CHANGE MAKERS: CROWDSOLVING THE ENERGY CHALLENGE THROUGH CYBER-ENABLED OUT-OF-SCHOOL CITIZEN SCIENCE PROGRAMS

> "*Access to productive out-of-school opportunities that engage young people in authentic STEM experiences is a critical piece of the STEM learning ecosystem. Such out-of-school opportunities can support STEM learning independently from classroom learning, and they are particularly well suited to building interest in STEM and identity as a STEM learner*."—Identifying and Supporting Productive STEM Programs in Out-of-School Settings, National Research Council, 2015

This is an *Innovations in Development* project in response to the *Dear College Letter: Change Makers*.

THE NEED

Solving the energy challenge is critical to fulfilling the Paris Agreement, a landmark international climate treaty that came into force on November 4, 2016. Science education can contribute to this undertaking through three main avenues: 1) Changing students' everyday behavior in using energy by teaching energy literacy, 2) preparing students with basic knowledge and skills needed to join the cleantech workforce of tomorrow, and 3) engaging students in solving real-world energy problems of today. The last four decades have witnessed many formal and informal education projects making progress on the first and second avenues. Projects on the third avenue, due to the complexity of real-world problems, typically require much stronger commitments of time and resources from both students and educators if meaningful solutions and deep learning are expected to be the end outcomes. Despite the favorability of learning through problem solving in the real world among students, educators, and policymakers, such projects are often constrained by the availability of school time in formal settings and by the shortage of resources and expertise in informal settings. As a result, opportunities in this avenue are relatively underexplored.

Given the threat of climate change, it is imperative to provide practical opportunities for young people to take part in finding energy solutions. In his annual letter, Bill Gates (2016) called for an "energy miracle" and urged high school students to "get involved." Productive out-of-school programs that entice and empower all students to take on the energy challenge collaboratively can provide a platform for them to answer Gates' call. The rapid advancement of open-source software, low-cost hardware, and supporting infrastructures in the past decade has made it possible to create *citizen science and engineering* (CS&E) programs through which students can meaningfully crowdsolve energy problems in out-of-school time with the assistance of scientists and engineers. These crowdsourcing projects can potentially turn millions of students into "change makers" to help accelerate the transition of our society to a sustainable future.

GOALS AND INNOVATIONS

In this *Innovations in Development* project, the Concord Consortium (CC) and the Alliance for Climate Education (ACE), along with experts from Borrego Solar, Boston Solar, CLEAResult, and FLIR Systems will join forces to develop, disseminate, and research out-of-school CS&E programs that enable secondary students to tackle energy problems in their own homes, schools, and towns using low- or zero-cost technologies such as smartphone-based infrared (IR) thermography and simulation-based computer-aided design (CAD). This project will be a five-year design-based study (The Design-Based Research Collective, 2003) that will engage approximately 5,000 students from diverse socioeconomic backgrounds in New England. These students will participate in the study via a network of collaborating formal and informal science educators who will be recruited, trained, and supported by this project. Sun Associates, which specializes in evaluating the impact of digital learning, will serve as the external evaluator.

This project will deliver three key innovations that aim to strengthen STEM learning infrastructure and explore new assessment and evaluation approaches, two of the six actions that the Committee on Successful Out-of-School STEM Learning has recommended (National Research Council, 2015).

The first innovation will be two cyberinfrastructures consisting of smartphone, desktop, and cloud-based apps that enable students to generate trustworthy scientific data and authentic engineering solutions, which they can contribute to industry-sponsored crowdsourcing programs designed to survey the energy efficiency and solar potential in their areas based on Google Maps. The **Infrared Street View Program**[1] will allow anyone to participate in the creation of a thermal version of Google's Street View using the $200 FLIR ONE IR camera[2] attached to an Android or iOS device (Figure 1a). As easy to use as a conventional camera, the FLIR ONE is in fact a high-throughput data acquisition instrument that collects thousands of temperature data points each time a picture is taken. With the participation of a large number of students, the Infrared Street View will produce massive thermal data that may have considerable scientific value and business potential (Box 1). The **Virtual Solar Grid Program** will allow anyone to search and choose a site to build a virtual solar project (Figure 2), be it a photovoltaic system on top of a roof, a solar farm in a brownfield, a solar canopy over a parking lot, or even a solar power tower in a desert. Such a solar project, once approved by an expert, will start generating virtual electricity in the Virtual Solar Grid based on real-time weather data from the selected site. The aggregated results can be used to estimate the *true* solar potential of an area. According to the taxonomy of public participation in scientific research (Bonney et al., 2009), the Infrared Street View is a contributory project whereas the Virtual Solar Grid is a collaborative or co-created project.

Box 1: Does the Infrared Street View have any real-world value?

Many people are unaware of energy waste in their homes or communities as heat transfer across the building envelope is often unnoticeable—until it is revealed by an IR camera. The massive geotagged IR data generated by this citizen science program will become the foundation of the Thermographic Information System (TIS), a thermal version of the Geographic Information System (GIS) that allows anyone to check the energy efficiency of buildings in an area of interest with unprecedented detail. Utility companies, real estate agents, and governmental agencies can all benefit from the data and analysis services provided by the TIS.

The second innovation will be "stealth assessment" or embedded assessment (Shute & Ventura, 2013; Zapata-Rivera, 2012) that addresses the challenge of research and evaluation of student learning in out-of-school settings (National Research Council, 2015). The consensus is that assessment should not inadvertently formalize informal settings or disrupt students' learning experiences. Due to the extensive use of technology in our CS&E programs, it is feasible to develop unobtrusive assessments for out-of-school learning based

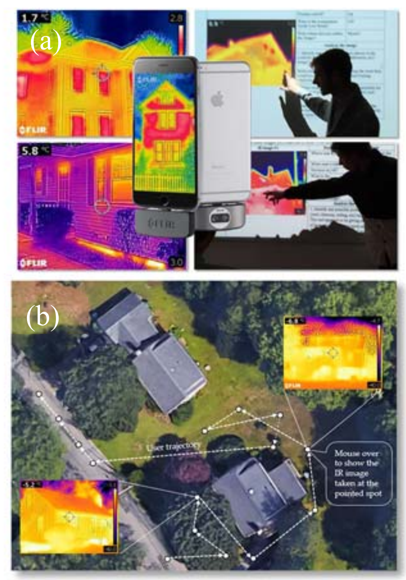

Figure 1: (a) Students took IR images of their home buildings and presented their analyses. (b) Tracking user trajectory in a map may provide unobtrusive means to document and measure out-of-school learning.

