Makahiki+WattDepot: An open source software stack for next generation energy research and education

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ABSTRACT
The accelerating world-wide growth in demand for energy has led to the conceptualization of a "smart grid", where a variety of decentralized, intermittent, renewable energy sources (for example, wind, solar, and wave) would provide most or all of the power required by small-scale "micro-grids" servicing hundreds to thousands of consumers. Such a smart grid will require consumers to transition from passive to active participation in order to optimize the efficiency and effectiveness of the grid's electrical capabilities. This paper presents a software stack called comprised of two open source software systems, Makahiki and WattDepot, which together are designed to engage consumers in energy issues through a combination of education, real-time feedback, incentives, and game mechanics. We detail the novel features of Makahiki and WattDepot, along with our initial experiences using them to implement an energy challenge called the Kukui Cup.

Keywords
smart grid, energy research, open source, game engine, energy repositories

1. INTRODUCTION
Several characteristics of the traditional electrical energy infrastructure of industrial societies have remained unchanged for almost 100 years. First, energy production has been centralized in power plants using "firm" energy sources such as coal, oil, nuclear, or hydro. Second, centralized production has promoted centralized control of the grid, typically through a single or small number of utilities with public regulation over their policies and rates. Third, centralized production and control has led to the predominance of "macro-grids", or grid infrastructures designed to service hundreds of thousands to millions of consumers. Finally, traditional grids have been designed to minimize the information about energy required by consumers to utilize the service. The typical consumer needs to know almost nothing more than how to plug an appliance into an outlet, and can assume that this exceedingly simple "user interface" will provide virtually unlimited amounts of high quality energy at any time for a relatively small cost.

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Unfortunately, the accelerating world-wide growth in demand for energy is leading to a breakdown in this approach to electrical energy infrastructure. Petroleum products such as coal and oil are nonrenewable, are no longer reliably inexpensive, and have been found to have a variety of adverse environmental effects. Nuclear energy, while low in emissions, has risks that have caused countries such as Japan and Germany to reevaluate this approach to energy generation.

Addressing these emergent problems has led to the conceptualization of a "smart grid", where a variety of decentralized, intermittent, renewable energy sources (for example, wind, solar, and wave) would provide most or all of the power required by small-scale "micro-grids" servicing hundreds to thousands of consumers. Such a smart grid will require consumers to transition from passive to active participation in maintaining efficient and effective use of the grid's electrical capabilities. For example, these "smart consumers" should be able to tailor their use of electrical energy to the types and amount of energy available in the grid at any point in time; minimizing the overall use of non-renewable resources as well as peak loads on the grid.

Satisfying the radically different requirements and operating assumptions of this next generation grid requires new kinds of software that enable research and experimentation into the ways that electrical energy production and consumption can be collected, analyzed, visualized, and provided to consumers in a way that enables a transition from passive to active participation. Since 2009, we have been designing, implementing, and evaluating an open source software "stack" to facilitate this research. This software stack consists of two custom systems called WattDepot [1] and Makahiki [11], along with the open source components they rely upon (Java, Restlet, Postgres, Python, Django, Memcache).

In this paper, we detail the novel features of WattDepot and Makahiki, along with our initial experiences using them to implement an energy challenge called the Kukui Cup.

2. WATTDEPOT
Software for energy collection, storage, and analysis tends to come in two flavors that support two ends of the scalability spectrum. At one end are utility-scale SCADA systems and protocols which are intended to manage macro-grid data [14, 15, 18]. At the other end are "personal scale"

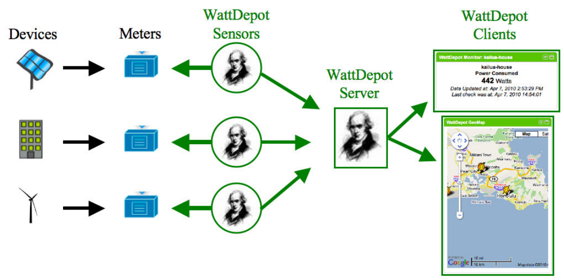


Figure 1: Architecture of WattDepot

systems such as those provided by energy meter or solar panel manufacturers which are intended to manage information about single households [6,19]. We designed WattDepot to support a middle ground that we refer to as "enterprise-level" energy management, in which data concerning energy production and consumption of hundreds to thousands of households can be usefully managed [2]. Figure 1 illustrates the architecture of the system, where WattDepot sensors send data from meters attached to energy devices to a server, which can then be queried by clients to provide visualizations and analyses.

