will monitor total harmonic distortion in addition to frequency and voltage, and we will also store waveform data for the past

24 hours in order to explore the possibility of diagnosis when thresholds are exceeded. Second, we expect to be able to produce the devices for approximately $60, a price point similar to conventional power strips with surge protectors. Third, our devices will use WiFi for communication with our cloud-based service via HTTP and Server-Sent Events protocols. Fourth, our devices will use Network Time Protocol (NTP) for synchronization. While GPS-based synchronization provides an accuracy below a single microsecond, NTP-based synchronization provides a much lower accuracy of a few milliseconds. Use of NTP limits the kinds of analytics that can be performed with OPQ, but reduces both the cost and constraints upon installation location.

2.2 Crowdsourced power quality data

Up to now, geographically distributed power quality data has been collected by and oriented toward the needs of utilities. The OPQ project proposes an alternative, crowdsourced approach, in which collection is by and analysis is oriented toward the needs of consumers.

According to Estelles-Aroles, crowdsourcing is "a type of participative online activity in which an individual, an institution, a non-profit organization, or company proposes to a group of individuals of varying knowledge, heterogeneity, and number, via a flexible open call, the voluntary undertaking of a task. The undertaking of the task [...] always entails mutual benefit. The user will receive the satisfaction of a given type of need, be it economic, social recognition, self-esteem, or the development of individual skills, while the crowdsourcer will obtain and utilize to their advantage that what the user has brought to the venture, whose form will depend on the type of activity undertaken." [18].

To our knowledge, crowdsourcing has never been successfully used for the purpose of collecting and analyzing power quality data. That said, Hammack proposed this very idea as "citizen engineering" in 2010, suggesting that the deployment of several thousand FNET frequency disturbance devices could be combined with publicly accessible online tools for visualization and analytics to enable consumers to see how their frequency data relates to that of the rest of the nation [25]. We believe his idea did not gain traction due to the cost of the devices and the relatively low benefits to individuals of a nation-wide perspective on frequency changes. In contrast, the OPQ project is designed to address both of these issues by the design of less expensive devices, and the deployment into a geographically small user community that is actively "suffering" from issues related to power quality.

Privacy is an important issue when crowdsourcing data about individuals or their environment. One successful example of a crowdsourced project that has addressed this issue is the Personal Genome Project (PGP), in which individuals are asked to share their genetic data in order to create a public repository that can advance the science of health care [11]. PGP data is placed in the public domain and contributors are required to sign an "open consent" form which states that the researchers cannot guarantee anonymity. In the OPQ project, we address privacy by allowing contributors to "coarsen" the published geographical location of their power quality data in order to address privacy concerns. We will also investigate the relationship of our data to broader smart meter privacy issues [1].

2.3 Analytics

Power quality data is traditionally used for four purposes: (1) *detection* of anomalies, (2) *diagnosis* of the cause and/or originating location of the anomaly, (3) real-time *control* of grid stability, and (4) *prediction* of future anomalies. Whether or not a given data set can be used for any of these purposes depends upon the characteristics of its generating device. A relatively simple device like the AC Scout can be used only for detection, FNET can be used for both detection and diagnosis [38], and PMU data can be applied to detection, diagnosis [55], control [37], and prediction [50, 24]). The OPQ project is designed to collect power quality data that can be used for detection of anomalies and a limited form of diagnosis: if a user lives in a neighborhood where several OPQ devices are installed, then an anomaly report will indicate if it was limited to the users household or co-occurred elsewhere in the neighborhood. Our devices are not sufficiently synchronized, nor can the data be communicated to grid operators quickly enough to support real-time utility-scale grid stabilization. However, when combined with IoT devices, OPQ can potentially enable useful control in limited circumstances, such as voltage collapse scenarios where useful response time can be measured in seconds, not milliseconds. We will also investigate whether or not OPQ data can support some forms of prediction when combined with other environmental, consumption, and generation data. From this traditional perspective on the use of power quality data, the OPQ project results in a data set that has somewhat more capability than the data collected from devices like the AC Scout, yet less capability than the data collected by devices like FDRs and PMUs.

