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 is limited 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 [17, 22, 24]. Feedback on consumption does 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 the way to active participation—in other words, sustained awareness and engagement at both personal and community levels. There is another, synergistic focus, however. 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 [51, 55, 19, 15, 14]. Hawaii thus serves as an ideal testbed for determining if consumer-oriented power *quality* feedback can lead not only to active participation in the Smart Grid but to public buy-in for the investments needed to make the overall grid more reliable.

To investigate this, we have initiated the Open Power Quality (OPQ) research project [31], which involves the design and implementation of a combination of low-cost hardware and cloud-based software that enables consumers to monitor power quality (voltage, frequency, and total harmonic distortion) in their household and upload that data to our Internet service to produce a crowdsourced perspective on power quality. Our approach enables consumers to learn: (a) whether their household is experiencing degraded power quality; (b) whether the observed problems are isolated to their own house or more widespread in their neighborhood; (c) whether the problems are intermittent, frequent, unpredictable, or regularly occurring; and (d) whether the problems are 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, shifting the focus from consumption to 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 are the very same devices that are 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 [18].

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, 21]. 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, but 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 research and development efforts over the past year have demonstrated the basic technical feasibility of our approach. We now propose an interdisciplinary study to assess whether the potential benefits of crowdsourced power quality data can be achieved in practice, and to better understand the social, behavioral, and economic trade-offs inherent in our approach. In general, we propose to investigate the following research questions:

1. *Can crowdsourced power quality data enable active participation in the Smart Grid?*

2. *What are the technical, social, behavioral, and economic requirements for crowdsourced data that make it effective for detection, monitoring, prediction and diagnosis of selected Smart Grid power quality issues?*

3. *How can our project outcomes improve "citizen science" in general and the kinds of intrinsic and extrinsic motivators needed for success?*

To investigate the first question, we will manufacture and distribute 150 power quality monitoring devices to volunteer households in three Oahu neighborhoods, producing power quality data to be stored in our public cloud-based 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.

To investigate the second question, 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.

To investigate the third question, we will compare and contrast the design and outcomes of our approach to other citizen science projects such as Frogwatch [41], Urban Coyote Sightings [1], and CosmoQuest [45].

To be successful, our approach requires a combination of 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 currently leads the NSF-sponsored Kukui Cup project [28] 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 [25] 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 to and impact upon the scientific community, 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 intent 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: power quality monitoring hardware, 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 [52]. As of 2012, there were approximately 500 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 $100,000. 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 [53]. 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." [20].

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 [27]. 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 [13]. 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 [2].

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 [54], control [37], and prediction [49, 26]).

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 control. We will also investigate whether or not the data collected from our devices 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*.

We observe that one cause of the societal and political issues involving the Smart Grid in Hawaii in-

volves 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. Our project is designed to provide preliminary evidence regarding whether or not this fifth purpose can occur in reality.

In summary, our OPQ project will design and produce innovative hardware for power quality monitoring. We will implement an innovative, crowdsourced appoach to power quality data collection. Finally, we will apply this data to both traditional and entirely new purposes.

3 Research plan

Our research plan has three basic three phases: *Design and implementation*, *Deployment*, and *Assessment*. The design and implementation phase will last approximately six months and will complete the 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. During assessment we will collect evidence to answer the primary research questions presented in Section 1.

3.1 Phase 1: Design and implementation

The OPQ Project has been working on the design and implementation of open source hardware and software for the past year. In essence, our OPQ hardware device plugs into a normal 120V outlet, monitors frequency, voltage, and THD, and sends *events* via WiFi to our cloud-based software service when thresholds are exceeded. Our OPQ cloud service gathers event data from devices and issues *alerts* to users via email or text message to inform them about power quality issues. Finally, our cloud service can send commands back to hardware devices, such as to change threshold values or retrieve recent waveform data for cloud-based analysis.

3.1.1 OPQ Hardware Device

Our OPQ hardware device has the following major design goals: (1) Unit price below $60 to support large-scale deployment; (2) easy to install and safe to operate; (3) 16/24 bit resolution and 50+ samples per grid cycle; (4) Support for frequency voltage, and THD measurement; (5) onboard processing and local storage; (6) inter-device synchronization via NTP; (7) easy extensibility; and (8) open source license.

