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Understanding citizen perspectives on open urban energy data through the development and testing of a community energy feedback system

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HIGHLIGHTS

- Open urban energy data is emerging data that can support energy decision making.
- Greater citizen awareness and action is critical to achieve needed energy savings.
- We develop a novel mobile-based community-scale energy feedback system.
- We collect citizen-centric perspectives assessing open urban energy data feedback.
- Citizens have strong interest in receiving this feedback at multiple spatial scales.

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ABSTRACT

With the rise of advanced and affordable sensors offering continuous monitoring of city infrastructure, cities are increasingly seeking to become more ‘smart’ and are adopting data-driven approaches to help meet sustainability goals. In the area of building energy efficiency, closely coupled with this effort is the prevalence of building energy benchmarking policies, which require public disclosure of vast new quantities of building-level energy data at urban scales (i.e., open urban energy data). While existing research efforts have focused on the potential of this data to transform energy efficiency markets and investments in the real estate sector, little research has been dedicated to assessing this information’s value to the general public. Given that achieving energy reductions in the built environment will require not only energy efficiency investments, but also greater awareness, engagement, and action from ordinary citizens, we study the potential of open urban energy data in providing citizen benefits. Energy-cyber-physical systems offer a pertinent framework to link data from the virtual world to citizens’ physical reality in order to improve their understanding and decision making. Adopting an energy-cyber-physical system perspective, we aim to connect open urban energy data to citizens through the development and evaluation of a novel community-scale energy feedback system. This mobile cyber-physical system transforms building-level electricity consumption and production data across Georgia Tech’s campus into a mobile application consisting of three features: spatial feedback, energy supply feedback, and energy consumption feedback. Augmented-reality visualization elements are integrated into the system, providing Georgia Tech community members a direct link between their experienced physical environment and data stored in the virtual world. Applying a user-centered design approach, prospective users evaluate the system via thinking aloud sessions and user surveys to assess understandings and perceptions of open urban energy data for the Georgia Tech campus. The results contribute to literature seeking to create energy feedback systems at the community-scale and expand research investigating citizen reactions to and opinions of open urban energy data. This research is an integral step to further engagement and participation from the public to help achieve a sustainable and citizen-valued energy future.

1. Introduction

Cities around the globe are heavily investing in becoming ‘smart’. World-wide investments in technology for smart city initiatives are expected to grow from more than $81 billion in 2018 to $158 billion in 2022 [1]. While smart city definitions encompass broad variations, common across all perspectives is the aim to address an urban issue—whether it be energy, safety, health, mobility, or financial in

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nature—with an approach that is mediated through technology [2]. Fostering citizen learning, participation, and benefit is an important element of smart city frameworks, and critiques have pointed out that this element is often glazed over, with greater emphasis put on technological progress and development in digitizing our cities. One prominent smart city paradigm area with a high potential to involve citizens is open data initiatives. Providing open data to citizens is envisioned to enable transparency of government operations, provide social and commercial value, and increase participatory governance [3].

Within the energy sector, open data is an emerging resource made possible through technological innovations, such as smart metering infrastructure [4], and new policies, such as building energy disclosure ordinances [5]. Although researchers have documented the potential value of this data to private stakeholders such as building owners, investors, and utilities, little research attention has been drawn to the use of this data to empower and promote engagement from citizens with their energy systems [6]. Connecting this data with citizen interest and decision making will require transforming it in a way that improves its usability and accessibility. Energy-cyber-physical systems (e-CPSs), applied in a citizen-centric manner, present an excellent opportunity to help transform energy data to be more useful to citizens. Energy-cyber-physical systems aim to link the physical world (i.e., where citizens are most familiar) with the virtual world (i.e., where data is collected and analyzed), to enable more informed decision making [7,8]. In this paper, we build on the concept of e-CPSs with a focus on citizens as the end-user in the context of what we define as *open urban energy data*. We transform this data into easily usable information through the creation of an open urban energy data feedback platform, and assess citizen interactions with this system to evaluate its viability and value in supporting citizen decision making.

2. Background

2.1. Open urban energy data and the role of citizens

Public reporting of energy data through mandated building energy disclosure laws is driving a shift in the transparency of building energy production and consumption information across cities [9]. For example, as of February 2019, 28 cities and 3 states in the US have enacted building benchmarking or disclosure ordinances [10], enabling public access to what we define as *open urban energy data*. Outside of the US, open urban energy data initiatives such as the European Union's Energy Performance of Buildings Directive have been enacted, requiring public buildings to present Display Energy Certificates [11]. Researchers from economics domains have focused on the potential of open urban energy data to transform energy efficiency markets by supporting building portfolio owners with performance management, guiding investors with energy financing decisions, and increasing the value and marketability of commercial buildings [9]. Noticeably, use cases and potential benefits of this data has focused on stakeholders interacting close to the real estate industry [6,12]. While the general public has been briefly mentioned as a potential user [6,12] little research has examined in detail the potential of citizens as data users in the context of open urban energy data. As one of the core tenets of open data is to provide use and benefit to the public [3], it is worthwhile examining public understanding of open urban energy data and their interest in using this information to help with decision making.

Importantly, the release of this data coincides with a growing interest from researchers and governments about the role of citizens with our future energy systems. A substantial body of research has called for a reconceptualization of ordinary citizens from passive energy consumers to active stakeholders and innovators in creating new and more sustainable energy systems [13,14]. Citizen participation during energy project assessments and development is integral to see a project successfully come into fruition and integrate into a community [15]; citizens increase the dissemination and adoption of energy technologies [16], improve the acceptance of projects or technologies [14], help designers incorporate social and environmental contexts into a project [17], and enhance the design of the project or technology itself [18]. The many ways citizens can improve energy systems reflect the broad roles citizens could have in the future in relation to energy in their community.

Expanded citizen roles with energy systems in the future will undoubtedly be mediated by technologies and data. E-CPSs integrating open urban energy data have immense potential to be a resource to citizens, and support education and decision making in their expanding roles. Integral to this effort is determining how to shape and present this data in a way that is meaningful, usable, and engaging to citizens.

2.2. Providing open urban energy feedback to citizens

Few researchers have focused on the best ways to shape and communicate open urban energy data to citizens. Kontokosta and Tull [19] commented on how the current format of such data is most often provided in tabular spreadsheet format, making it cumbersome to analyze and relatively inaccessible to most potential users. To address this, they created an interactive web-based platform visualizing New York City's building energy benchmarking data. While the tool was built for a variety of stakeholders, it was primarily geared towards building portfolio owners and managers. Since the development of this tool, other cities have released web-based visualizations of open urban energy data such as Chicago [20], Los Angeles [21], and Seattle [22], and researchers have created platforms displaying detailed building sustainability metrics across groups of buildings [23]. These tools apply a variety of techniques to communicate building energy information. While there has been a growing interest by governments and researchers in creating these platforms to improve accessibility and awareness of open urban energy data [24,25], two critical elements have yet to be examined by researchers in the development of these platforms: (a) how to design these systems for *citizen* understanding and engagement, and (b) incorporation of user feedback during the platform *design* stage.