Our use of WattDepot has led to a novel set of capabilities to support this middle ground.

2.1 Meter Agnostic

Unlike personal-scale systems that are typically tied to a particular manufacturer's product, WattDepot is agnostic about the kinds of meters used to monitor energy production and consumption data, and whether the data is personal-scale or utility-scale. It provides a REST protocol for data transmission that can be used to implement clients for a wide variety of devices; the major constraint is that these devices need to have network access. WattDepot clients can be written in any language that supports the HTTP protocol. We provide a high-level client libraries for Java and JavaScript.

Due to the architectural decoupling of data collection from the rest of the system, WattDepot can be effectively used for simulation and what-if scenario development. This flexibility makes it appropriate as a kind of technological "scaffolding" for smart grid applications, where WattDepot can provide clients with simulated production and consumption data early in development, with the simulated data transitioning to live data as these sources go online later in development.

2.2 Source Aggregation

WattDepot can represent aggregations of power sources. For example, a building might have multiple meters monitoring energy consumption, one per floor. WattDepot can represent the power consumed by individual floors, as well as an aggregate source representing the building as a whole. Aggregations can be nested, so that floors can be aggregated into buildings, buildings into neighborhoods, and neighborhoods into cities. It is quite common for the level of abstraction desired by client developers and end users (such as a floor of a building) to actually consist of multiple meters. By providing this aggregation of sources at the server level, client development becomes easier.

2.3 Data Interpolation

WattDepot automatically performs data interpolation when necessary. For example, a meter might provide a snapshot of energy usage once per hour for a given device. Clients can request the power consumed by this device at any time instant, and WattDepot will automatically provide interpolation when the requested time does not match a time for which actual sensor data is available. This is essential for the common case where meters do not have perfectly synchronized clocks and are not polled simultaneously, and when making use of the source aggregations discussed in the previous section.

2.4 Flexible Data Storage

WattDepot is architecturally decoupled from the underlying data storage technology. This decoupling supports experimentation with both traditional relational as well as NoSQL technologies, and facilitates scalability. Currently, WattDepot implements support for Derby, PostgreSQL, and BerkeleyDB storage systems. Administrators looking for simplicity may opt for the embedded Derby database, while those looking to integrate with existing database infrastructure might decide to use PostgreSQL for data storage.

WattDepot also implements support for "ephemeral" data. In some application scenarios, it is useful to send energy data to the WattDepot server quite frequently (i.e. every few seconds) so that clients can monitor current energy consumption with low latency. However, that rate of data sampling is not necessary for historical analyses, which may only require energy data sampling at the rate of every few minutes. WattDepot supports this situation through ephemeral data, which creates an in-memory window during which all recently received energy data is available for retrieval, but stored in the repository only at a much lower sampling rate.

2.5 WattDepot in the Cloud

In addition to installation on a local server, WattDepot has been designed to support cloud hosting, sometimes referred to as Platform-as-a-Service (PaaS). In particular, WattDepot can be deployed on the Heroku [13] cloud-based hosting service. The Heroku PaaS solution allows users to deploy the system and start collecting data without the requirement of server hardware, and Heroku offers flexible capacity depending on the expected workload.

2.6 Beyond WattDepot

While WattDepot provides the software infrastructure to collect, store, and analyze energy data, ensuring that the data is collected reliably and accurately reflects reality requires additional effort. As an example, we will examine the steps required to collect data on electricity use in a building. First, the administrator should work with manager of the building to understand the electrical infrastructure: how is power distributed in the building, and how does the distribution relate to the goals to be accomplished through measurement? If electricity is to be monitored at the per-floor level, do the distribution panels match that segmentation?

If the building does not have meters already installed, the administrator will need to select a meter vendor and acquire the meters. The meters will typically need to be installed by licensed electricians. The administrator will need to verify that the installation was performed correctly by checking whether the received data agrees with the expected amount of usage. To allow WattDepot to collect data, reliable network connectivity must be provided for the meters. The meters will also need to be configured to support remote data collection.