Figure 2 shows a block diagram and photo of the prototype hardware. In order to make our device safe to operate, it is galvanically isolated from the power grid via a UL-listed wall plug transformer. This transformer is used both for powering the meter and monitoring the power grid. The output of the transformer's secondary windings is passed through

Figure 2: *Hardware block diagram*

a low-pass filter which is responsible for scaling down the voltage to the analog-to-digital converter(ADC) range, as well as filtering out frequencies above 1Mhz. Furthermore this filter protects the sensitive inputs of the ADC.
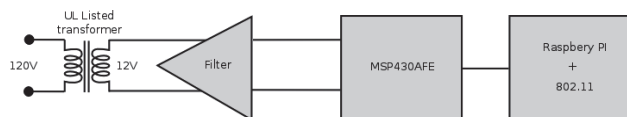
The output of the filter is digitized using an ADC on an MSP430AFE microcontroller. This microcontroller is specifically designed for power metering. As illustrated in Figure 3, we combine an analog front-end, a 24bit SAR ADC capable of sampling at 4kHz, and a 16bit MCU into a single integrated circuit to reduce the bill of materials.

For our sensor network to scale, a significant amount of processing must be performed on the device itself. This includes power quality event detection, as well as buffering of historic data leading up to the event. Furthermore, event data needs to be uploaded to the cloud for further analysis. Currently, we use a Raspberry Pi single board computer for the main processing unit. The MSP430AFE sends digitized samples to the Raspberry Pi via the SPI protocol. Data is compared to the expected waveform, and if the deviation is significant, an event containing the raw data is send to the cloud via a USB 802.11 adapter. We have designed a custom protocol for data transmission to reduce the bandwidth required [12]. The device and cloud service communicate using server-side events (SSE) over HTTP, which enables the device to be sent commands from the cloud even though it will be located behind a home wireless router.

Figure 3: *OPQ Board*

During this phase, we will hire a professional engineer experienced in this kind of product design to review our hardware for safety issues.

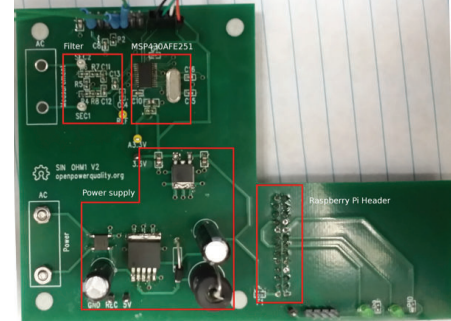### 3.1.2 OPQ Cloud-based software service

In parallel with hardware, we have developed a cloud-based service for collection and analysis of the data. All source code is licensed under the GPL V3 and is available on GitHub [30]. When a consumer receives a device, they use a browser to access our service and begin by completing a registration wizard. First, the wizard helps users to specify the kinds of alerts they want to receive and how they want to receive them (email or text message). Users can specify both thresholds for event triggering, frequency of alert delivery (immediately, or as part of a daily or weekly summary), and whether they want to be alerted to only their own quality events or to quality events (and annotations of these events) in their neighborhood.

Figure 4: *Cloud service page illustrating zoomable grid*

Second, the wizard provides a privacy-preserving means to specify the location of the hardware device. It does this by presenting users with a map overlaid with zoomable tiles allowing them to select a 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). This is illustrated in Figure 4.

There are two addition forms of energy data that the user can choose to provide to the OPQ service through the wizard. Some users may have PV and/or smart meters installed that provide internet access to consumption and/or generation data. When available (and if the user is willing to share this data), the wizard will collect the information required to automatically retrieve this data as well. Thus, in the best case, our service will have access to consumption, generation, and quality data about a single household.
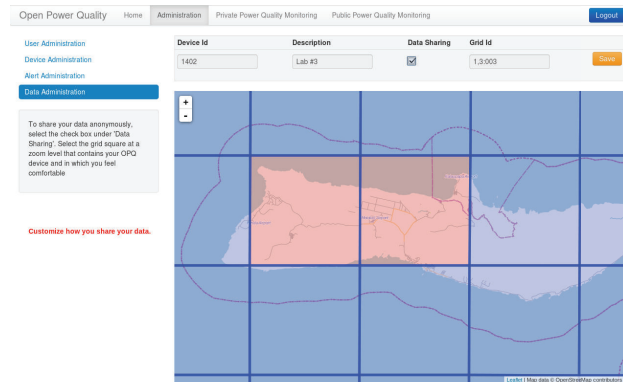
After configuration, the service will push events to the user as specified in the user's preferences. Beyond simple numerical data, the service can provide interpretation of the data, such as whether the frequency and/or severity of events is relatively low or high, and if high, actions that the user 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.