[1] The Infrared Street View, originally conceptualized and prototyped by PI Xie, was the grand prize winner of the 2016 DOE JUMP Smartphone Innovation Challenge (U.S. Department of Energy, 2016). As part of the award, the National Renewable Energy Laboratory (NREL) and industry partner CLEAResult will provide free technical assistance to "incubate" this project. DOE, however, does not provide direct funding support to this project.

[2] The price of IR cameras has fallen from a few thousand dollars to about $200 in recent years and the trend is expected to continue. While this may still seem expensive to underserved communities, the cost per person is low considering that an IR camera can be shared by many students for many years. With educational technology vendors such as Pasco and Vernier now selling IR cameras to schools, more and more students will have access to their incredible power (Haglund et al., 2016; Vollmer & Möllmann, 2010; Xie, 2011; Xie & Hazzard, 2011). In this project, we will lend FLIR ONE IR cameras to participants. In the future, students can borrow them from the science labs of their schools.

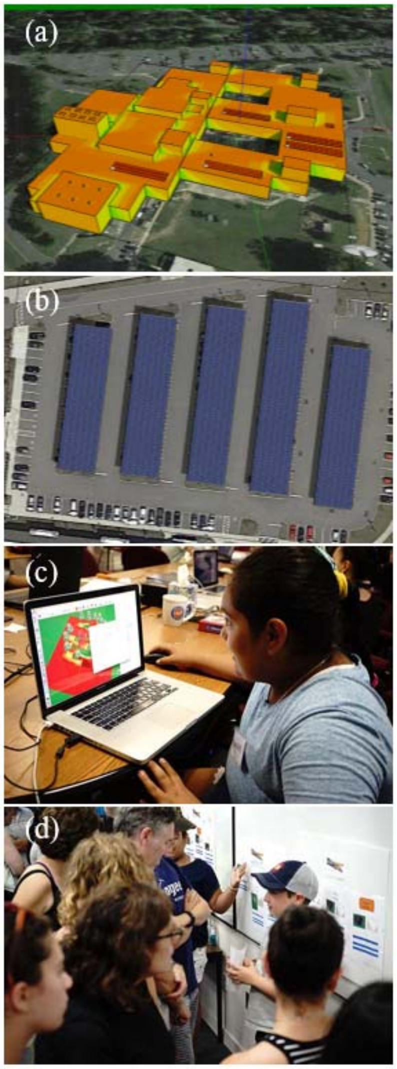

Figure 2. In the Solarize Your School project, high school students used Energy3D to simulate and design Charlottesville High School's rooftop solar arrays (a, installed in 2012) and Natick High School's solar canopies (b, planned for 2017). In the Solarize Your House Summer Camp hosted by CC, middle school students designed rooftop solar systems for their own houses (c) and presented their work to families in a poster session (d).

on mining large quantities of user data automatically logged in the background by the envisioned cyberinfrastructures (Bienkowski, Feng, & Means, 2012; Romero, Ventura, Pechenizkiy, & Baker, 2010). For example, when students are using IR cameras attached to their smartphones to inspect buildings, we can infer their performance by analyzing their IR images and by tracking their locations, the orientations of their phones, the timestamps of each image, and other types of sensor data. As suggested by Melero et al. (2015) and Sailer et al. (2015) based on their studies on mobile learning, superimposing these location-based data onto Google Maps (Figure 1b) can visualize how well students performed (e.g., did they scan all sides of the buildings?). Another example is that, when students are designing solar panel arrays for their schools' roofs, the CAD software they use can record all their actions and artifacts, based on which researchers can analyze their engineering learning and design performance (e.g., Gopsill, Snider, Shi, & Ben, 2016; Ishinoa & Jin, 2006; Xie, Zhang, Nourian, Pallant, & Bailey, 2014; Xie, Zhang, Nourian, Pallant, & Hazzard, 2014). These data mining techniques represent a leap forward in developing valid and reliable metrics for student performance and learning in informal, idiosyncratic settings.

The third innovation will be *instructional intelligence* built into the cyberinfrastructures to automatically generate formative feedback to users based on context detection and unobtrusive assessment. We define the instructional intelligence of a software system broadly as its ability to mimic a human instructor to some extent. This ability can support basic forms of project-specific, just-in-time instruction often inadequately available in out-of-school programs due to the high turnover rate and background diversity among frontline staff, especially in under-resourced communities. For CS&E programs in which students conduct research independently in field trips, in-app instruction may be the only form of guidance they can receive while carrying out the task. At the simplest level, rule-based expert systems (Buchanan & Shortliffe, 1984) and context awareness (Gellersen, Schmidt, & Beigl, 2002) can prevent students from making common mistakes. For example, IR inspection of buildings requires the indoor-outdoor temperature difference to be at least 18°F. In cold climates, when viewing a building from the outside, nighttime is preferred as there will not be any false positives caused by solar heating. By using the clock or ambient light sensor of the smartphone, an app can tell whether students are taking an IR image during the day or at night. By using the temperature data from a weather service, it can determine whether the temperature difference is large enough. If an ideal condition is not detected, the app will suggest that students wait until nightfall eliminates the side effect of solar heating and lowers the outside temperature. More advanced forms of instructional intelligence can utilize historical data to analyze user activities comprehensively to make high-level recommendations. Instructional intelligence that can guide students is not only important in informal settings, but it is also critical to improving the data integrity in CS&E programs. Without appropriate ongoing formative assessment and feedback, the data students collect and the solutions they design may contain many low-quality entries.