Expanding on the first critical element, one well-developed area of research focusing on developing tools to assist in communicating of energy data to lay audiences is energy feedback system research. Energy feedback entails communicating building energy consumption information to occupants through typically computerized means in a way that aims to be appealing to building occupants, improve awareness, and motivate pro-environmental behaviors [26,27]. More recent literature on energy feedback has called for the expansion of energy feedback to the community-scale [28,29]. While the definition and scope of community-scale energy feedback has not yet been formally characterized, several recent studies have explored the potential of community-scale aspects within energy feedback. Burchell et al. [30] deployed an energy feedback system as part of a larger community-scale program, and focused on how community-specific communications affected engagement. Their findings highlighted how communication strategies that are specific to a community's context, such as placing an individual's performance in the context of the community's energy events or goals, can improve the engagement with an energy feedback system. Another recent study took a different approach by creating a spatial map to communicate neighborhood-level energy consumption, and found it was useful for community groups engaging with energy issues in their community [31]. While both of these studies represent novel approaches for expanding energy feedback to the community-scale, to our knowledge an approach for designing community-scale energy feedback in the context of open urban energy data and citizen engagement has yet to be explored.

In addition, gathering feedback from users beyond the system designers and during the design stage is integral to ensure the system is appropriate for citizens as end users. User feedback can also help gather information on ways people envision open urban energy data could be useful. Literature has long drawn attention to importance of end user engagement during the design of technologies that humans will interact with [32,33]. In the context of smart energy feedback technologies, such systems have been typically designed in a way that reflects the needs and desires of the designer(s) rather than the intended users of the system [34,35]. Geelen et al. [29] evaluated the extent that energy technologies for smart building systems empower and enable citizens to undertake more involved and educated roles. Their findings illuminate an often observed disconnect between smart energy technology design and the end-user; design decisions rarely involved the end-user, and instead focused on technical and financial incentives grounded on the assumption of a rational end-user. Neglecting user involvement during the design phase impacts technology acceptance, engagement, and effectiveness over the long term [33,36].

Across cities, open urban energy data is becoming increasingly available online [6,10], however, public availability of this data does not imply usability, particularly for ordinary citizens. As there is considerable research attention stressing the need for increased citizen engagement and understanding of our future energy systems [13,14], access to and interaction with open urban energy data may have a role in expanding citizen understanding and involvement. However, currently little research has focused on development of feedback tools for citizen engagement and their perspectives on open urban energy data. There are two primary objectives of this paper to help address this. The first objective is to develop a community-scale energy feedback system designed for citizens as data users, and document the design and development framework for this system. In this process, we leverage open urban energy data and integrate elements from cyber-physical systems to connect virtually stored data with the built environment [8]. The second objective is to engage prospective users in the design of the developed system, gather feedback from expected future users about the system and assess more broadly the potential of these data for use by the general public to support decision making. It is envisioned that the developed system has potential to connect citizens with open urban energy data in a way that was previously not possible without this approach (schematic in Fig. 1). In the following section, the approaches applied in the development and user evaluation of this system are described.

3. Methods

To carry out the first objective of the study, development and documentation of the design of a community-scale energy feedback system, we adopted a theory-driven approach [37]. This entails basing our design on findings previously established within the energy feedback literature, which is appropriate given the amount and depth of research already conducted on energy feedback system design and energy information communication. From these findings, which are summarized in the following sections, we identified three main functionalities to include in our community-scale energy feedback system: *augmented reality* feedback, *energy supply* feedback, and *energy consumption* feedback. Following the development of this system, we pursued the second objective of the study: to engage real, prospective users and gather their feedback regarding the design and information included in the system. For this aim, we employed a user-centered approach employed in the human-computer interaction field, which has been used for decades to evaluate user interfaces and gather feedback from prospective users [36]. We sought to examine not only if users could accurately interpret the energy feedback system, but also how interested people are in having access to this information in the first place. Through this approach, we sought to answer the following research questions:

1. Do users accurately understand and interpret open urban energy data portrayed through community-scale: (a) Augmented Reality feedback, (b) Energy Supply feedback, and (c) Energy Consumption feedback?
2. Do people want to seek out open urban energy data provided by community-scale energy feedback interfaces? Why or why not?

The following sections detail the technical architecture, design, and user testing approach; Section 3.1 pertains to the first objective of the study, while Section 3.2 details methods related to the second objective.

3.1. System design and architecture

Georgia Institute of Technology's (GT's) campus served as the testbed community to build our platform on. While city functions are generally more diverse and broad compared the functions across an academic university, university campuses have been regarded has embodying the heterogeneous facilities across a community or small town, as they are composed of a combination of offices, laboratories, recreation, health, food, retail, and classroom facilities [38]. In addition, similar to city municipalities, universities manage large and diverse property portfolios, and largely benefit from energy efficiency investments over the long-term. On GT's campus, each building is equipped with a smart meter, recording building electricity consumption and production data every 15-minutes. The system was designed to communicate both electricity consumption and production data. This data is comparable to open urban energy data, which is typically released at the building level and offers time granularity of varying degrees (from annually to every 15 min) [39]. The intent of the application is to place individual building performance in the context of the entire community's energy production and consumption goals as a whole. The application was built for mobile devices. The choice to create the platform for mobile device access was primarily to support the augmented reality functionalities. Additionally, mobile access to energy information also has potential to enable more timely feedback [40] and encourage simultaneous learning with multiple users [41]. As mentioned, a theory-based approach was adopted for the initial design of the system, as a substantial amount of empirically-tested design information exists within energy feedback. These findings are summarized in the following section, and are an expansion of the work conducted in [42].

3.1.1. Augmented reality feedback

Fundamentally, energy feedback systems aim to change people's energy behaviors through increased visibility and access to building energy consumption information. The Spatial view was developed to

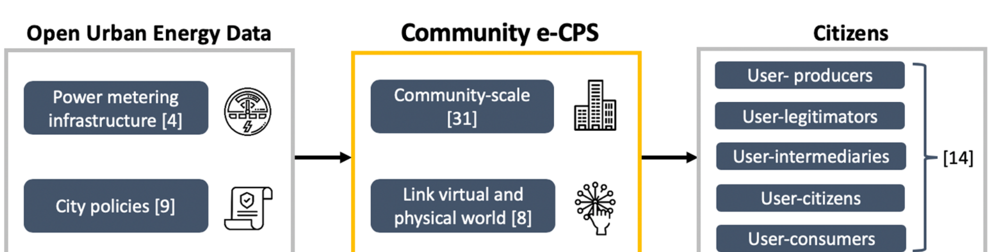

Fig. 1. High-level schematic depicting a community e-CPS as the mechanism linking citizens to open urban energy data.