However, in addition to the four traditional purposes, the OPQ project is designed to investigate whether power quality data can be used for an entirely new purpose: (5) *enabling active participation by consumers*. To do this, we will develop some simple guidelines for interpretation of the data, helping consumers to decide if: their problems are severe enough to contact the utilities; their problems correlate with environmental events such as thunderstorms and can be ameliorated by unplugging; or their problems are frequent, severe, and unpredictable enough to recommend installation of UPS systems to protect sensitive electronics. This interpretation makes power quality data *actionable* even without integration with IoT.

We observe that one cause of the societal and political issues involving the Smart Grid in Hawaii involves a fundamental disengagement by consumers from the grid: they want the utility to support unlimited installation of distributed generation by consumers (and resulting lower utility bills) without any perceivable impact on quality, price, or availability. We hypothesize that a low-cost approach to providing consumers with increased visibility into grid stability can increase engagement (by enabling consumers to see how power quality varies from time to time and from neighborhood to neighborhood) followed by active participation (through policy and civic engagement) to create a Smart Grid satisfying everyone's needs. Among other things, our project is designed to provide preliminary evidence regarding whether or not this fifth purpose can occur in reality.

3 Research plan

Our research plan builds upon our 2014 pilot study with three phases: *Design and implementation*, *Deployment*, and *Assessment*. The design and implementation phase will last approximately six months and will complete the second generation hardware and software systems now under development. The deployment phase will follow the design and implementation phase and last approximately one year. Deployment involves the distribution of our hardware to three neighborhoods and collection of power quality data. The assessment phase will begin in parallel with deployment and last one and a half years.

3.1 2014 Pilot Study

We performed a two month pilot study in August 2014 using our first generation OPQBox hardware and OPQHub software [28]. The pilot study involved the installation of three OPQBoxes in three separate locations on Oahu. These devices generated over 8000 voltage events (i.e. voltages outside the range of 114 - 126 V, exceeding the 5% variability for normal operation established by our utility). The devices also generated 16 frequency events (i.e. frequency fluctuation outside the range of 59.5 - 60.5 Hz). Our first generation OPQHub server provided a simple analytic to classify events according to the ITIC/CBEMA power tolerance curve [45]. During the pilot study period, our devices detected two abnormal power quality events according to this metric. We were also able to distinguish between local and grid-level power quality events, and even correlate power quality fluctuations to PV power output.

Despite the short length and small number of devices, the pilot study still generated evidence of relationships between power quality and residential PV. It also produced valuable findings about the shortcomings of our first generation hardware and software. For this project, we will build upon these preliminary findings with improved hardware, software and analytics, and with a larger scale study to test our research questions more rigorously.

3.2 Phase 1: Design and implementation

3.2.1 OPQBox hardware device

Figure 2 shows a block diagram of our second generation OPQBox hardware device [41]. It improves upon the pilot study hardware with respect to safety, accuracy, and reliability. It can be plugged into a standard U.S. two prong outlet with expected power at a frequency of 60 Hz and with a voltage of 120 V. It can operate under a frequency range of 50 Hz to 70 Hz and under a voltage range of 80 Vac to 200 Vac. Sampling is phase locked to the utility frequency. The 16 bit 100KSPS ADC allows for 5mV resolution with over 1024 points per grid cycle. On board ARM floating point DSP is able to perform the IEEE 1159 outlined analysis, as well as user defined code.