If the building already has meters installed, the administrator will need to confirm that the meters are configured correctly and that the data they produce is sane. When working with existing meter infrastructure, the WattDepot administrator may not have administrative access to the meters, so any configuration changes required may need to be requested from the meter administrator.

Once data collection has been established, the WattDepot administrator will need to establish monitoring of the meters and WattDepot infrastructure so that hardware or software faults can be detected and corrected before they lead to excessive loss of data. By understanding these issues, administrators can ensure that systems built on top of WattDepot receive accurate energy data at appropriate levels of abstraction.

3. MAKAHIKI

The feature set of WattDepot creates attractive infrastructure for management of energy data, but research suggests that effective participation of consumers in a next generation smart grid requires more than simple feedback to consumers about their consumption, particularly given the passive nature of their involvement for the past 100 years [8, 9, 17].

The second component of our open source software stack, Makahiki, represents research intended to create synergy between the need to create knowledge and engagement regarding energy and the ability of so-called "serious game" techniques and energy feedback to create participation and engagement [4, 5, 7, 16]. In Makahiki, online game mechanics are employed with the goal of affecting real-world energy behaviors [3]. The ultimate goal is to not just affect energy behaviors during the course of the game, but to produce long lasting, sustained change in energy behaviors and outlooks by participants. Figure 2 illustrates the architecture of Makahiki.

Makahiki consists of a configurable game engine that can be customized to the needs of different organizations. It includes a library of pre-built game "widgets" that implement a variety of game mechanics. Using the widgets, an organization can create a custom energy challenge in which players can compete individually and/or in teams to earn the most points by reducing their energy consumption as well as by learning about energy concepts in general. The next sections present some of the most important widgets in Makahiki.

3.1 Smart Grid Game

The Smart Grid Game widget shown in Figure 3, is the primary place players go to learn about energy issues and earn points. Actions are organized into a grid of squares

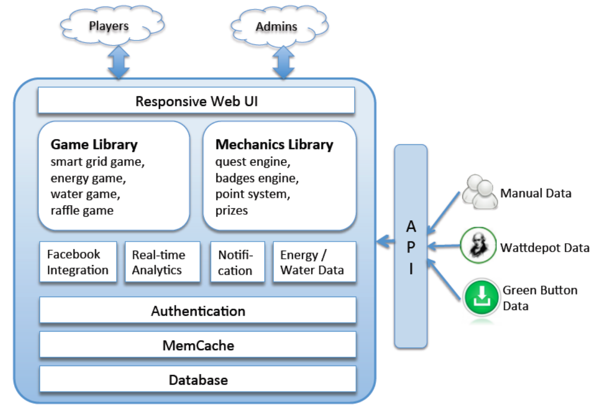


Figure 2: Architecture of Makahiki

(hence the name "Smart Grid") and organized by category columns. The game supports levels so that a large number of activities can be presented in a sequence of smaller grids. Each grid contains four different types of actions: activities, commitments, events, and excursions.

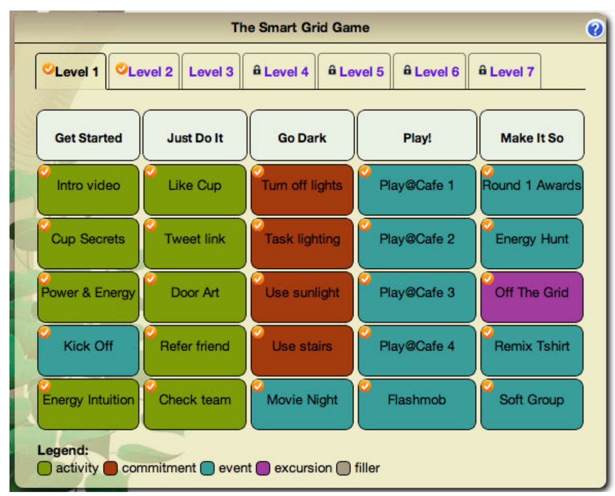


Figure 3: *Smart Grid Game widget*

Activities are the most basic action available in the Smart Grid. In order to get points for an activity, a player will have to provide a response to the administrators. These responses can be a short textual answer or an uploaded picture. Administrators access a special section of the web application to approve or deny submissions. If a submission is approved, the player will receive the points for their submission. Otherwise, a player will be sent a website notification informing them that their submission was not approved, and a textual description by an administrator of why it was rejected. The player can change and resubmit their response and still earn the full point value for that activity.