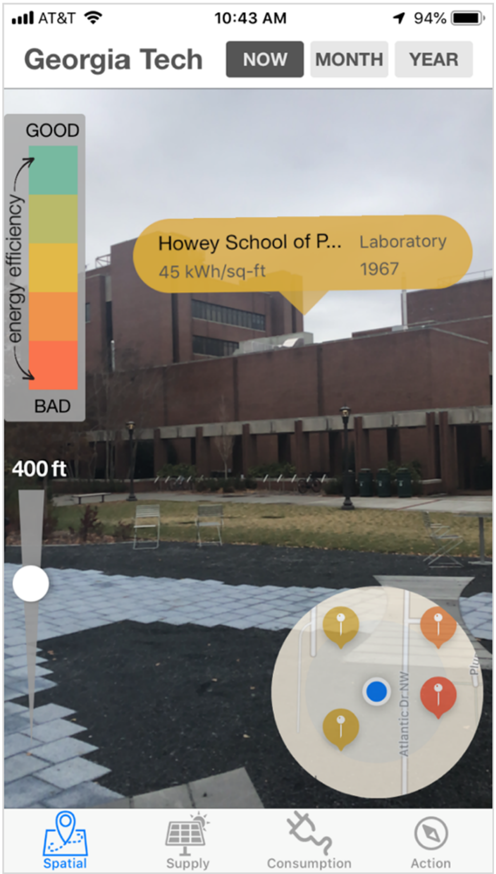

Fig. 2. Screenshot of spatial view.

promote the visibility of energy consumption using mobile Augmented Reality (mobile-AR) [43]. While application of AR technologies is limited within energy feedback research, educational fields have shown AR can increase learning by enabling users to explore technical information that is invisible in the real-world and engage with the spatial relationships contained in this information. Combining AR with portable and location-aware devices, such as mobile phones and tablets, mobile-AR affords greater context-aware and social learning through merging experiences in the real world with interactive virtual information [44]. Unlike conventional energy feedback displaying graphs, charts, or images on a screen, mobile-AR energy feedback combines the affordances of a real environment with the virtual world, adding more connections to a user's sense of reality. Applying mobile-AR energy feedback across buildings within a community may encourage interest in energy data, social learning, and discovery of more context-aware insights.

In the Spatial view, users look through a mobile device to visualize virtualized building energy efficiency information, demonstrated through color-coded icons augmented on top of the physical buildings in the real world (Fig. 2). As users stand or move around outside, icons appear based on their orientation and distance from a building. The color of the icon indicates the level of energy efficiency, based on a 5-color scale defined in the legend. Previous studies have encountered some user difficulty in interpreting color scales [45], thus the legend labels are added to explicitly indicate how a building should be performing (i.e., injunctive norm). Viewing energy use in this manner enables users to compare energy performance relative to other buildings in their community. Previous studies have shown normative feedback in energy feedback systems can evoke pro-environmental behaviors [46,47]. The color-coded icons also display energy efficiency levels in a numerical format, as combining color-coded aesthetics with numerical representation has been found to be preferable to users [45,48]. To calculate a building's energy efficiency level, its Energy Use Intensity (EUI) is compared to the rest of the buildings in the sample for each time range (i.e., now, month, year). The following equation expresses the calculation performed to construct the yearly EUI,

$$YearlyEUI_i = \frac{\sum_{j=1}^{35,040} e_j}{area_i} \tag{1}$$

where i is each building in the sample, e is the electricity consumption (kWh), and j is each 15-minute increment, totaling 35,040 increments per year. Building EUI is calculated for each time range, where j is adjusted to be the number of 15-minute increments in each time interval. In addition to the augmented icons, user interactivity, which has been shown to improve engagement [27], is enabled through: (a) toggling efficiency values between different time ranges (buttons at top of screen), and (b) adjusting the distance from the user that the icons will appear (slider at left of screen). 'Now' indicates the building's current EUI (i.e., EUI during the most recently reported 15-minute interval), while the 'month' and 'year' are equivalent to the calculated EUI over the past 30 or 365 days, respectively. Visualization of efficiency icons have duel-coding in the map at the bottom of the screen, showing a bird's eye view of the icon locations.

3.1.2. Energy consumption feedback

Energy consumption is a fundamental metric represented in energy feedback systems. The Energy Consumption view aims to communicate energy consumption relative to four different benchmarks: historic consumption, peer consumption, community consumption, and consumption goals. Previous studies have shown that contextualizing energy consumption can promote user understanding of performance and encourage behavior change [49]. Other studies have gathered through user interviews that users can mistrust some comparisons, particularly with their peers, due to inherent differences between building characteristics and operations [37]. Combining multiple points of comparison, such as peer and historic or peer and goals may help ensure metrics resonate with users.

At the top of the Energy Consumption view (Fig. 3), the campus' energy reduction goal is stated. Below, an interactive graph is provided where the user can toggle between different buildings on campus. The bar graph demonstrates the four points of normative comparison. The x-axis shows historic energy consumption from previous years. The blue bars show campus energy consumption in relation to the selected building (red bars). The horizontal lines indicate the baseline threshold from 2013 and the energy goal reduction for 2020. An injunctive norm is constructed through the emoticon on the screen, which changes based on the individual building performance. If the building's energy use increased over time, the emoticon changes to an unhappy expression. If the building reduced energy use, but at a slower rate than the rest of the campus, the emoticon expression is neutral. Injunctive norms have been found to be particularly effective at encouraging efficient performers at sustaining efficiency levels [50]. Finally, community-based language (e.g., "together we can…", "spread the word…") is included at several points in the interface to encourage a shared group identity [30].

3.1.3. Energy supply feedback

While traditional energy feedback platforms have focused on energy consumption, greenhouse gas emissions of energy sources delivered to a community varies drastically. In addition to improving energy efficiency, transitioning to low carbon energy sources is just as important a way to achieve clean energy goals. Studies have recognized that transitioning to low carbon sources will likely involve greater citizen engagement, such as coordinating with neighbors to help match supply and demand for individual or co-generation [29]. The Energy Supply view aims to connect users not only with how energy is consumed in a

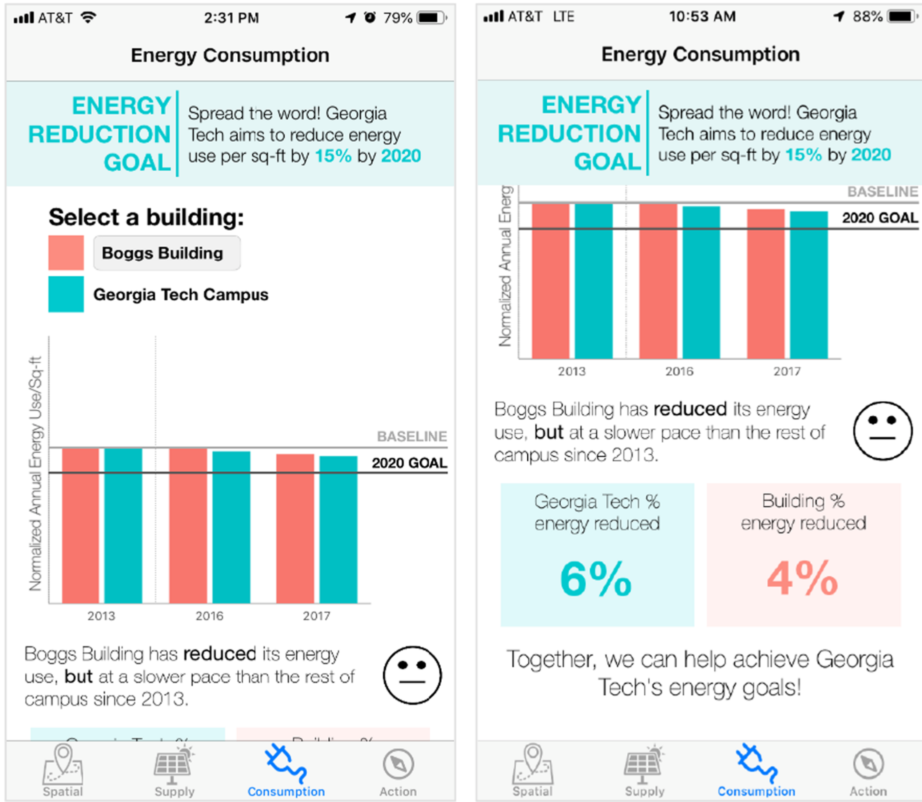

Fig. 3. Screenshot of consumption view.

community, but also how it is supplied.