Theoretical Frameworks and Research Questons

This project will be guided by pedagogical and theoretical frameworks such as **project-based learning** (Thomas, 2000) and **situated learning** (Lave & Wenger, 1991). To promote science learning, out-of-school projects need to "create the demand" for science content and practices (Kanter, 2010). For example, to make meaningful contributions to the Infrared Street View, students must learn and understand heat transfer and building science. To develop optimal solar power solutions for the Virtual Solar Grid, students must learn and understand solar science and engineering design. While formal learning can cover the basics, informal learning can deepen students' understanding of science by situating learning in solving real-world problems outside school walls. Research suggests that situating learning in **communities of practice** (Wenger, 1998; Wenger, McDermott, & Snyder, 2002) can also foster collaborative learning, engage the public in scientific research, spur innovations, and increase social capital. Our CS&E programs will have all three essential elements of communities of practice: Clean energy provides a **domain** that is vital to our society, crowdsourcing mobilizes a **community** that is interested in solving the energy challenge, and the cyberinfrastructures enhance science and engineering **practices** that are one of the three dimensions of learning defined in the Next Generation Science Standards (NGSS Lead States, 2013). Furthermore, the use of mobile technology in the Infrared Street View Program will also engender opportunities for **location-based learning** (e.g., Brown et al., 2010; FitzGerald, 2012). Being able to sense the context and location of the student can open up possibilities to create more personalized and responsive out-of-school learning experiences (Harley, Poitras, Jarrell, Duffy, & Lajoie, 2016; Tan, Chang, & Kinshuk, 2015).

Despite many exciting research opportunities made possible by this project, we will focus on three research questions (RQs) that are closely related to the research agendas set by the community of informal science educators (CAISE, n.d.; National Research Council, 2015). Investigations on these RQs will shed light on the value of the three innovations for enhancing out-of-school learning. These RQs are:

- **RQ1: Under what circumstances can technology bridge out-of-school and classroom science learning?** Connecting STEM learning in out-of-school and classroom settings is one of the three criteria for productive out-of-school programs (National Research Council, 2015). A common model is to prepare students with the basic science concepts and skills in school and then direct students to out-of-school programs that allow for extended learning. This model generally requires the collaboration between formal and informal educators (Schamper, 2012), an alignment of theory and practice between school subjects and out-of-school programs (Newbill, Drape, Schnittka, Baum, & Evans, 2015), and a pathway of skill and identity development (Riedinger & Taylor, 2016). These requirements are often challenging to meet in reality. We hypothesize that the proposed cyberinfrastructures can reinforce this model as they engender new integration strategies using technologies. Figure 3 shows an example of how IR cameras can facilitate and connect learning across settings. Adding a connecting tissue, however, does not guarantee connection. Our research will seek to characterize how technology can create opportunities for out-of-school and classroom learning to mutually enrich and enhance each other in this project.

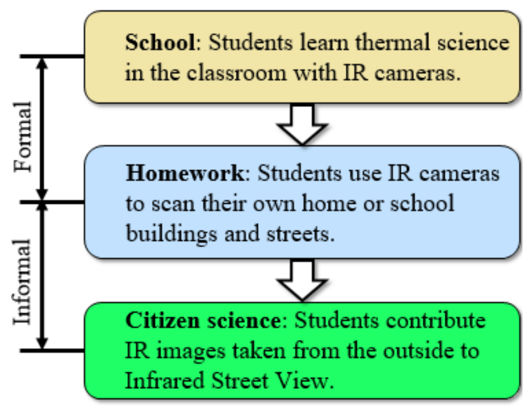

Figure 3. Connecting classroom and out-of-school learning with IR-based investigations.

- **RQ2: To what extent can unobtrusive assessment based on data mining support research and evaluation of student learning in out-of-school settings?** Being able to capture, categorize, and analyze students' diverse responses without impinging on their learning is fundamentally important in researching and evaluating out-of-school programs (National Research Council, 2015). We will examine how the proposed measures can address a wide range of assessment goals at individual, program, and community levels. This is feasible because our cyberinfrastructures will be able to track an individual student's actions throughout each task, over time, and across space. Data from many participants can be aggregated for statistical analysis and for outcome comparison among programs or cohorts.

- **RQ3: To what extent can instructional intelligence built into the envisioned cyberinfrastructures help students learn in out-of-school CS&E programs?** This direction of research is crucial because such intelligent systems can supplement out-of-school staff with domain-specific expertise, assist them to guide students through low-level tasks, and allow them to focus on managing their programs at higher levels. We will track students' responses to in-app instruction and their performance outcomes to gauge the effectiveness of the instructional intelligence. This data will also be used to guide our design-based research on improving the system intelligence iteratively.

Team and Partners

Our team is uniquely qualified to realize the envisioned innovations and conduct the proposed research. **CC is a leading innovator in educational technology** that has produced numerous free digital resources in STEM for millions of students. Two members of the CC team (Chao and Massicotte) have experiences in managing out-of-school programs. PI Xie has a seven-year track record of developing cutting-edge technologies that successfully support research and education in the field of energy efficiency and renewable energy. His contributions to IR thermography have been recognized by DOE (U.S. Department of Energy, 2016), InfraMation (Xie, 2012b), and *Journal of Chemical Education* (Jacobsen & Slocum, 2011). His energy simulation software (Xie, 2012a) have over 50,000 users. Seven research papers that used his Energy2D software to simulate natural phenomena and engineering problems have been published by scientists worldwide in the past two years, indicating high acceptance of his work by the science community. Meanwhile, the CC team has also been spearheading data-intensive research on project-based learning (Chao et al., 2016; Xie, Zhang, Nourian, Pallant, & Bailey, 2014; Xie, Zhang, Nourian, Pallant, & Hazzard, 2014). The Visual Process Analytics, a cloud-based process mining platform for visualizing and analyzing complex learning, has been in ongoing development (Xie, 2014, 2015). The Prior Support section will provide further details. The CC team will lead the research and development of this project.