3.2 Phase 2: Deployment

After the hardware is designed and a small pilot manufacturing run has established device quality, we will manufacture 150 units for trial deployment. Although our current hardware design requires WiFi, the 2012 US Census Report indicates that 85% of Hawaii households have internet access [11], 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 [16], 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, including Kanu Hawaii, the Blue Planet Foundation, and the Kokua Foundation. Hardware devices will be provided free of charge to participants, with their incentive for participation being increased access to information about their household power quality.

Our devices 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.

3.3 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 hardware devices are being used, that they maintain high levels of uptime, and that power quality alerts are being observed and sent to users. Based upon our experience with household installation of an AC Scout, 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.

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 recommendations 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: [6, 7, 4, 8, 3, 32, 36, 9, 5, 10, 50]. Research products are available at the Kukui Cup site [28], the WattDepot site [48], and the Makahiki site [29].

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: [23].

5   Broader Impacts

We believe this project defines an ambitious, aggressive, yet feasible approach to obtaining significant insight into the following important sustainability questions: Can crowdsourced power quality data enable active participation in the Smart Grid? What are the technical, social, behavioral, and economic requirements for crowdsourced data that make it effective for detection, monitoring, prediction and diagnosis of selected Smart Grid power quality issues? And finally, how can our project outcomes improve "citizen science" in general and the kinds of intrinsic and extrinsic motivators needed for successful outcomes?

We will gain new insights into these questions through a number of innovations. We will develop low cost, open source hardware for residential power quality monitoring of voltage, frequency, and total harmonic distortion. This data will be uploaded to an open source cloud-based internet service we have designed for storage, retrieval, and analysis. 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 from publicly available sources in order to investigate relationships that may aid in prediction and diagnosis. We will use a pre and post-test experimental design in order to gain 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, and so our project data has the potential to provide unprecedented insight into power quality issues at the household level.

To achieve these innovations, we will build upon our prior experiences with open source software development, empirical software engineering, energy challenge game design, power systems for renewable energy sources, environmental planning, and community ecology. We will build upon established relationships with University of Hawaii organizations (Renewable Energy and Island Sustainabity Group, Sustainable UH) and community organizations (Kanu Hawaii, Blue Planet Foundation, Hawaiian Electric Company). Hawaii is an EPSCOR state and approximately 84% of University of Hawaii undergraduates are minorities, so this research will benefit under-represented populations.

Crowdsourcing is a growing technique for citizen science. We believe this project will provide useful new insights into the strengths and weaknesses of this approach. Can intrinsic motivation suffice for this form of data collection? How does this effort compare to other citizen science projects?

The project will create a interdisciplinary community of researchers including professors, graduate students and undergraduates from computer science, electrical engineering, and urban and regional planning. Through the development of graduate seminars and open source repositories, we will pursue workforce development related to power quality, crowdsourcing, user interface design, community development, and the Smart Grid.

This research creates a mechanism for rapid implementation and deployment of community-based power quality monitoring. While Hawaii is the ideal location to develop this capability due to its nation-leading penetration of distributed renewables, we expect that other communities will find it useful in future.

References

[1] Audubon Society of Portland. Urban coyote. http://urbancoyoteproject.weebly.com/, 2013.

[2] C. Balough. Privacy implications of smart meters. *Chicago-Kent Law Review*, 86(1), 2011.

[3] Robert S. Brewer. The Kukui Cup: Shaping everyday energy use via a dorm energy competition. In *Proceedings of the CHI 2011 Workshop on Everyday Practice and Sustainable HCI*, Vancouver, Canada, May 2011.

[4] Robert S. Brewer. *Fostering Sustained Energy Behavior Change And Increasing Energy Literacy In A Student Housing Energy Challenge*. PhD thesis, University of Hawaii, Department of Information and Computer Sciences, March 2013.

[5] Robert S. Brewer. Three shifts for sustainable HCI: Scalable, sticky, and multidisciplinary. In *Proceedings of the CHI 2014 Workshop "What have we learned? A SIGCHI HCI & Sustainability community workshop"*, Toronto, Canada, April 2014.

[6] Robert S. Brewer and Philip M. Johnson. WattDepot: An open source software ecosystem for enterprise-scale energy data collection, storage, analysis, and visualization. In *Proceedings of the First International Conference on Smart Grid Communications*, pages 91–95, Gaithersburg, MD, October 2010.

[7] Robert S. Brewer, George E. Lee, and Philip M. Johnson. The Kukui Cup: a dorm energy competition focused on sustainable behavior change and energy literacy. In *Proceedings of the 44th Hawaii International Conference on System Sciences*, pages 1–10, January 2011.