The Energy Supply view displays a breakdown of electricity sources, from fossil fuels to renewables, in the context of the community's renewable energy goals (Fig. 4). The header of the screen contains the renewable energy target for a community. Goal setting has been implemented in many energy feedback applications [51] and has been

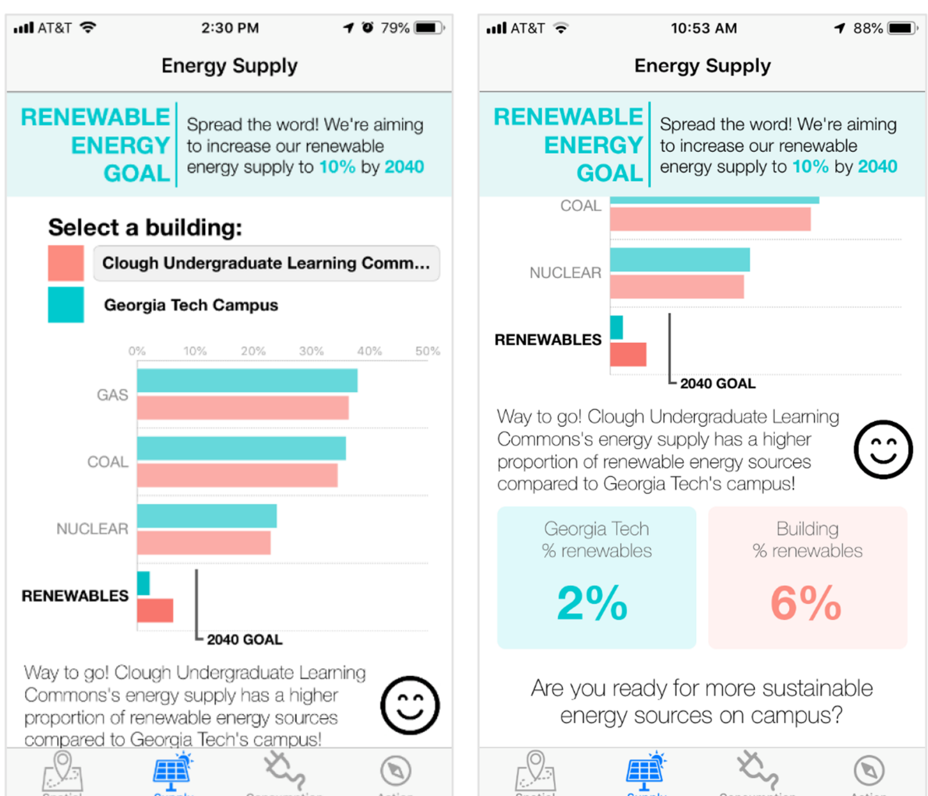

Fig. 4. Screenshot of supply view.

Table 1
Participant interpretation of community-scale energy feedback features (Survey Questionnaire Part 1).[a]

Question ID	Question	Question type
AR1	If a building's icon is red, what do you think this indicates about the energy efficiency of the building?	Open-ended
AR2	If the button "Month" is selected, why do you think the color of some icons change?	Open-ended
S1	What do you think the happy face on the screen indicates?	Open-ended
S2	Based on the screenshot above, how much of the Georgia Tech campus energy supply comes from renewable energy sources?	Open-ended
S3	Based on the screenshot image above, has the Georgia Tech campus reached its renewable energy goals yet?	Open-ended
S4	Based on the screenshot image above, most of Georgia Tech's energy comes from what resource?	Open-ended
C1	What do you think the 'Baseline' label refers to?	Open-ended
C2	What building(s) do the red bars in the graph refer to?	Open-ended
C3	Based on the screenshot image above, has the Boggs building reduced its energy use at a faster or slower pace compared to the rest of the campus?	Open-ended
C4	Based on the screenshot image above has Georgia Tech reached its campus energy consumption goals yet?	Open-ended
Overall	As a whole, do you think this application offered: (A) Too much information, (B) Too little information, and (C) Just the right amount of information. • (*conditional follow-up for responses A or B*) Why? If you could add/remove one feature, what would it be?	Multiple Choice

[a] Each of these questions were followed with a 5-point Likert scale question asking users to report how confident they were in their answer, which are not listed in the table above for brevity.

shown to motivate pro-environmental behaviors [52,53]. Below the goal, an interactive chart displays the community's progress in reaching their goal. The types of energy sources provided include coal, natural gas, nuclear, and renewable energy sources. In this case, the percentage breakdown for each source came from Georgia Power, the sole electricity provider to the campus. Thus, building comparisons of electricity sources only change if a building produces its own electricity, such as through a solar installation or the use of geothermal. Users can interact with the graph to compare any building's electricity source breakdown to that of the entire campus in the context of the campus's renewable energy goals. Normative comparisons are complemented by injunctive norm, similar to the Energy Consumption view. Normative feedback literature has documented a boomerang effect, where users that are performing better than average sometimes reduce their performance. Injunctive norms have been found to help combat this behavior by indicating approval of their actions [50].

3.1.4. Platform architecture

The mobile-based application was created by the authors. We chose to develop the application using Swift 4 programming language and the Xcode Integrated Development Environment (IDE), thus the application is available on iOS mobile devices. Multiple packages were used to support the development. Within the Spatial view, ARKit, MapKit, CoreLocation and SpriteKit frameworks [54] were applied to implement augmented reality effects, render graphics, estimate geolocation and orientation, and generate maps. User location was updated every 0.5 s (extracted by the *userLocation* instance property in the class *MKMapView*), providing the user with their exact location in the bottom-right map. Using the user's current location, a function calculated all buildings within the user-specified radius (default being 300 feet), which dictated which building icons and information appeared to the user. Back-end implementation of the AR capabilities relied extensively on the open-source code provided by ProjectDent [55]. Generation of graphs displayed in the Energy Supply and Consumption views were designed and implemented using the Charts framework [56]. Within each view, multiple IBOutlets and IBActions facilitated user interaction (e.g., pressing the time range button, selecting a building from a dropdown). Electricity and building data were cleaned and summarized using the R programming language, compiled into .json format, and stored directly within the application. In future iterations of the application, data will be retrieved by the application through an API to enable near real-time (15-minute interval) energy updates.