ACE combines climate science with pop culture to create unforgettable experiences for students. ACE connects students to learning opportunities across settings and offers them a chance to take actions. Since 2009, ACE has reached over two million students and brokered numerous STEM learning activities for them. In total, ACE participants have completed over 2,100 climate and environmental projects including industrial composting systems, school-wide energy audits, and solar panel installations. The ACE team will lead the dissemination and outreach of this project.

The CC-ACE team is **reinforced by a strong partnership with industry**. Borrego Solar is the third largest company in U.S. commercial solar market, Boston Solar is the number one solar installer based in Massachusetts, CLEAResult is the largest provider of energy efficiency programs and services in North America, and FLIR Systems is the global leader of IR technology. Borrego Solar and Boston Solar will co-develop and co-sponsor the Virtual Solar Grid Program and review students' virtual solar projects. CLEAResult and FLIR will provide free technical assistance and consultation to the development of the Infrared Street View Program. In addition, an eight-member Advisory Board consisting of cleantech experts, science educators, and educational researchers will oversee this project. These partners and advisors will jointly ensure the integrity, authenticity, and practicality of the proposed CS&E programs.

Project Objectives

This project will accomplish its goals through the following objectives:

- **Bring the innovations to life**. We will build the envisioned cyberinfrastructures with the capabilities of stealth assessment and instructional intelligence as described above. As the project must first address the educational need, supporting learning is a priority in our development work. With this as a guideline, our apps will be enriched with many interactive, visual features that illuminate science concepts at work in the real world. The Development Plan section will provide the details.

- **Develop the citizen science and engineering programs**. We will create these out-of-school programs that situate STEM learning in the context of energy efficiency and solar power at both residential and commercial levels. These programs will highlight a series of real-world energy challenges, along with the supporting instructional materials, that will be posted on the Internet and shared through citizen science portals such as SciStarter. The development of the programs will be guided by two principles: **1) Foster learning across settings**: These programs will prioritize helping students acquire science and engineering concepts and skills defined in NGSS, such as computational modeling, scientific inquiry, and engineering design, that are essential to solving energy problems in the real world. **2) Teach students to think, act, and communicate like professionals**: These programs will support students to compile an energy assessment report or a solar energy proposal addressed to potential customers based on their investigation results and industry standards. These documents will become "naturalistic" data sources for assessing their learning. Throughout the project years, we will conduct design-based research to improve the programs iteratively based on assessment results and participant feedback (Recommendation 3, National Research Council, 2009). We will administer the online activities of the programs while frontline staff will manage the day-to-day operations with students.
- **Promote diversity and equality**. Energy affects everyone's life, irrespective of socioeconomic status, gender, or culture. It is, therefore, critical that our programs be designed to serve all students. Box 2 describes a scenario in which our IR program can motivate and empower students from low-income families to make a difference in an area where the energy efficiency of a building envelope is traditionally a low priority. Our inclusion strategies are as follows: **1) To reach a diverse student population**, we will work with a network of formal and informal educators from both urban and rural areas across New England (Table 1). Carter Wall, a board member of the New England Women in Energy and Environment and the former director of the Massachusetts Clean Energy Center, will advise us on engaging girls in our programs. **2) To provide fair access to technologies**, CC will maintain a pool initially comprising 100 IR cameras, 50 computers, and 20 used smartphones that can be loaned to participants on a rotating basis. As the project unfolds, we expect to increase the capacity of the pool through donations. **3) To help every participant find opportunities to succeed in this project**, we will strive to respond to their diverse abilities, interests, and needs by offering a variety of program choices. For example, students who do not live in a house can choose to design solar solutions for their schools or towns instead. Students who do not feel comfortable with math and science can team up with those who do. **4) To support minority participants**, we will build multilingual interfaces for our apps.

> **Box 2: How can this project help low-income families?**
>
> Low-income families spend 13% of their earnings on power bills, a percentage nearly twice as much as the national average (Barber, 2016). Many of them live in rental properties where energy efficiency has been long neglected, resulting in energy waste, thermal discomfort, and higher costs. Our project will equip students from these families with powerful IR cameras so they can reveal energy losses to landlords and urge them to take action.

- **Collaborate with formal and informal educators to implement the programs.** We will provide free professional development workshops and webinars to any school, afterschool, or out-of-school instructor who is interested in our programs. Many of them have enthusiastically responded to our request for collaboration (Table 1). From these partners and attendees of our training events, we will select 10 sites to pilot test the programs in the first two years and then 20-30 sites annually in the subsequent years to include a gradually larger student population. Depending on the challenges students choose to solve and the availability of support, each implementation will last from one to four weeks. Whenever applicable, students will be encouraged to create their own teams to take on each challenge.

- **Cultivate change makers**. As students collaborate to tackle energy problems in their homes, schools, and towns, they will naturally engage family members, schoolmates, neighbors, and town officials. For example, they will share their home energy assessment reports with family members, explain their discoveries to them, and brainstorm solutions together. These actions may influence the decision makers and trigger positive changes. Box 3 provides a real-world case in which students can be engaged in a constructive discussion with a solar company on the efficiency of solar power production in their own school. When more and more students are empowered to participate meaningfully in these kinds of activities that matter deeply to them, they will collectively change the world. This project will document their stories and amplify their impacts through ACE's national networks. We will invite successful teams to present at ACE's acclaimed assemblies and serve as role models for other students.
- **Conduct research and evaluation**. At the individual level, the formative data come from students' process data logged by the cyberinfrastructures and the summative data come from students' energy assessment reports and solar energy proposals. CC will develop analytics and rubrics to glean student performance and learning from these data. To cross-validate the results, a few case studies will be conducted to gather data through traditional instruments such as surveys, observations, and interviews, as well as in-app questionnaires. Subjects for these case studies will be selected from diverse backgrounds to ensure broad applicability of results. Sun Associates will evaluate project outcomes at individual, program, and community levels. CC and Sun Associates will establish a data sharing agreement between research and evaluation so that evaluation can draw from micro data about individual students as well as macro data about the overall program performance synthesized from micro data. In addition, results from Google Analytics of access to our cyberinfrastructures will also provide useful information for evaluating project impacts.