Commitments are pledges that the player will do something sustainable for a period of five days. Examples include: reducing shower time, taking the stairs, and turning off the lights when leaving a room. Because these commitments are not verifiable, they are worth fewer points than activities. Furthermore, a player can only have up to five active commitments at any given time. After the five day period is up, the player can then declare that they completed the commitment and immediately earn their points. They can then sign up for another commitment, including the one they just completed.

Events and excursions are tied to real world activities. Events are held locally while excursions require transportation. Seating is limited, so players are asked to sign up for events they wish to attend. Players that do so are provided with a 2 point signup bonus. Players can also set up a reminder that is sent to their email and/or their mobile phone before the event takes place. At the event, an administrator will hand out attendance codes printed on slips of paper that can be entered on the website. These attendance codes are generated by Makahiki and can only be used once. To discourage players from signing up and not attending, a 2 point penalty is assessed to players who do not submit an attendance code. If the player submits an attendance code for the event after receiving this penalty, the penalty is reversed.

Not all of the actions in the Smart Grid Game are necessarily available at the start of the game. We provide a set of predicates that can be used to determine if a action is locked or unlocked for a player. These predicates include: completed a certain number of actions within a category, completed all actions within a category, completed certain actions, and time-based unlocking (available after a certain date).

These predicates are implemented using a limited subset of Python and can be changed within the administrative interface. Challenge designers can use logical operators to combine any of these functions in order to organize the players' path through the Smart Grid Game.

3.2 Power Meter

A fundamental requirement for enabling more active participation by consumers in the smart grid is feedback regarding their energy usage. One of the most simple mechanisms provided by Makahiki for this purpose is the Power Meter widget, illustrated in Figure 4.

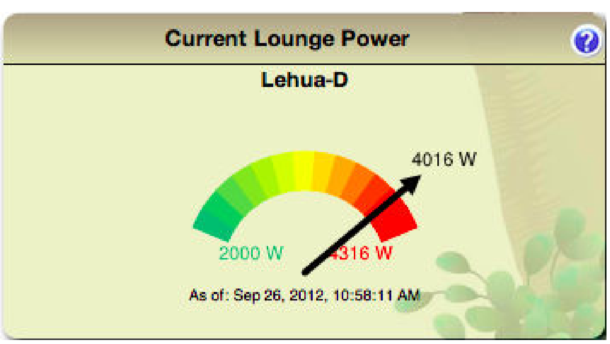


Figure 4: ***Power Meter widget***

The Power Meter widget provides basic feedback on energy consumption via a display of the team's power consumption, updated every few seconds. The visualization can normalized using baseline values so that when the needle is pointing straight up, the power consumption is the average for that team during that specific hour of that specific day of the week. Thus, if the needle leans left toward the green side, the team's power consumption at that moment in time is below average, while if the needle leans right toward the red side, the team's power consumption at that moment in time is above average.

The Power Meter widget obtains its values by querying the WattDepot system for the latest power data consumed by the associated team. The use of WattDepot, rather than directly querying the meter(s), simplifies the widget design significantly. First, the physical meters can vary significantly in the protocol implemented to obtain current power consumption. These protocol variations are handled by the WattDepot sensors, so this widget can simply query the WattDepot server using a simple single HTTP request that is independent of the physical meter characteristics. Second, the power consumed by a team might be measured by one or multiple meters. Again, the WattDepot source aggregation capability means that this physical difference can be abstracted away by WattDepot, enabling the widget to obtain the aggregate power for the team through a single HTTP request.

The Power Meter widget is a useful, though simple mechanism for energy feedback that uses the WattDepot+Makahiki stack. The next section presents a more sophisticated mechanism called the Daily Energy Goal Game.

3.3 Daily Energy Goal Game

The Daily Energy Goal Game widget provides a way for players to earn points by reducing their current energy consumption from a baseline. This baseline can be calculated using historical data or dynamically throughout the competition. Both the baseline data and the current consumption is typically provided by API calls from Makahiki to an underlying WattDepot server. Figure 5 illustrates this widget.