3.2. Citizen-centered evaluation

Drawing from user-centered design best practices within human-computer interaction fields [36], the second objective of the paper involved a pilot study to evaluate the community-scale energy feedback system developed above from the perspective of prospective citizen users. A wide range of quantitative and qualitative methods have been employed to gather data on user perceptions and understanding of technologies. Quantitative methods are generally used to test products where the user needs are already well-defined. As community-scale energy feedback is a relatively novel concept to most people, the aim of our user testing was exploratory and prioritized collection of qualitative data.

For the evaluation, 16 study participants were recruited to complete two activities: (1) a thinking aloud session, and (2) a survey questionnaire. Thinking aloud methods have been used for decades by researchers to diagnose usability issues and improve user interfaces [57]. The thinking aloud procedure involved a one-on-one session between a researcher and participant, where the participant was instructed to vocalize their thoughts out loud as they interacted with the interface. To prompt user interactions, they were provided with tasks to direct the user to test specific functionalities. Before beginning the thinking aloud session, the researcher provided participants with details on how to 'think out loud', such as specifying what they believe is happening, why they are taking an action, and what they are trying to do. The same researcher tested each participant, and read the same instructional script prior to the session. While the participant completed each task, the mobile device's screen and microphone recording were turned on. This provided data on how the participant accomplished each task and what their quasi-raw thought stream was as they encountered different functionalities.

Immediately following the thinking aloud session, the participants completed a web-based survey questionnaire. A copy of the survey can be referred to in the Supplementary Material. The survey was divided into three parts. First, participants were asked questions to assess how accurately they interpreted each functionality. We opted for open-ended responses to these questions, as multiple choice options could influence how a user reports their understanding of the interface. Because this is an exploratory pilot study without statistical interpretation, we argue it is best to capture raw user thoughts rather than pre-constructed, limited responses to assess user interpretation. A list of these questions can be referred to in Table 1. The second part inquired more broadly about users' opinions of community-scale energy feedback. It captured users' desire to have access to this information, at what geographic scale, as well as motivations for wanting to seek out this information. A full list of questions and response types can be

Table 2
Participant desire and motivations for seeking out community-scale energy feedback (Survey Questionnaire Part 2).

Question ID	Question	Question type
B1	In general, how interested are you in having access to a Community Energy Feedback System in the following locations: – Georgia Tech Campus. – The neighborhood or community I live in. – The city I live in.	5-point Likert Scale
B2	Please specify how likely or unlikely you think a Community Energy Feedback System would motivate you to: see list of behaviors in Table 5.	5-point Likert Scale
B3	How often do you think you would seek out the information provided by a Community Energy Feedback System? (A) Daily (B) Weekly (C) Monthly (D) A few times (E) Once (F) Never (G) Only for specific occasions	Multiple Choice
B4	We are interested in why people would want to seek out information included in a Community Energy Feedback System. Below, please describe why you would want to have access to such a system. If you do not want to have access, please describe why.	Open-ended

referred to in Table 2. The third part of the survey included demographic questions to learn more about respondents. Sixteen participants were recruited to take part in the user testing. While we expected that the primary users of this system would be people who are professionally or personally interested in local energy issues, we recruited people from a variety of backgrounds, from inexperienced to energy experts. This was done to gather a more holistic understanding of user interpretations. The user testing was approved through IRB protocol #H18398 and participants were compensated monetarily for taking part in the study.

4. Results

Sample screenshots from the resulting community-scale energy feedback system can be referred to in Figs. 2–4, and it source code with additional documentation of its capabilities is available for download within a Github repository [58]. Thinking aloud and survey data was collected from December 2018 through January 2019. A total of 16 participants completed the user testing activities. As an important aspect of the developed application is that users are familiar with the community it represents, participants were required to identify as a member of the GT community. Participants' affiliation with the GT community consisted of being an undergraduate student (n = 6), Master's student (n = 4), PhD student (n = 4), or staff member (n = 2). About half (n = 9) of the participants identified as female and the remaining participants identified as male. The survey also inquired about peoples' previous familiarity with AR technology and their previous involvement and interest in energy issues. These results are presented in Figs. 5 and 6. In the following sections, the results pertaining to each of the research questions will be discussed.

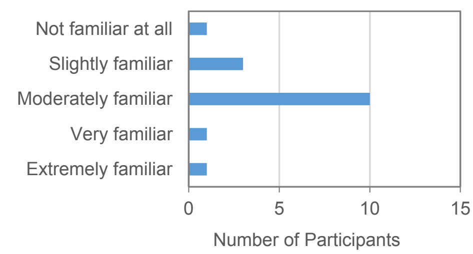

Fig. 6. Results from the survey question, "Prior to this study, how familiar were you with Augmented Reality technology?"

4.1. Do users accurately understand and interpret community-scale: (a) Augmented Reality feedback, (b) Energy Supply feedback, and (c) Energy Consumption feedback?

Participants' ability to accurately interpret the interface was assessed through the thinking aloud procedure and the survey questions listed in Table 1. A summary of the number of participants who answered each accuracy question correctly and their associated confidence in their response is provided in Table 3. Importantly, the thinking aloud procedure shed light on how a participant's understanding of each feature evolved as they completed each task. Understanding tended to improve as their exposure to the interface increased. As a result, sometimes participants initially misinterpreted a particular feature in the thinking aloud portion, while at the same time they were able to accurately interpret the same feature in the follow-up survey. The combination of these methods enabled a more in depth understanding of the user learning process. Such events are explained in more detail in the following paragraphs, which discuss each of the application's features.

4.1.1. Augmented reality feedback

In the Spatial view, participants were able to use the augmented

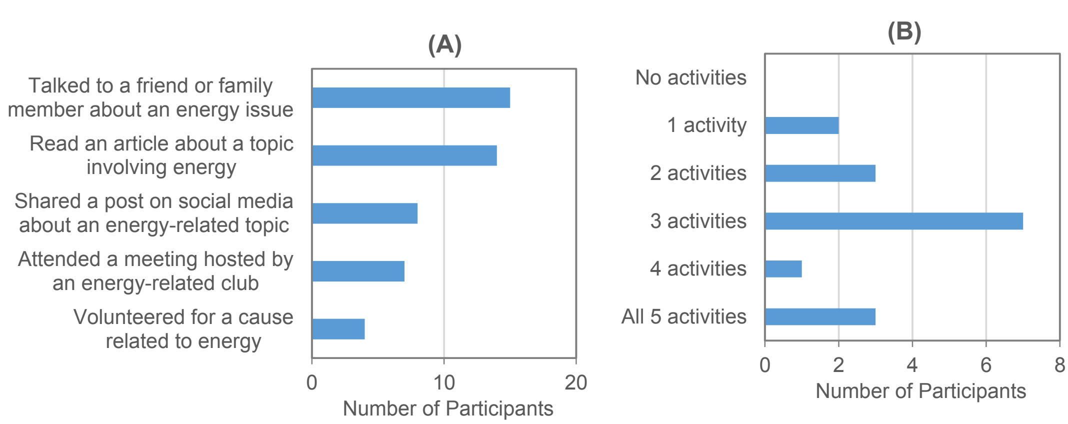

Fig. 5. (A) Results from the survey question, "Consider the following and check all that apply. In the last three months have you:"; (B) Total number of activities each participant reported from chart (A).