Box 3: What can students do to influence decision makers?

The Natick High School is planning to hire a solar company to install solar canopies over its parking lot in 2017. The company has proposed a design (Figure 2b) that basically aligns the solar canopies with the existing parking layout, which was designed years ago without considering that one day solar canopies would cover the lot. As a result of this design decision, the output of the solar canopies may be 5-10% less than that from a south-facing layout with the same tilt angle. While the company may have other considerations, Natick High School students should be given a chance to explore alternative designs and open a discussion. This kind of participation and education is exactly what our programs can offer. We are currently collaborating with Ms. Haverstick, a science teacher at the high school, and the sustainability manager of the town to incorporate this learning opportunity into their formal and informal education programs.

- **Disseminate project outcomes**. Throughout the five project years, we will widely disseminate our products and findings through the Internet, science fairs, and partner networks. Our apps will be freely available through the app stores. ACE will distribute project information and materials to a national network that currently covers 270,000 students. We will present at conferences related to energy education, citizen science, and informal science education. Research results will be published in computer science, educational research, and learning analytics journals.
- **Plan long-term growth**. We have already established solid partnerships with industry. If this project succeeds in attaining its goals, these partners will likely support further development as the data accumulated in the project will ultimately benefit the industry as a whole. It is also possible that the Infrared Street View and Virtual Solar Grid Programs attract investments to fund themselves if this project proves their business potential. For instance, real estate companies may be keen to invest in the Infrared Street View as the program provides an additional, nondestructive way to appraise a building (poor thermal conditions usually indicate bigger problems that cannot be seen with the naked eye).

Through these objectives, this project will address the four AISL priorities: **1) Knowledge building**: Our research will build knowledge in the areas defined by the three research questions; **2) Innovations**: The three innovations will advance the agendas of research, development, and evaluation of CS&E programs and add valuable STEM resources to the out-of-school community; **3) Strategic Impact**: The intersection between STEM education and clean energy on which this project focuses is strategically important; and **4) Collaboration**: This project will bring together developers, researchers, educators, scientists, and engineers to create high-quality CS&E programs.

Broader Impacts of the Proposed Work

This project will create exciting, authentic CS&E programs to meet the vast need for out-of-school STEM programs. In Massachusetts alone, 21% (213,966) of K-12 youth are responsible for taking care of themselves after school. Of all Massachusetts children not currently enrolled in afterschool programs, 44% (362,312) would be likely to participate if a program were available (Afterschool Alliance, n.d.). Given the public concern about energy security and environmental sustainability, this project is expected to create broader impacts. Through crowdsolving the energy challenge, thousands of students will become change makers who can profoundly impact the world.

Box 4: What did students think about IR thermography?

"It felt as if I was getting some amazing experience that professionals do and I am only in high school."

"It really helped me understand the material I was learning and it may also save my family a lot of money."

"I found it particularly interesting to examine the energy efficiency of my home and see the application of thermodynamics in a real world environment."

Prior Support

This project is based on the following prior work:

1) **Next Step Learning: Bridging Science Education and Cleantech Careers with Innovative Technologies** (NSF 1512868, $1,187,365, 2015-2018, PIs: Xie, Massicotte, & Spangenberg). **Summary of results**: This project created a learning pathway from school to home and then to cognate careers, establishing a testbed for developing and evaluating strategies for translating technology experiences into consistent science learning and career awareness. The project has developed the Building Science Investigation curriculum, which was pilot-tested with about 100 students in classrooms and received positive responses (Box 4). It is now being scaled up to over 10 schools. **Intellectual merit**: This project is designed to meet the goals of workforce development and science education simultaneously by providing students a technology-enabled pathway from classroom to workforce. **Broader impacts**: This project promotes the energy literacy and technical competency of students from diverse socioeconomic backgrounds and inspires an even greater population as their families are also involved. **Publications**: Three conference papers and one magazine article.

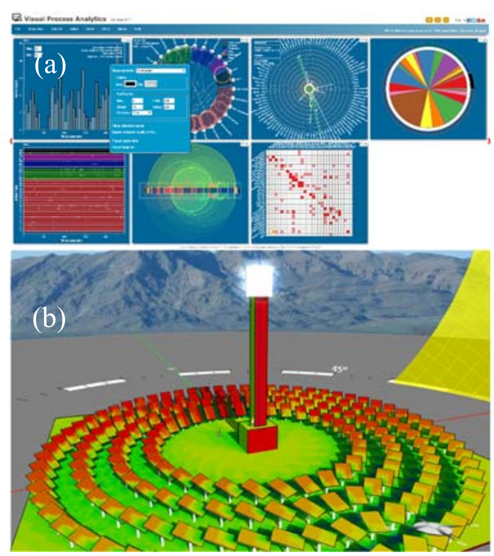

Figure 4: (a) Visual Process Analytics supports many types of visualization and analysis of process data. (b) Energy3D is a powerful CAD program for designing various solar power solutions, including solar thermal power tower as shown.