[8] Robert S. Brewer, George E. Lee, Yongwen Xu, Caterina Desiato, Michelle Katchuck, and Philip M. Johnson. Lights Off. Game On. The Kukui Cup: A dorm energy competition. In *Proceedings of the CHI 2011 Workshop on Gamification*, Vancouver, Canada, May 2011.

[9] Robert S. Brewer, Yongwen Xu, George E. Lee, Michelle Katchuck, Carleton A. Moore, and Philip M. Johnson. Energy feedback for smart grid consumers: Lessons learned from the Kukui Cup. In *Proceedings of Energy 2013*, pages 120–126, March 2013.

[10] Robert S. Brewer, Yongwen Xu, George E. Lee, Michelle Katchuck, Carleton A. Moore, and Philip M. Johnson. Three principles for the design of energy feedback visualizations. *International Journal On Advances in Intelligent Systems*, 3 & 4(6):188–198, 2013.

[11] US Census Bureau. Computer and internet access in the United States (2012). https://www.census.gov/hhes/computer/publications/2012.html, 2012.

[12] Anthony Christe and Sergey Negrashov. OPQ communication protocol. https://github.com/openpowerquality/opq/wiki/OPQ-Communication-Protocol, 2013.

[13] George Church. The personal genome project. *Molecular Systems Biology*, 1(1), 2005.

[14] Sophie Cocke. Want solar panels? You may have to pay HECO thousands in studies. http://www.civilbeat.com/articles/2012/02/09/14771-want-solar-panels-you-may-have-to-shell-out-to-heco/, February 2012.

[15] Sophie Cocke. HECO says residents with solar aren't paying their fair share of costs. http://www.civilbeat.com/articles/2013/07/11/19488-heco-says-residents-with-solar-arent-paying-their-fair-share-of/, July 2013.

[16] Hawaiian Electric Company. Locational value map. http://www.hawaiianelectric.com/portal/site/heco/lvmsearch, 2014.

[17] Sarah Darby. The effectiveness of feedback on energy consumption: A review of the literature on metering, billing and direct displays. Technical report, Oxford University Environmental Change Institute for UK Department for Environment, Food and Rural Affairs, April 2006. http://www.eci.ox.ac.uk/research/energy/downloads/smart-metering-report.pdf.

[18] D. Dorr. National Power Laboratory power quality study based on 600 site-months. In *14th International Telecommunications Energy Conference*, October 1992.

[19] Wade Elston. Don't trust HECO to manage solar energy use. http://www.staradvertiser.com/s?action=login&f=y&id=227019421, October 2013.

[20] Enrique Estelles-Aroles and Fernando Gonzales-Ladron de Guevara. Towards an integrated crowdsourcing definition. *Journal of Information Science*, 38(2), 2012.

[21] Joseph Eto and Kristina LaCommare. Tracking the reliability of the U.S. power system: an assessment of publicly available information reported to state public utility commissions. LBNL-1092E, Environment Energy Technologies Division, Lawrence Berkeley National Laboratory, 2008. http://certs.lbl.gov/pdf/lbnl1092e-puc-reliability-data.pdf.

[22] Ahmad Faruqui, Sanem Sergici, and Ahmed Sharif. The impact of informational feedback on energy consumption: A survey of the experimental evidence. *Energy*, 2009.

[23] S. Fatemi, A. Kuh, and M. Fripp. Online and batch methods for solar radiation forecasting under asymmetric cost functions. *to appear in: IEEE Transactions on Neural Networks and Learning Systems*, 2014.

[24] Ben Foster and Susan Mazur-Stommen. Results from recent real-time feedback studies. Technical Report Technical Report B122, American Council for an Energy-Efficient Economy (ACEEE), February 2012.

[25] Matthias Fripp. Switch model (website). http://sourceforge.net/projects/switch-model/, 2012.

[26] F. Gao, J. Thorp, A. Pal, and S. Gao. Dynamic state prediction based upon auto-regressive (AR) model using PMU data. In *Power and Energy Conference at Illinois*, 2012.

[27] Bill Hammack. *Why engineers need to grow a long tail*. Articulate Noise Books, 2010.

[28] Kukui Cup home page. http://kukuicup.org.

[29] Makahiki home page. http://makahiki.io.

[30] Philip Johnson. Open power quality (github). https://github.com/openpowerquality, 2013.

[31] Philip Johnson. Open power quality (website). https://openpowerquality.org, 2013.