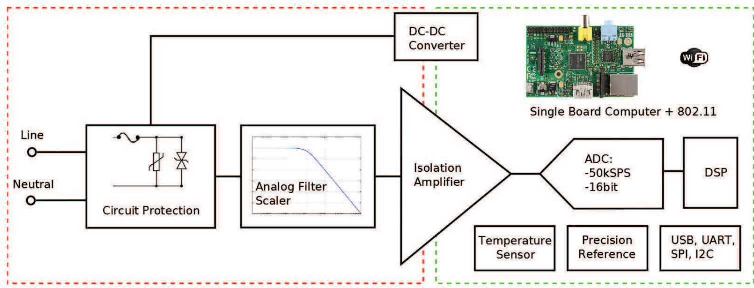

Figure 2: *OPQBox block diagram*

OPQBox also includes 512k of ferromagnetic RAM (FRAM). FRAM will be used as a circular buffer, containing up to 1 min of high resolution voltage measurements. FRAM will maintain its state through a power cycle, which will be sent to the OPQHub once the OPQBox comes back online.

OPQBox is meant to bypass power filters and surge protectors. Thus, it incorporates extra protection elements to keep the device operating safely during power disruptions. Fuses will disable OPQBox2 in case of a fault. All of the user accessible components are isolated from the mains. Finally, the OPQBox uses a Raspberry PI for WiFi-based communication with the OPQHub.

3.2.2 OPQHub software service

Figure 3 shows a screenshot of our open source OPQHub cloud service for collection and analysis of the data [29]. After installing an OPQBox, consumers use a browser to access an OPQHub and register their device. This includes specifying the kinds of alerts desired and how to receive them. Users can specify both thresholds for event triggering, frequency of alert delivery, and what kinds of events trigger notification.

Device registration also includes a privacy-preserving means to specify the location of the hardware device. This is accomplished by presenting users with a map overlaid with zoomable tiles allowing them to select the device location with resolutions from 500 square feet (typically revealing the actual building containing the device) to 1 square mile (revealing only the neighborhood containing the device).

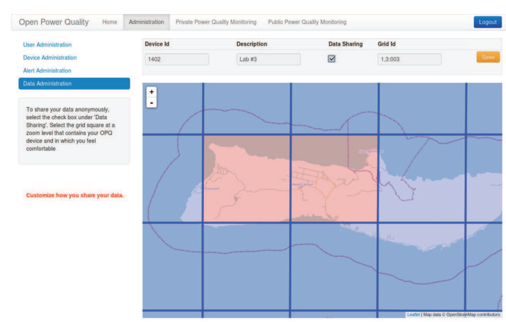

Figure 3: *OPQHub Zoomable Grid*

After registration, OPQHub sends notifications to the user based upon the data uploaded by their OPQBox. Building upon the results of our pilot study, our second generation OPQHub will provide new analytics for the data, such as whether the frequency and/or severity of events is relatively low or high, and if high, actions that the user might want to consider. These actions could include: (1) contacting the utility to request service (contact information supplied in the email); (2) Communicating with neighbors to see if they have power quality problems (via the creation of public annotations of their events); or (3) advice regarding actions (such as installation of UPS line conditioning for sensitive electronics, or unplugging them during events such as thunderstorms) depending upon the frequency/severity of power quality problems.

3.3 Phase 2: Deployment

After a small pilot manufacturing run of our second generation OPQBox has established device quality, we will manufacture 150 units for trial deployment. Although it requires WiFi, the 2012 US Census Report indicates that 85% of Hawaii households have internet access [10], so we do not expect this to be a problematic constraint.

Our deployment will begin by dividing the units among three Oahu neighborhoods based upon the penetration of photovoltaics on their associated circuit. Our utility publishes a "Locational Value Map" indicating the penetration of PV on a daily basis [14], and we will use this to choose one neighborhood with low penetration (i.e. where PV comprises less than 50% of the circuit's daytime minimum load), medium penetration (i.e. where PV comprises 75% to 100% of the circuit's daytime minimum load) and high penetration (i.e. where PV comprises 120% or greater of the circuit's daytime minimum load). Within a single neighborhood, we will choose participants to receive devices in order to obtain households both with and without photovoltaics. We want to obtain variety in monthly electricity bills (small being below $50, medium being between $50 and $150, and large being above $150). We hope at least 20% of the households will opt-in to providing consumption and/or generation data in addition to power quality data.