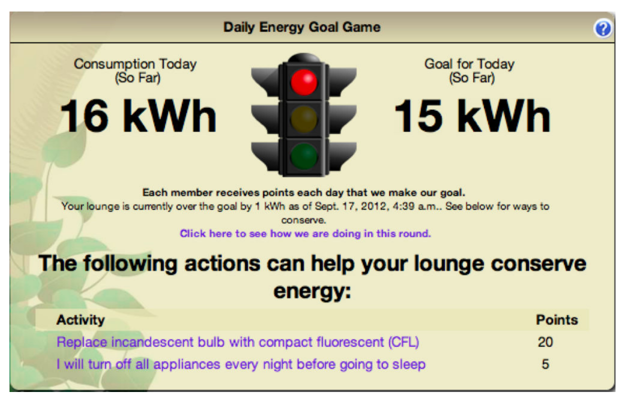


Figure 5: ***Daily Energy Goal Game widget***

The goal for each team is typically a percent reduction from their baseline usage. When a player goes to the energy page of Makahiki, they can view their team's current progress toward their daily energy goal. Near the end of the day, Makahiki checks the energy data from Wattdepot to see if a floor reached their goal. If the floor did reach their goal, each member of the floor that is participating in the game receives points. The energy goal game provides a link between the energy conservation competition and the point competition.

The Daily Energy Goal display shows both their current progress and their goal so far for two reasons. First, everyone will be under their actual energy goal for most of the day, so this display would not be very useful. Second, we have noticed that our participants use more energy at night rather than during the day. Thus, it is easy to be under for most of the day and then jump over the goal at the very end. Displaying their progress toward the goal so far provides a pace for players to follow.

3.4 Raffle Game

The Raffle Game widget provides a way to incentivize participation from all individuals, even those who are not in the running for a top prize. For every 25 points a player earns, they receive one virtual raffle ticket. Players can dynamically allocate their tickets to any raffle prizes they are interested in at any time, up to the end of the raffle. Figure 6 shows an example of the Raffle Game.

Round 2 Raffle Game

Your total raffle tickets: 5 Allocated right now: 2 Available: 3

Prize	Value	Your tickets	Total tickets	Current odds	Change ticket allocation
Recycled bike	$200.00	1	2	50.0%	+1 -1
UH t-shirt (1)	$28.00	1	1	100.0%	+1 -1
Outback card	$25.00	0	0	0.0%	+1 -1
Smart strip (2)	$25.00	0	0	0.0%	+1 -1
Smart strip (1)	$25.00	0	0	0.0%	+1 -1
Down to Earth card	$25.00	0	0	0.0%	+1 -1

Figure 6: ***Raffle Game widget***

Players can dynamically allocate their tickets to any raffle prizes they are interested in at any time, up to the end of the raffle. Each round of the competition has its own set of raffle prizes and any unused raffle tickets carry over to the next round. Raffle tickets are independent from a player's score; allocating a raffle ticket does not affect their rank.

3.5 Social and Referral Bonuses

The Social and Referral Bonus widgets provide game mechanics that help encourage participation by providing additional points to players who participate in activities with other players and/or facilitate the entry of new players into an energy challenge.

The social bonus is an configurable option when an action is created in the Smart Grid Game. Players receive earn extra points if they perform the action with another player. Examples of actions with a social bonus include attending an event, recording a song related to energy, or measuring a shower water flow rate. When a player submits a response for a action with a social bonus, the player can provide the email address of the person who jointly completed the action. Once the other player completes the action, the social bonus is awarded. Social bonuses are not bi-directional; if the second player doesn't provide the first player's email address, only the first player will get the social bonus.

Players are led through a setup process when logging into Makahiki for the first time. One of the steps in this process is the referral bonus. If a player was referred by another player in the system, they can use this step to input their email address. Once the new player earns a certain number of points in the competition, both players are awarded a referral bonus of a configurable number of points. Typically, going through the setup process gives you 25 points, so setting a point threshold of 30 points encourages the new player to at least complete one additional action in order to get the referral bonus.