Table 3
Count of participant confidence levels for each accuracy question assessing accuracy of interpretation.

Question ID	Number of correct responses	Very confident	Confident	Slightly confident	Not confident
AR1	15	14	2	0	0
AR2	15	5	8	2	1
S1	13	9	7	0	0
S2	16	13	2	1	0
S3	15	15	1	0	0
S4	15	14	2	0	0
C1	11	7	6	2	1
C2	16	15	1	0	0
C3	16	13	0	3	0
C4	15	15	0	1	0

reality feedback to identify a building's energy efficiency level with relative ease and accuracy. When asked in the survey, "*If a building's icon is red, what do you think this indicates about the energy efficiency of the building?*" (AR1), the vast majority of participants accurately interpreted the meaning of the color scale with high levels of confidence (Table 3). This was also evident from the thinking aloud exercise, where participants were able to interpret the meaning behind the colors without difficulty or error. Furthermore, the double-coded numerical and color-coded efficiency representations also appeared effective; some participants focused initially on the colors to determine efficiency levels, while others were more inclined to focus on the numerical representations. By the end of the exercise, participants tended to use both. Notably, the building characteristics integrated into the color-coded icon (e.g., year built, building type) stimulated comments from the participants as to why they thought a building had a certain efficiency level in relation to its listed characteristics, or how they were surprised by the results. For example, after visualizing a building with a green icon, one participant commented, "*that's interesting, oh and it was built in 1988 it appears, compared to this one that was built in 1967, so that's surprising. I would think that it would be less energy efficient since it's older, but it's not*".

One oversight by the participants in the Spatial view was highlighted by the survey question, "*if the button "Month" is selected, why do you think the color of some icons change?*" (AR2). While the vast majority (n = 15) answered this question correctly, people were less confident in their response compared to the other survey accuracy questions. From the thinking aloud session, it was notable that most users failed to notice the time range buttons at the top of the screen. Thus, the lower confidence levels may be reflective of the minimal interaction participants had with these buttons during the tasks. In addition, participants commented in the survey that they would prefer to have more detailed information about the time ranges. Specifically, several commented they wanted to know if the time ranges reflected averages (i.e., the annual energy use divided into monthly or daily averages), or represented real-time changes in energy use. In a similar vein, participants also were looking for more detailed information about the energy efficiency color scale. More specifically, they wanted to know what 'bad' or 'good' was in reference to (e.g., the GT campus, national averages, etc.).

4.1.2. Energy supply feedback

In reference to the Energy Supply feature, participants were asked, "*What do you think the happy face on the screen indicates?*" (S1). While 13 respondents answered this question correctly, they were relatively less confident in their responses. From the thinking aloud session, participants expressed confusion about what level of building performance 'deserved' a smiling face. Moreover, it was not clear what emoticon options a building could potentially achieve. One participant summed up these concerns tellingly with, "*what is the smiley face scale*?". Questions S2, S3, and S4 were all answered with high rates of accuracy and confidence, indicating that participants were accurately able to identify from the bar graph Georgia Tech campus' current level of renewable energy production, renewable energy goal, and the energy resources the campus supply is composed of. An important main design issue in the Energy Supply page was determined through the thinking aloud activity, where most participants took a long time to notice the renewable energy goal listed at the top of the screen. Instead, their eyes and attention went immediately to reading and interpreting the graph on the center of the page.

4.1.3. Energy consumption feedback

In reference to the Energy Consumption feature, participants were asked, "*What do you think the 'Baseline' label refers to?*" (C1). Compared to the rest of the accuracy questions, this question had the lowest correct response rate, and one of the lowest confidence rates. While most of the participants (n = 11) understood that the 'baseline' represents a reference point to compare a building's current energy efficiency to, only 6 participants reported that the baseline referred to a building's performance in the year 2013. From the thinking aloud session, most participants (n = 9) had noticeable trouble interpreting the meaning of the 'baseline' and '2020 goal' horizontal lines on the Energy Consumption page. While most participants were eventually able to correctly interpret the graph, they commented that they were initially confused because on the previous Energy Supply page, a building achieves the goal when its bar exceeds the '2040 goal' line. Conversely, the way the Energy Consumption graph was designed, the farther the bars are below the goal line, the better a building is performing relative to the goal. This created confusion when the conceptual model for interpreting the graph was reversed between the Energy Supply and Consumption features (i.e., wanting to go below instead of above the goal line).

Questions C2, C3, and C4 were answered with high rates of accuracy and confidence, showing that by the time of the survey users were able to accurately and confidently interpret from the bar graph what the red bars refer to, a building's level of energy reduction compared to the campus, and the energy reduction goal. With regards to C4, which inquired, "*Based on the screenshot image above has Georgia Tech reached its campus energy consumption goals yet?*" it is important to note that while users answered this question correctly and confidently, many had trouble interpreting the graph when they were initially encountered it, as described in the previous paragraph. This demonstrates the effectiveness of the thinking aloud activity combined with the survey in helping understand the users learning process and difficulties.

4.1.4. Overall application feedback

Judging the application as a whole, 75% of survey respondents (n = 12) reported the application provided 'just the right amount of information'. The remaining participants (n = 4) indicated it provided 'too little information'. No respondents felt the application provided 'too much information'. A follow-up question was asked when respondents selected 'too little' or 'too much' information, inquiring about what they would like to add to or remove from the application (this was presented on the next page, after submitting the answer to the previous question). For the four respondents who were asked this follow-up question, two themes emerged. First, two commented they would like to see the information in the Spatial feature better integrated with the information in the Energy Supply and Consumption feature. As one participant explained, "*The Spatial Tab tracks energy efficiency, but that information is not available for easy searching. Conversely, the supply and consumption tabs do not offer an interesting spatial visual for their respective metrics*". This could potentially be accomplished by allowing the user to transition to the Energy Supply or Consumption graphs by clicking on a building icon in the Augmented Reality feature. Design improvements will be discussed in more detail in the Discussion section. In addition, the second theme focused on wanting more detailed information about

Table 4
Summary of participant open-ended responses to why they would or would not want to have access to a community-scale energy feedback interface.

Category	Motivation	Count
Individual (n = 12)	Financial- to save money or inform purchasing/renting decisions	8
	Curiosity – to stay informed or have fun	7
	Values- care for the environment or their community	3
Peers (n = 7)	Learn about how their building is performing compared to others	5
	Learn about community buy-in to energy goals	1
	Promote peer learning about energy use	1
Institutional (n = 4)	Hold cities/institutions accountable to goals and lobby for better practices	2
	Learn about energy related programs in their area	1
	Support neighborhood energy organizations with targeting efforts	1
	Support energy efficient businesses	1

retrofits implemented or sustainability features for each building. Participants reported they wanted this information to understand better *why* a building may be performing poorly or efficiently.