To facilitate deployment, we will request the aid of local environmental and sustainablity groups. OPQBoxes will be provided free of charge to participants, with their incentive for participation being increased access to information about their household power quality. Each OPQBox will be installed with a unique ID that is sent with each communication to the cloud-based service to identify the originating device. We can use this information to determine whether users have installed and configured the device successfully, and if a previously functioning device has ceased to transmit data. In either of these cases, we will contact the user to see if they no longer wish to participate and if so, retrieve the device for redistribution.

We plan to collect data during the Deployment phase for at least six months. However, if the deployment is proceeding successfully we will continue with data collection for up to 18 months (or the end of the grant period). Further data collection at that point will depend upon the availability of funds for the cloud-based service. During the course of deployment we will be accessing online NOAA weather data to collect environmental data (temperature, humidity, winds, insolation) for the neighborhoods selected for participation.

In parallel with the deployment phase, we will begin the Assessment phase.

3.4 Phase 3: Assessment

Assessment of this project will involve both qualitative (questionnaire) and quantitative (power quality) data, and is designed to provide insight into the general research questions presented in Section 1 as well as test several specific hypotheses described below. Our assessment procedure is as follows:

First, we will ask users to fill out a questionnaire when they receive their hardware device. The questionnaire will assess their attitudes toward the electrical utility and the Smart Grid as well as their current electricity-related behaviors (i.e. recent electric bill amount indicating their consumption, presence of PV installation, use of hybrid or electric car). This will provide baseline information regarding attitude and behavior that we can use to assess the impact of access to power quality data.

Second, we will monitor the data over the course of deployment in order to ensure that the OPQBoxes are working, that they maintain high levels of uptime, and that power quality alerts are being observed and sent to users. Based upon our pilot study, we are confident that power quality problems will be observed in a significant fraction of the households. In the event that a deployment does not generate a significant number of alerts in a given neighborhood after three months, we will manufacture additional devices and deploy to additional neighborhoods as necessary until we are able to obtain enough alerts to test our hypotheses.

Third, as soon as deployment begins, we will begin analysis of the collected power quality data to see if we can determine relationships with the environmental data we are also collecting. We will also analyze the data to see if we can develop new analytics for the impact of power quality on consumer electronics, on the ability of power quality data to manage sensitive consumer electronics through the IoT, and the attendant security implications.

Fourth, upon conclusion of the deployment phase, we will ask users to fill out a second questionnaire. This questionnaire will ask many of the same questions as the initial questionnaire, but will also ask if users made any changes with respect to their electrical behavior during the study period (such as installation of PV, installation of line conditioners, buying a hybrid vehicle, etc.) and to what extent these changes were motivated by information about their power quality. This pre and post-test design will provide evidence regarding the ability of power quality data to enable active participation in the Smart Grid. In addition to this self-reported data, we will also be able to observe "active participation" in the form of annotations users provide to their timeline.

Based upon analysis of the qualitative and quantitative data, we will test the following specific hypotheses: (1) Knowledge of personal power quality problems leads to actions such as contacting the utilities, installing UPS, or unplugging on alerts; (2) Intrinsic motivators (insight into personal and neighborhood power quality) plus a free device will suffice for participation in crowdsourced data collection; (3) Knowledge of neighborhood power quality issues leads to active engagement with neighbors; (4) Consumers find the new analytics provided by the OPQ system to be useful; (5) The frequency and severity of events is positively correlated with the degree of penetration of distributed PV on that circuit; (6) Consumers find crowdsourced power quality data to be more useful than their own power quality in isolation; (7) Participation is positively correlated with high monthly bills, installation of rooftop PV, or high numbers of severe PQ events.