2) Large-Scale Research on Engineering Design Based on Big Learner Data Logged by a CAD Tool (NSF 1348530, $999,921, 2014-2018, PIs: Xie & Nourian). **Summary of results**: This project has advanced the data mining capability of Energy3D, a CAD tool for building energy simulation and solar power design. It has also developed the Visual Process Analytics (Figure 4a), a cloud-based platform for visualizing student performance and learning through complex projects such as engineering design using CAD. **Intellectual merit**: This project probes how students learn and apply science concepts in engineering design processes, an important topic in research on K-12 engineering education. **Broader impacts**: Data mining is emerging as a promising method for assessing student learning. This project contributed to this frontier from the perspective of engineering education. **Publications**: Four journal papers, four conference papers, and two magazine articles.

3) SmartCAD: Guiding Engineering Design with Science Simulations (NSF 1503196, $2,192,610, 2015-2019, PIs: Xie & Nourian). **Summary of results**: This project has greatly expanded Energy3D's engineering capacities in the direction of solar power simulation. Capable of modeling both photovoltaics (Figure 2a/b) and concentrated solar power (Figure 4b), Energy3D has become one of the most sophisticated CAD software in the field of solar modeling and design. It was featured on the Facebook of SolarPACES, a technology collaboration program of the International Energy Agency. **Intellectual merit**: This project is developing intelligent CAD software that can automatically generate formative feedback to guide students design and learning based on computationally analyzing their process data in real time. **Broader impacts**: This project demonstrates that modern CAD programs capable of virtual prototyping can support engineering education at a level and scale comparable to the role of modeling and simulation in science education. **Publication**: One journal paper and one conference paper.

PARTICIPANTS

This project will work with classroom teachers, afterschool instructors, and out-of-school program providers to recruit 5,000 students from New England. These students will come from diverse socioeconomic backgrounds. For example, among Lowell High School's nearly 4,000 students, 63% are minorities and 70% receive free/reduced price lunches. Many schools have afterschool programs that can readily adopt our CS&E activities. For instance, the Youth Climate Action Network at Boston Latin School, which organizes 200 students annually, will join our project. These students will participate in our design-based study and provide data for our research and evaluation. Note that this does not mean that our dissemination will be limited only to New England—our CS&E programs will be open to anyone anywhere.

Table 1. A list of out-of-school and in-school partners that will participate in this project

Types	Partners	Leads
Out-of-school program providers	Build the Out of School Time Network (MA)	Maryellen Coffey
	Center for Green Schools, U.S. Green Building Council (national)	Jenny Wiedower
	City Year Boston (MA)	Mark Pierce
	Climate Literacy and Energy Awareness Network (national)	Tamara S. Ledley
	Green Schools (MA)	Robin Organ
	Institute for Sustainable Energy (CT)	Laurel Kohl
	Maine Mathematics & Science Alliance (ME)	Janice Mokros
	New England Aquarium ClimaTeens Program (regional)	Heather Deschenes
	Vermont Energy Education Program (VT)	Cara Robechek
	Youth on Board (MA)	Rachel Gunther
Schools (classes and/or afterschool clubs)	Boston Latin School (MA)	Cate Arnold
	Everett High School (MA)	Anna Seiders
	Inter-Lakes High School (NH)	Mark Parsons
	Lowell High School (MA)	Roger Morneau
	Malden High School (MA)	Kathy Maglio
	Natick High School (MA)	Susan Haverstick
	North Reading High School (MA)	Jessica Weathers
	Portsmouth High School (RI)	Tyler Angers
	South Burlington High School (VT)	Matthew Dransfield
	Westborough High School (MA)	Marci D'Onofrio

Recognizing that out-of-school program staff need opportunities to develop their ability to nurture students' interests and understanding of STEM content and practices, we will provide free professional development workshops and webinars in each project year. A total of $85,000 has been budgeted to support these frontline staff to participate in this project and faciliate the research.

THE DEVELOPMENT PLAN

The development of each CS&E program includes two parts. Program development focuses on creating the CS&E challenges, the instructional materials, and the operational structures. Technology development focuses on building the cyberinfrastructures that support the program.

The Infrared Street View Program

The *MIT Technology Review* has reported that several companies are working on creating thermal images for homes from streets or producing thermal maps for cities from aircrafts (Hartnett, 2016; LaMonica, 2013; Simonite, 2010). Our plan differs significantly from those projects, as summarized in Table 2.

Table 2. Comparison of the Infrared Street View Program with existing projects

	Our project	Other projects
Strategy	Start with the education of students who may influence homeowners	Start with IR images
Scalability	Engage a large number of student volunteers through a crowdsourcing citizen science program	Rely on drive-by trucks or fly-by aircrafts
Holism	Take 360° images of buildings	Front or aerial images
Accuracy	Instruct students to assure that all the windows and doors are closed	No assurance
Appeal	Present 360° panoramic view and even virtual reality (VR) view	2D images
Privacy	Advise students to scan their own houses and neighbors' and publish images only when permitted by homeowners	Unsolicited IR scan may be illegal

Unlike the commercial projects, the Infrared Street View Program is a citizen science project that puts science education first. The program will be implemented through a collaboration between schools and out-of-school program providers. As illustrated in Figure 3, students will learn thermal science through hands-on experiments with an IR camera (Xie & Hazzard, 2011) in classrooms and then, equipped with knowledge and skills and guided by an inspection protocol, study the energy efficiency of their own home, school[3], or town buildings with the camera as a homework assignment or afterschool project. They will analyze their IR images using physics concepts such as three modes of heat transfer and optical properties of materials. They will prepare building energy assessment reports based on their analyses and share them with their families, teachers, principals, or anyone concerned with energy efficiency. At the end of the out-of-school work, students will acquire permissions from the property owners to submit their IR images to our