3.6 Quest Engine

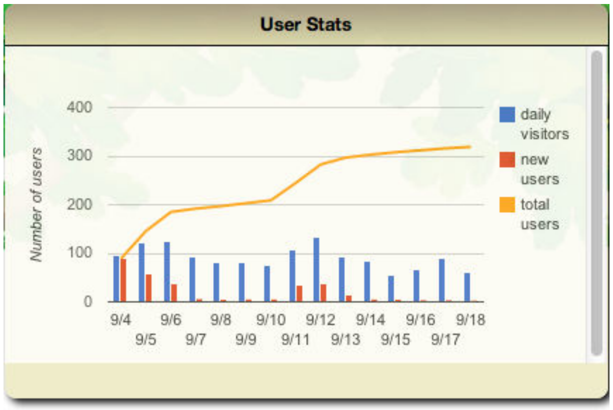
One challenge we faced when designing Makahiki was providing adequate help to the player. The game needed to be intuitive, even if a new player coming to Makahiki has not participated in an energy competition. Unlike many web applications, such as email, game players generally do not know in advance what specific actions they wish to accomplish. In an effort to provide a player with guidance through Makahiki after the setup process, we implemented the Quest Engine. Quests are used to guide the player through the various workflows of the site, like completing a action, signing up for an event, or allocating a raffle ticket. These quests can be created using the administrative interface. Quests use a set of predicates to determine unlock and completion conditions. These predicates include: participating in a action or type of action, completing a action or type of action, having a certain number of points (in a round or overall), completing a certain number of actions in a category or of a given type, being awarded a badge, writing a post on their floor wall, and adding a picture to their profile.

3.7 Game Analytics

Makahiki is designed to support energy challenges involving hundreds or thousands of users lasting weeks or months. In these circumstances, effective use of the technology requires the ability to understand the state of the game, such as: Who is using it? What are they doing? What is the player response to activities, commitments, excursions, and events? Such state information is important for planning purposes, such as assessing the transportation needs for an upcoming excursion by seeing how many players signed up. It can also be used for making in-game changes to game design, such as changing the point values associated with activities to encourage or discourage participation. It can also help identify breakdowns in game play, such as significant numbers of unallocated raffle tickets indicating that users do not understand the nature of that game mechanic.

To address these needs and others, Makahiki includes a variety of widgets that work together to provide high level overview of game play state to the administrators of a challenge. Figure 7 shows an example of two game analytic widgets.

The top widget, User Stats, shows trends in the total number of players, the total number of new users, and the total number of players visiting the site each day. The bottom widget



Energy Goal Status

Team	09/16	09/15	09/14	09/13	09/12	09/11	09/10
Lehua-A	-16 87	-2 87	-5 86	-9 87	-8 85	-5 88	-3 87
Lehua-B	-14 101	-7 100	-14 100	-11 101	-12 100	-9 104	-13 99
Lehua-C	-9 91	-2 85	-4 90	-5 92	-4 92	-2 94	-9 92
Lehua-D	-1 94	0 91	-1 92	0 95	2 98	2 97	2 99
Lehua-E	-14 82	-6 77	-4 85	-12 88	-6 91	-4 92	-13 86
Ilima-A	-14 87	-6 89	-5 87	-13 85	-8 87	-13 86	-15 83

Figure 7: Game analytic widgets: User Stats and Energy Goal Status

provides information on the ability of teams to achieve their daily energy goal each day and over time.

We have now introduced the primary components of our software stack, WattDepot and Makahiki. The next section presents our experiences and lessons learned so far.

4. EXPERIENCES

To better understand the strengths and weaknesses of the Makahiki+WattDepot software stack, we have been designing and implementing an "Energy Challenge" called the Kukui Cup. Development of the Kukui Cup challenge began in 2009, and the first Kukui Cup challenge was held in 2011 for over 1,000 first year students living in the residence halls at the University of Hawaii (UH) in Fall, 2011. In Fall 2012, the second Kukui Cup challenge was held at the University of Hawaii using Makahiki+WattDepot. In addition, Hawaii Pacific University (HPU) held a Kukui Cup challenge using Makahiki+WattDepot. Finally, an international organization called the East-West Center (EWC) held a Kukui Cup challenge using just Makahiki (their energy data was manually gathered by reading meters and entering the data by hand, so WattDepot was not needed for their challenge).

The successful creation of four challenges by three different organizations over two years provides evidence that the software stack can be tailored to the differing needs of separate organizations. First, UH uses meters by Electro-Industries Inc., while HPU uses meters by EGauge Inc., and EWC collected their energy data manually. Second, while UH and HPU challenges involved only energy consumption data, the EWC challenge involved both energy and water consumption data (which was also collected manually). Third, the IT infrastructure at UH and HPU provided authentication services using CAS and LDAP, while EWC used the built-in Django authentication. Fourth, the user interface was customized to "brand" each challenge with the logo and other thematic elements of the sponsoring organization.