4 Results from prior NSF support

P. Johnson, *Human centered information integration for the Smart Grid*, NSF Grant IIS-1017126, 8/15/10 to 7/31/14, $413,467. *Intellectual Merit:* The research provided novel insight into: the inadequacy of baseline data for energy competition research, the design of experimental studies for assessing energy behaviors, the design of energy competitions incorporating educational activities. *Broader Impacts* include: the creation and distribution of two open source systems, WattDepot and Makahiki, that can be used for collection and analysis of energy data and the design and implementation of sustainability games; the publication of data regarding the impact of energy education and gamification techniques on energy literacy and behavior; the training of approximately 9 undergraduate students, 3 M.S. students, and 3 Ph.D. students in research techniques, sustainability concepts, and software design and development. Selected publications: [5, 6, 3, 7, 2, 31, 36, 8, 4, 9, 51]. Research products are available at the Kukui Cup site [26], the WattDepot site [48], and the Makahiki site [27].

A. Kuh and M. Fripp, *Sensing, Modeling, and Control of Smart Sustainable Microgrids*, NSF Grant ECCS-1310634, 7/1/2013-6/30/2016, $360,000. *Intellectual Merit:* This project explores the potential of future power distribution by designing, building and evaluating a microgrid that offsets local energy usage using distributed generation (i.e. rooftop PV). *Broader Impacts* include: By developing an operational structure analogous to the larger utility grid, the campus microgrid is being instrumented to serve as a platform for gathering field data on load, generation, local grid quality and usage patterning. Using this platform, students, faculty and partners can immediately advance their knowledge on the challenges of operating, monitoring and assessing the conditions of a modern grid. Selected publications: [21].

5 Broader Impacts

This project defines a transformational approach to obtaining computational insight into the cyberinfrastructure implications of two sustainability questions: Can crowdsourced power quality data enable active participation in the Smart Grid? What are the technical, social, behavioral, security, and economic requirements for crowdsourced power quality data that make it effective for detection, monitoring, prediction, control, and diagnosis of the Smart Grid?

We will gain new insights into these questions through a number of cyberinfrastructure innovations. We will develop low cost, open source hardware and software for residential power quality monitoring of voltage, frequency, and total harmonic distortion. The collected data will be open source, and we will address privacy concerns by allowing consumers to "coarsen" their locational information when providing the data to others. We will combine power quality data with other environmental data to support prediction and diagnosis, and investigate IoT for control. We will use a pre and post-test experimental design in order to gain empirical insight into the effect that power quality data has upon consumers with respect to their attitudes and behaviors toward the Smart Grid and the utility implementing it. According to LaCommare [34], there is no publicly available dataset regarding power quality at the household level. If successful, these innovations could be adapted to other sustainability resource problem domains, including water, waste, and food.

We will perform education and outreach activities to create a interdisciplinary community of researchers including professors, graduate students and undergraduates from computer science, electrical engineering, and urban and regional planning. For example, PI Johnson teaches a graduate seminar on "Software Engineering in the Smart Grid", and PIs Fripp and Spirandelli will develop related coursework in EE and Urban Planning. Our residential study will require significant outreach to the community, and further outreach will occur though the building of our open source repositories and associated communities for hardware, software, and data. Workforce development activities will include power quality, crowdsourcing, user interface design, community development, and the Smart Grid. Hawaii is an EPSCOR state and approximately 84% of University of Hawaii undergraduates are minorities, so this research will benefit under-represented populations.

While Hawaii is the ideal location to develop this capability due to its nation-leading penetration of distributed renewables and current consumer dissatisfaction, our results will have broader applicability: according to a report by the North Carolina Clean Energy Technology Center, rooftop PV is now cheaper than utility-supplied power in 42 of America's 50 largest cities [32]. The power quality problems Hawaii faces now may soon be faced by many other communities across the nation. As evidence for the broader interest and support for this project, we include letters of support from Hawaiian Electric, the Blue Planet Foundation, and the Electric Power Research Institute as supplemental documents.