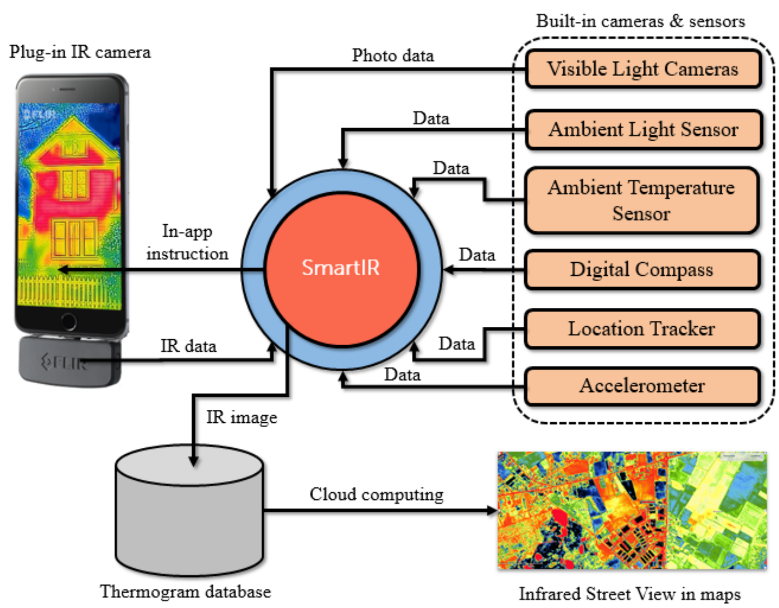

Figure 5: The SmartIR app, the front end of the Infrared Street View, makes extensive use of the plug-in FLIR ONE camera as well as the built-in cameras and sensors to support context awareness, unobtrusive assessment, and instructional intelligence. Users can submit IR images for creating the Infrared Street View on top of a map in the back end.

[3] Energy costs are second only to salaries in K-12 school budgets, totaling $8 billion annually (U.S. Environmental Protection Agency, 2011). An estimated $2 billion can be saved by improving energy efficiency in K-12 schools.

thermogram database. To protect privacy, only images taken from outside a building and only images without humans in the scene will be accepted. In the following subsections, we will introduce our plan to develop the needed cyberinfrastructure, including the technology for excluding improper submissions. This cyberinfrastructure comprises the following three parts.

The SmartIR app. While it is easy to use an IR camera to take a picture, there are legitimate concerns about the accuracy of IR images taken by students. Indeed, when students are examining a building independently, they can make mistakes. Part of our solution to this problem is a smartphone app called SmartIR. The app will provide a simple user interface for taking an IR picture and manipulating the data (while preparing for this proposal, we have created an alpha version of SmartIR for iOS that does these). Basic interactive features, such as plotting a graph that shows temperature changes over time at selected locations or temperature distributions along selected axes, allow students to investigate the science behind the scenes when necessary. What makes SmartIR unique is that, based on analyzing the data gathered from the FLIR ONE plug-in IR camera and the built-in sensors and cameras of the smartphone in real time (Figure 5), the context-aware app can walk students through an IR inspection process. We have mentioned earlier how this kind of instructional intelligence can help students avoid mistakes. In addition to the examples of checking time and temperature to ensure optimal conditions for data collection, SmartIR can also detect the presence of humans or animals in the scene as warm-blooded creatures have distinctive thermal signatures that can be picked up by image analysis (e.g., any area at temperature close to the body temperature can be marked as a potential human subject). An IR image with humans in it is problematic, because it not only raises privacy concerns, but is also undesirable as the image should present a clear thermal view of the building being examined. Therefore, SmartIR will not allow any such image to be submitted. As the imaging is based on thermal radiation from the subject, this ability will not be hindered at night.

Virtual infrared reality (VIR). Like Google's Street View, the Infrared Street View will require students to take a set of images to create a 360° panoramic view. SmartIR will realize this functionality based on using the orientation and location sensors of the smartphone to detect the direction and position of the IR camera. To guide the user to take images in the right direction and at the right position, SmartIR will display dots on the screen that prompt the user to aim at for taking IR snapshots. At each location and along the street, these snapshots form an "image sphere" and an "image tube" that will then be knit to create a seamless street view (Figure 6a). These images will also be displayed in a stereoscopic 3D mode that can be viewed using a VR headset, such as Google's Cardboard Viewer (Figure 6b). We call the integration of VR technology and IR imaging *VIR*. This innovation will give rise to likely the *first-ever VR image shot entirely in thermal IR light*, as well as SmartIR that will be the first app for anyone to create such immersive VIR content.

Cloud computing. Geotagged IR images submitted by students will be handled by a server that utilizes cloud computing to create seamless Infrared Street View in Google Maps. For instance, considering that the images may have been taken with different temperature ranges and coloring schemes on different dates, the server will first extract the temperature data from the images, normalize the data (it is the *contrast* that is important in revealing thermal anomalies, not the absolute values), and then redo the color mapping to ensure visual consistency across images. By aggregating a large amount of geotagged temperature data from an area, the server will create a normalized heat map for the area, from which users can identify the "hot spots" where improvements in energy efficiency may be needed.

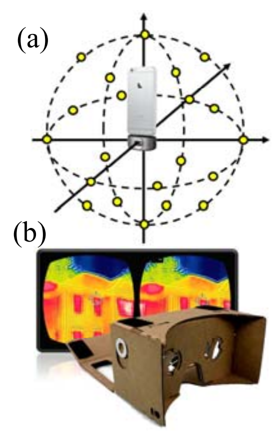

Figure 6: (a) The dot array directs the user to aim a cursor on the smartphone screen at them to produce an image sphere for making a seamless 3D view. (b) Side-by-side IR stereograms allow the Infrared Street View to be viewed in the VR mode.