On the other hand, it should be recognized that these organizations are in other ways quite similar: they are all institutions of post-secondary education, and they are all based in Hawaii. These organizational similarities are mostly due to the desire by the 2012 challenges to reuse a significant amount of the content developed in 2011, which was oriented toward the Hawaii-based, college-aged demographic. For 2013 and beyond, we hope to expand our experiences with the software stack "downward" into primary and secondary schools, and well as "outward" into residences and businesses.

User response to the 2011 UH Kukui Cup challenge was positive, and provided evidence regarding the software stack's usability, functionality, and performance characteristics. Over 400 students participated, for an adoption rate of approximately 40%. In a user survey conducted near the end of the challenge, over 90% of users said they would participate in the challenge again if offered an opportunity. 60% said "ease of use" was the thing they liked best about the website. 40% responded "Nothing" when asked what was confusing about the website, and 32% responded "Nothing" when asked what they would change about the website. The survey did yield insights into what could be improved, including the ability to introduce new games at points during the challenge, to provide better access to other player data, and to simplify navigation. There was virtually no downtime during the 2011 challenge, and only one significant bug in the system (affecting scoring) was discovered during the challenge, which was fixed within a day of its discovery. Finally, a pre- and post-challenge survey questionnaire yielded statistically significant evidence that participants in the challenge learned more about energy concepts than those not participating, demonstrating that the approach can serve to improve consumer knowledge of energy as needed for active engagement with the Smart Grid.

The 2012 challenges are ongoing as of the time of writing, so the following results must be viewed as preliminary, but our current experience is similarly positive to 2011. The UH challenge participation rate so far appears to be slightly lower than last year, at about 33%, though the HPU challenge participation rate so far is higher (approximately 50%), and the EWC participation rate is much lower (around 6%). None of the challenge instances have experienced significant downtime, and so far only 1 significant bug (affecting scoring) has been reported (and has again been fixed within a day). Load testing of the software stack just prior to the 2012 challenge indicates a hypothetical throughput of around 200 concurrent users with acceptable page loading times, though we have not experienced that level of load in the current challenges.

Our experiences over the past two years has provided many lessons learned, and some of the most important regarding the Makahiki+WattDepot software stack are:

Collecting energy data is challenging. As alluded to in our discussion of WattDepot, collecting accurate energy data requires significant planning and effort. The process of installing meters for the 2011 UH Kukui Cup started over one year before the meters were finally installed and ready for use, despite the cooperation and goodwill of all involved parties. Gaining an understanding of the electrical infrastructure of the residence halls proved crucial in the success of the UH Kukui Cup, as a renovation project led to the installation of additional distribution panels and thereby doubled the number of meters that were needed to measure electricity use. Due to delays in the installation of the meters for the 2011 UH Kukui Cup, a meter installation problem that led to inflated energy readings for one floor was not discovered until after the competition was complete and an energy audit of the building could be performed. Manual data collection also poses a variety of challenges. Existing meters for electricity and water may be configured for coarse monthly readings rather than the daily readings that are needed for a competition. Existing meters may also be installed in dirty or difficult to reach areas that make daily data collection unpleasant. If the challenge administrators wish to examine energy or water use after the challenge is complete, to determine if behavior changes made during the challenge are sustainable, daily manual data collection requires a long-term commitment. The lesson learned is for challenge administrators to start planning how they will obtain energy or water data as early as possible, since they are likely to encounter many challenges in collecting the data.

Cloud-based hosting simplifies installation. During 2012, we have gained experience with both cloud-based hosting as well as local installation for the Makahiki+WattDepot software stack. We have found that cloud-based hosting significantly simplifies the installation process and avoids certain types of installation-related bugs from occurring, particularly when system administrators are not familiar with the stack components that Makahiki+WattDepot depend upon (Django, Java, Python, git, etc.) On the other hand, cloud-based hosting incurs costs (in our experience, between $50-$100/month for these challenges) and may incur constraints (for example, the Heroku hosting platform currently has minimal support for LDAP authentication). The Makahiki Manual [12] provides instructions for both cloud-based and local installation, providing some idea of the differences between the two approaches. The lesson learned is to use cloud-based hosting when possible, or allow plenty of time for administrators to work through the software stack installation issues. Makahiki+WattDepot is not yet a "plug-and-play" system.