4.2. Do people want to seek out the information provided in community-scale energy feedback interfaces? Why or why not?

Participant openness and desire to seek out the information provided in a community-scale energy feedback interface was assessed by the questions listed in Table 2. For the open-ended question, "*We are interested in why people would want to seek out information included in a Community Energy Feedback System. Below, please describe why you would want to have access to such a system. If you do not want to have access, please describe why*" (B4), several trends emerged. These trends were aggregated and sorted into three categories: (a) individual motivations, (b) motivations in relation to their peers, or (c) motivations in relation to their institutions (Table 4). In Table 4, specific motivations and the number of participants who mentioned each motivation is grouped by each category. As the question was an open-response, participants' responses could include comments related to multiple categories or motivations. The total number of participants who had at least one comment in a category is specified in the first column. The most frequent motivations were related to the 'individual' category, and are comprised of motivations driven by personal interest, values, or financial reasons. Motivations belonging to the second group were less frequent, and involved commentary in relation to their peers or community. Comments falling under the last category were least common, but covered a wide range of concepts related to government or institutional structures. For example, one participant commented that access to community-scale energy feedback, "*would make me want to use the data to lobby for policy changes or programs that could help expand energy efficiency upgrades at a community level. I think the visualization is most helpful for outside my home and thinking at a neighborhood, campus, or city level*".

A few participants commented on why they would not want access to or use a community-scale energy feedback system. One participant expressed they do not think they would check out this type of feedback system unless there was a stimulus that prompted them to be curious about building energy use (e.g., the building looked new and/or efficient, when buying a home). In addition, another respondent expressed that they felt that public reporting of residential data would be an invasion of privacy, and they would not be supportive of open access to this type of data.

Participants were also asked about how likely or unlikely they were to change certain behaviors after having access to a community-scale energy feedback system (B2). A summary of these results is provided in Fig. 7. Of all of the behaviors listed, participants were most likely to report that a community-scale energy feedback system would motivate them to check a home's energy efficiency before buying or renting decisions. Fewer participants selected that this type of feedback system would encourage them to attend local energy meetings or participate in an energy related club. It is important to note that differences in the responses between the behaviors is largely dependent on the types of behaviors participants are predisposed to (i.e., in general less people are likely to volunteer for a club than use something for personal benefit). The effect of community-scale energy feedback on behaviors should be compared to baseline levels of behaviors to gain an accurate understanding of its impact. However, these preliminary results speak to the wide variety of behaviors community-scale energy feedback systems could potentially impact. Across all of the behaviors mentioned, at least 10 participants selected that a community-scale energy feedback system was 'somewhat likely' or 'extremely likely' to change that associated behavior.

Table 5
List of behaviors referenced in Fig. 7.

ID	Behavior
1	Check a home's energy efficiency before buying
2	Check a home's energy efficiency before renting
3	Buy smart technologies
4	Talk to my neighbors or peers about energy use
5	Help to try and meet energy consumption goals in my community
6	Invest in renewable energy
7	Purchase more energy efficient equipment or technologies
8	Opt to go to a place because it is efficient
9	Change energy behaviors (e.g., turn off lights or appliances more)
10	Call my representatives about energy issues
11	Become involved with an energy project in my community
12	Choose to shop at a different store because it is inefficient
13	Attend a local meeting about energy in my community
14	Share information about energy use on social media
15	Participate in a local energy club

Participants were also asked to specify how interested they were is having access to community-scale energy feedback spanning different geographic regions (B1). All locations, including the Georgia Tech campus, neighborhood they live in, and city they lived, received overwhelmingly positive responses (Table 6). When asked how often they would use such a system (B3), 5 participants responded 'weekly', 7 responded 'monthly', and the remaining 4 reported 'a few times' ('daily', 'once', and 'never' received zero votes).

5. Discussion

The first aim of this study was to develop and document the design framework for a community-scale energy feedback system, a novel approach for connecting community residents with open urban energy data. Building from previous work incorporating community-based communication and mapping elements into energy feedback [30,31], we developed a platform facilitating user connections between building energy data and their physical community through augmented-reality

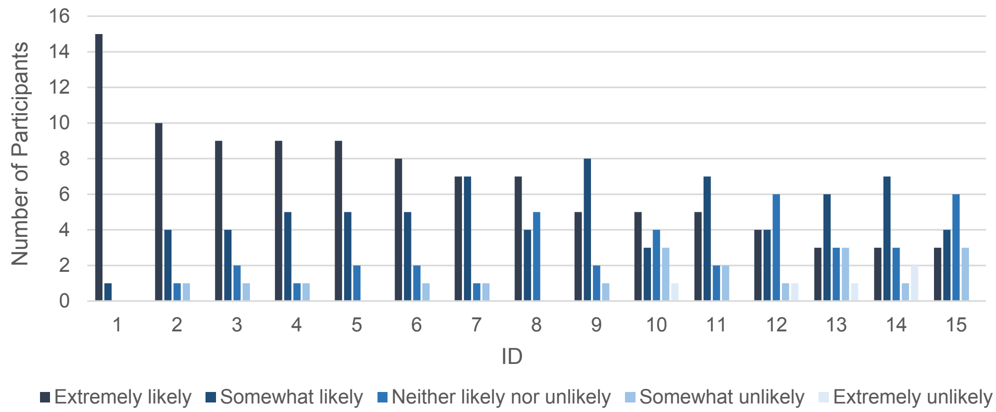

Fig. 7. Participant responses to how likely or unlikely they are to use a community-scale energy feedback system for each behavior (refer to Table 5 for the list of behaviors).

visualization strategies and graphical views of energy use and supply. While visualization platforms have been developed in response to the increasing release of open urban energy data, these platforms have been primarily intended for use by entities in the real-estate sector or those with the capital and resources to make sense of the data [19,25]. In response to calls for reconceptualizing citizens as active innovators and stakeholders in preparation for significant energy transitions [13,14], we document the design principles and develop a prototype community-scale energy feedback system designed for use by ordinary citizens or community members. In addition, our second aim was to evaluate the prototype by gathering feedback from prospective users. To engage prospective users, thinking aloud procedures were applied, which have been used effectively for prototype evaluation in the field of human-computer interaction for decades [57]. This evaluation approach was critical as engaging prospective users during the design stage is an often overlooked step in the development of energy technologies, which can substantially impact the success of these technologies during implementation [29,34].

The thinking aloud and survey results indicated there was high interest among most participants in having access to open urban energy data across all three geographic community scales (i.e., the Georgia Tech campus, the neighborhood, and the city level). These results agree with previous community-scale energy feedback studies that established citizen interest in energy data at the neighborhood scale [30,31], and expand positive citizen interest to the campus (e.g., universities, workplace campuses) and city scale, which have yet to be empirically investigated by research. This provides support for the development of campus and city-scale energy feedback, which from a data availability and privacy perspective, whole building data at the campus and city-scale is more readily available due to emerging open data requirements [12], and may be more feasible to implement compared to neighborhood-level feedback.

Regarding why participants wanted to have access to such a system, the open-ended responses had substantial variation. Aggregated responses showed participants wanted to seek out this information for individual, peer-related, or institutional-related reasons. Individual motivations were most commonly listed (e.g., financial or ethical reasons). Nevertheless, the responses show a wide variety of ways people reflected that community-scale energy feedback could affect them and the way they engage with their energy systems. The diversity of comments corroborated previous work examining the diverse roles citizens can have when engaging with emerging energy systems [14]. This has implications for literature developing frameworks for energy consumption behaviors across a group or campus of buildings [59] by informing considered behaviors in future work. This also has implications for future experimental work on community-scale energy feedback; the diversity of citizen roles in energy systems and broad scale of community-scale energy feedback behaviors widens the range of variables researchers could potentially measure to assess behavior change. An important consideration for future research, however, is designing how to measure the potential effects of this type of feedback.