[32] Philip M. Johnson, Yongwen Xu, Robert S. Brewer, Carleton A. Moore, George E. Lee, and Andrea Connell. Makahiki+WattDepot: An open source software stack for next generation energy research and education. In *Proceedings of the 2013 Conference on Information and Communication Technologies for Sustainability (ICT4S)*, February 2013.

[33] Power Standards Lab. PQube electric power measurement instrument. http://www.powerstandards.com/PQube.php, 2013.

[34] Kristina LaCommare and Joseph Eto. Understanding the cost of power interruptions to U.S. electricity consumers. LBNL-55718, Environment Energy Technologies Division, Lawrence Berkeley National Laboratory, September 2004. http://certs.lbl.gov/pdf/55718.pdf.

[35] S. Laskar and M. Mohibullah. Power quality issues and need of intelligent PQ monitoring in the smart grid environment. *International Journal of Emerging Technology and Advanced Engineering*, 2(9), September 2012.

[36] George E. Lee, Yongwen Xu, Robert S. Brewer, and Philip M. Johnson. Makahiki: An open source game engine for energy education and conservation. Technical Report CSDL-11-07, Department of Information and Computer Sciences, University of Hawaii, Honolulu, Hawaii 96822, January 2012.

[37] Z. Liu and M. Ilic. Toward PMU-based robust automatic voltage control and automatic flow control. In *IEEE Power and Energy Society General Meeting*, 2010.

[38] Penn Markham. *Data Mining and Machine Learning Applications of Wide-Area Measurement Data in Electric Power Systems*. PhD thesis, University of Tennessee, 2012.

[39] A. Moreno-Munoz and J. de la Rosa. *Electronic loads and power quality*. Springer, 2007.

[40] National Energy Technology Laboratory. The modern grid strategy: Characteristics of the modern grid. http://www.netl.doe.gov/moderngrid/opportunity/vision_characteristics.html, 2008.

[41] Association of Zoos and Aquariums. Frogwatch. http://www.aza.org/frogwatch/, 2013.

[42] Jonathan Rodriguez and Gavin Saldanha. No harmony in harmonics. Eaton Power Systems White Paper, http://www.eaton.com/ecm/idcplg?IdcService=GET_FILE&allowInterrupt=1&RevisionSelectionMethod=LatestReleased&Rendition=Primary&dDocName=WP10-03, January 2010.

[43] Greg Rouse and John Kelly. Electricity reliability: Problems, progress, and policy solutions. Technical report, Galvin Electricity Initiative, February 2011. http://www.galvinpower.org/sites/default/files/Electricity_Reliability_031611.pdf.

[44] AC Scout. AC scout. http://www.acscout.com, 2013.

[45] STEM Center at Southern Illinois University. Cosmoquest. http://cosmoquest.org/projects/mercury_mappers/, 2013.

[46] A. von Meier. Micro-synchrophasers for distribution systems. http://pqubepmu.com/about.php, 2013.

[47] A. von Meier, D. Culler, A. McEachern, and R. Arghandeh. Micro-synchrophasers for distribution systems. In *IEEE Innovative Smart Grid Technologies Conference*, 2014.

[48] WattDepot home page. http://wattdepot.googlecode.com/.

[49] X.Liu, L. Ying, Z. Liu, Z. Huang, Y. Miao, Q. Jiang, and W. Chen. A novel fast transient stability prediction method based upon PMU. In *Power and energy society*, 2009.

[50] Yongwen Xu, Philip M. Johnson, Carleton A. Moore, Robert S. Brewer, and Jordan Takayama. SGSEAM: Assessing serious game frameworks from a stakeholder experience perspective. In *Proceedings of the First International Conference on Gameful Design, Research, and Applications (Gamification 2013)*, October 2013.

[51] Alan Yonan. Solar saturation could mean new HECO charges. http://www.staradvertiser.com/s?action=login&f=y&id=222652251&id=222652251, September 2013.

[52] P. Zhang, J. Chen, and M. Shao. Phasor measurement unit implementation and applications. Technical report, Electric Power Research Institute, November 2007.

[53] Y. Zhang and P. Markham. Wide-area frequency monitoring network (FNET) architecture and applications. *IEEE Transactions on the Smart Grid*, 1(2), September 2010.

[54] W. Zhao, X. Chen, Y. Cao, and M. Peng. A novel method of fault diagnosis based on synchronized phasor measuring and flow fingerprint identification technology. In *International Conference on Sustainable Power Generation and Supply*, 2009.

[55] Ira Zunin. Outcry over new solar rules putting pressure on HECO. http://www.staradvertiser.com/s?action=login&f=y&id=228436641, October 2013.