Challenge design and administration is time consuming. Despite the freely providing the Makahiki+WattDepot software stack to HPU and EWC, along with content developed specifically for college-age residents of Hawaii, the administrators still expressed surprise at the how time consuming it was to design and administrate the running of their respective challenges. This appears to be due to the fact that the software stack enables a variety of game mechanics (such as the Smart Grid Game, Raffle Game, Badges, and point-based Prizes) not present in more simplistic energy challenges. For example, the Smart Grid Game requires configuration of the widget including what activities to include and when/where they appear in the game. The Raffle Game and point-based awards requires the collection of appropriate prizes. While we provided a library of almost 100 activities from 2011, all of the 2012 challenges required the definition of at least a few new events. Thus, although the result is a more sophisticated experience for the participants, the up front design and overhead during execution was generally surprising to the administrators. The Kukui Cup Challenge Planning Guide [10] provides more details on this process. The lesson learned is to make sure that potential organizational sponsors understand that the use of this software technology is not intended to make it more simple for them to run an energy challenge, but rather to enable them to create a more sophisticated energy challenge than would otherwise be possible.

Scalability cuts across both design and implementation. So far, the use of the Makahiki+WattDepot software stack has been limited to relatively small user communities of 1,000 participants or less. We believe that the system and approach would scale relatively well to some small number of multiples of that number, say to a maximum of 10,000 challenge participants. On the other hand, there are both design and implementation challenges in scaling the software stack to communities of significantly larger than 10,000 participants.

On the design side, Makahiki currently requires administrators to approve each submission by a participant in order for that participant to receive points. In the UH challenges, that results in administrative approval of around 4,000 individual submissions over the course of the challenge. This incurs administrative overhead, but makes it easier to verify that players are actually taking part in activities and improves the sense of fairness in the game. On the other hand, we do not believe this approach would be practical if there were an order of magnitude more submissions to process. To scale, the current manual approval process must be automated, and must be done in a manner that preserves essential game mechanics. For example, simply changing the current short answer verification format by multiple choice could result in players just randomly selecting values until they find the right one. Multiple choice also does not support certain types of activities where the submission consists of a link, a photo, or even a poem. So, scaling up by an order of magnitude might affect the types of activities that can be supported in the challenge. Peer review of action submissions is one possible solution, but would require careful design and testing to ensure the competitive nature of the challenge does not encourage unfair evaluation of submissions.

On the implementation side, our current performance testing indicates a maximal throughput of approximately 200 concurrent users. Interestingly, increasing the number of server/web processing resources available through cloud-based hosting does not appear to appreciably increase maximal throughput. Thus, it does not appear to be true that cloud-based hosting will magically "solve" the scalability problem for the Makahiki+WattDepot software stack. Because the current level of throughput is adequate for the communities we are current targeting, we have not investigated this issue further. The lesson learned is that if an organization wants to perform an energy challenge for a community of more than 10,000 users, significant design and implementation challenges must be addressed.

5. CONCLUSIONS/FUTURE DIRECTIONS

Our experiences thus far with the Makahiki+WattDepot software stack have shown it to be a reliable and performant system for the provision of sophisticated energy challenges to address the need for informed consumers in the development of the Smart Grid. Its tailorability and game analytics provides a useful platform for research on gamification, energy education, and behavior change.

One future direction involves the development of a consortium of local organizations in order to explore the use of this software stack in new settings. This will create challenges at both the design and implementation levels. Moving outside of the context of either Hawaii or college-aged users will necessitate development of significant new forms of content, including activities, workshops, events, and videos. This challenge, while significant, does not necessitate significant changes to the Makahiki+WattDepot software stack.

A far more challenging future direction is an island-wide Kukui Cup, in which all of the residents of Oahu would be able to login to the system and play the game. This creates challenges on multiple levels: providing content appropriate to the user (an elementary school student should have activities different from her mother and father), obtaining energy data for residential users from the local utility in a manner appropriate for the challenge and interfacing this data with the system, and finally resolving the scalability problem identified in the last section. We will require the engagement of multiple stakeholders from across the community spectrum to identify and resolve these issues.

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