In comparing the Augmented-Reality, Energy Supply, and Energy Consumption feedback, the AR view appeared to be the easiest for participants to understand. Users quickly and accurately understood the meaning behind the color-coded icons and additional building data within the icons, while they were slower to interpret the Energy Supply and Consumption views correctly. These findings agree with the results of other studies examining the impact of color-coded spatial views [45,48], where users reported color-coded information helped them understand energy use and found this information more intuitive compared to typical bar charts. In addition, one of the advantages of augmented reality is it can integrate greater amounts of information into the visualization [43]. In the AR view, this feature was able to integrate building characteristic data into the visualization, stimulating comments regarding efficiency levels in relation to these characteristics. Participants still found utility in the graph view information, but preferred this information to be better integrated with the AR view. This supports a previous study where people preferred color-coded and numerical data to be integrated together [48]. We extend these findings by suggesting that integration of AR features with graphical views has the potential to improve engagement and understanding by representing the information in a multitude of ways.

Another trend that emerged was participants wanting more information in general within the application. For example, participants desired more information about why a building was performing efficiently or inefficiently (e.g., sustainability features, recent renovations). Some participants even became skeptical of the data because there was not additional information to provide context for the reported

Table 6
Results from the survey question on what geographic scale the respondent is interested in having access to community-scale energy feedback.

Location	Extremely interested	Somewhat interested	Neutral	Somewhat uninterested	Extremely uninterested
Georgia Tech Campus	7	9	0	0	0
Neighborhood or community I live in	10	4	1	1	0
City I live in	8	7	1	0	0

efficiency levels. Providing detailed building retrofit or system information, particularly at larger scales, is a challenge as it is difficult to collect, standardize, and maintain the reporting of this information. The implication of this finding is that future design and deployments of community-scale energy feedback systems should strive to provide context to users to improve their trust in the information, while also limiting the information scope so that it is feasible to maintain and ensure the accuracy of the feedback.

Several limitations exist in this study, prompting avenues for future research. Regarding the design and development of the application interface, while our current community-scale energy feedback system has the potential to increase user understanding of community energy systems, incorporation of action-oriented elements is currently limited, which are important for behavior change [60]. This is in part due to the low granularity inherent in whole building data, which does not allow for disaggregation of energy use by behavior or appliance to give users feedback on the impact of their own behaviors. At the same time, installing more granular meters, such as plug-load monitoring, is not financially viable in a commercial context for many buildings [61]. Given that open urban energy data (e.g., whole building data) is substantially more feasible to collect, maintain, and report at scale–and as such has become cities' primary public output for building energy data–we argue that research examining potential citizen use of this data has critical and meaningful value. Furthermore, granular building data is not required to add action-oriented elements; incorporation of energy tips or events, which can be personalized to one's own community, as well as adding interaction between users to support social engagement and connection should be considered by researchers looking to expand on community-scale energy feedback.

Regarding the system evaluation, applicability of our findings to new contexts should be carefully considered. The platform was designed for the GT campus, a university located in an urban setting, and the study's evaluation engaged people identifying as members of the GT community. As documented through the demographic data, most participants had previous involvement or interest in energy issues. Thus, our evaluation results capture responses to community-scale energy feedback from the perspective of relatively energy-cognizant populations in a university setting. Extending this system across an entire town or city will likely elicit different and more varied feedback based on the new context and less homogenous population. The results of this study provide a basis for such an extension; community-scale energy feedback is a relatively novel and promising concept, and the aim of this paper is to propose an initial proof-of-concept for others to build from, critique, and apply to new contexts. Relatedly, inherent in the creation of energy feedback systems, which are designed to reach broader populations, is that there is no design that will engage everyone; differing values, routines, and interests will impact adoption and use across populations. We expect that the initial adopters of community-energy feedback systems, for both university and city settings, will be those with existing interest or involvement with energy issues. Therefore, those who participated in this evaluation were likely representative of people most likely to adopt this system at GT.

At the same time, the aim of this application is ultimately to engage and support citizens with decision-making and action regarding energy-related behaviors. We acknowledge that, particularly when expanding such systems to a larger urban context, citizen use of data is not solely dependent on individual interest and ease of access to data, and that many other factors–such as prior knowledge, resources, and constraints–will influence a person's ability to make effective use of this data [62]. Striving towards open data's promise for empowering citizens and promoting democratic action requires purposeful collaboration with existing programs, incentives, or workshops to promote broad use of data. Many community-based energy initiative researchers have demonstrated how tools and feedback technologies can be most effective when integrated with existing community programs to promote broad citizen use, engagement, and benefit [30,31]. This is critical for researchers to consider in the testing of the impacts of community-scale energy feedback systems.

Finally, while there were not enough participants to perform a statistical evaluation, limiting the number of respondents allowed the evaluation to include more extensive data from each participant that would not have been possible with a larger group. Capturing qualitative and descriptive data was also important given the novelty of community-scale energy feedback systems to participants; this type of data facilitates a more nuanced understanding of participant perspectives on open urban energy data and avoids biased results from prescribing perspectives. The results of this broad examination establishes a foundation to improve quantitative and qualitative evaluations in future studies.

6. Conclusion

As cities invest in technologies to solve urban issues and become 'smart', vast quantities of open data will be produced and made available for public use. In this paper, we explore and evaluate open urban energy data. For this data to be useful, particularly to citizens, it is important for it to be shaped in a way that is accessible, engaging, and actionable. In the area of energy and sustainability, this is of critical importance as our future energy systems will require a deeper level of understanding and engagement from citizens in order to reach our sustainability aims. Energy-cyber-physical systems have immense value in working to transform data in the virtual world and link findings to our physical reality in order to improve understanding and decision making. Based in an energy-cyber-physical systems perspective, our objectives for this study were to connect open urban energy data to citizens by: (a) developing a novel community-scale energy feedback system, and (b) evaluating this system using a user-centered approach. The developed system applies new visualization techniques in energy feedback (i.e., augmented reality) to enable links between physical infrastructure and smart meter data, and complements this feature with interactive, graphical displays of data. We involved 16 prospective users in the evaluation process to assess how accurately they interpreted the feedback system and gauge how interested they are in having access to this type of emerging data. The results can be used to identify specific strategies to improve the system design. The results also indicated high interest among participants in having access to this system ($\geq$85% somewhat or extremely interested) across all geographic scales presented (campus, neighborhood, and city). Overall, this study presents the development and evaluation of a novel citizen-centric community-scale energy feedback system, which establishes a foundation for future work in the area of open urban energy data feedback to citizens. As open data becomes a prevalent potential resource in the era of smart cities, energy-cyber-physical systems have the potential to improve the accessibility of this information for citizen benefit. This study presents a critical step examining technologies' role in engaging the public to help achieve a sustainable, low-carbon, and people-oriented energy future.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.113804.

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