The Virtual Solar Grid Program

In 2015, only 0.6% of electricity generated in the U.S. came from solar power (U.S. Energy Information Adminstration, 2016). While there is enormous room for growth, there are also challenges. Reuters recently reported that, as more and more homes ideal for solar installations have gone solar, the residential solar market is now shifting towards customers who need more "information and explanation," a trend that is driving up costs and slowing down growth (Groom, 2016). Although there have been many formal and informal programs that teach solar energy, students are not deeply involved in the solarization of their own homes, schools, and towns in most cases. It is true that students are not professionals and adults may not trust them when making serious investments in solar energy. But there is a safe way to let them try: computer simulation. This project will build cyberinfrastructures that enable students to construct and provide the needed information and explanation to property owners based on rigorous simulation and analysis of their particular situations. While learning STEM knowledge and skills in this process, students can also become the change makers who help solarize our nation. To determine the viability of this idea, ACE recently administered a survey through their networks. Among 274 respondents, 95.6% of them indicated that they would be interested in building virtual solar projects and 77.7% would share their ideas about solarizing their communities with local leaders. These enthusiastic reactions suggest that a CS&E program on solar power will likely be a productive one.

Unfortunately, CAD programs for solar simulation typically cost $1,000 per annual subscription and most hardly support student learning. To address these problems, we have been developing a free alternative—Energy3D, which integrates geometric, physical, and financial modeling in a single program to provide an agile design environment in which users can rapidly explore ideas. To model the real world, this CAD tool allows users to import site images from the Google Maps upon which they can draw their designs. With a simulation accuracy that rivals its pricy counterparts, this versatile tool can be used to design rooftop solar systems for residential and commercial buildings (Figure 2a), solar canopies for parking lots (Figure 2b), ground-mounted photovoltaic solar farms with or without trackers, and concentrated solar power stations (Figure 4b). Furthermore, Energy3D is full of visual effects and graphing tools that are essential to teaching and learning solar science. This important feature allows us to adopt an integrated formal-informal model similar to that shown in Figure 3: Students first learn solar science in an Earth science or environmental science class and then choose to work on one or more of the following citizen engineering projects in out-of-school time: **1) Solarize Your School**. Students design solar solutions that turn the roof and parking area of their schools into small power plants. If their schools have already installed solar panels, students can model the existing designs as a baseline and investigate whether they can be revised to produce more electricity. **2) Solarize Your Home**. Students design solar panel arrays for the roofs of their own home buildings. They sketch up Energy3D models of the buildings, add solar panels, and use simulations to decide whether their families or communities should go solar. **3) Solarize Your Town**. Students explore all sorts of solar solutions for their towns. This open-ended project aims to unleash creativity. Students have flexibility in selecting different types of solar technology, sites, and scales. In all three types of projects, students must perform feasibility analyses to evaluate the costs and benefits of their designs. They should also leverage governmental incentives and policies available in their areas, such as net metering.

For student work to make broader and lasting impacts, this project will develop the Virtual Solar Grid, a cyberinfrastructure that will bring their solar projects online in the virtual world and provide the underlying support for communities of practice. This cyberinfrastructure is important in two ways. On the one hand, it promotes learning as constructionism suggests that sharing creation processes and produced artifacts can motivate students and stimulate creativity (Papert, 1991). On the other hand, a large number of student projects will collectively generate a map of solar potential that allows businesses and policymakers to locate their next areas of growth, including those "unused irregularly shaped areas" that have traditionally been overlooked (McSweeney, 2016). Solar professionals can analyze these virtual projects to evaluate their feasibilities and determine whether they should follow up with the leads. We are fortunate to have Borrego Solar and Boston Solar on board to provide expertise to experiment with this bold citizen engineering idea. We will also draw on lessons learned from other projects. For instance, the Virtual Solar Grid is similar in many ways to FoldIt, an online game that engages the public to crowdsolve protein folding puzzles

(Marshall, 2012). The role of solar engineers in this project resembles that of the scientists who review the submitted protein structures to determine whether they are scientifically probable.

THE RESEARCH PLAN

This project will address the three research questions based on 1) mining students' process data logged "stealthily" by the cyberinfrastructures and 2) analyzing students' "naturalistic" products and reports. The data mining method not only represents an innovative approach to conduct formative assessment in out-of-school cyberlearning environments, but it can also facilitate our design-based research as its agility in deploying an intervention and getting the data back allows researchers and developers to iterate at a much faster pace and with more fine-grained controls. Our plan for investigating the three RQs is as follows:

RQ1: Under what circumstances can technology bridge out-of-school and classroom science learning? Research on this question will be carried out at sites where classroom and out-of-school learning can be connected. When students move from simplified classroom experiments to complex real-world problems, they are confronted by so many confounding factors that their ability to make connections is impeded. Using the same technology, for example IR cameras and CAD tools, across settings alleviates this impediment. But there are questions. For example, do students use the same technology differently in the classroom and out of school? In other words, do the environment change and context switch alter students' views about what the technology can do? These are not obvious questions. If an out-of-school activity is not well designed and aligned with science, a powerful scientific instrument like an IR camera may be reduced to a toy that is only good for taking some color pictures and the learning opportunities will be lost. Thanks to the ability of SmartIR in tracking user actions, we will have a way to know whether students are taking images randomly or systematically. From their energy assessment reports, we will have information about their reasoning about their actions and their analyses of their images. We will compare these out-of-school data with the classroom data to explore the correlation between out-of-school performance and classroom learning for each student (or each team). The classroom data will come from traditional assessments typically administered by teachers or researchers. The results will be divided into four categories: 1) high out-of-school performers who are high classroom achievers, 2) high out-of-school performers who are low classroom achievers, 3) low out-of-school performers who are high classroom achievers, and 4) low out-of-school performers who are low classroom achievers. We will study each category separately.

RQ2: To what extent can unobtrusive assessment based on data mining support research and evaluation of student learning in out-of-school settings? We will probe this question based on analyzing the correlation between performance indicators computed from the process data and 1) the performance scores calculated using student report rubrics and 2) the results of a small number of case studies based on traditional instruments such as surveys, questionnaires, observations, and interviews, whenever applicable. The computation of the performance indicators will draw upon methods such as spatiotemporal analysis of learner trajectories (Sailer et al., 2015) and time series analysis of events (e.g., Esling & Agon, 2012).

RQ3: To what extent can instructional intelligence built into the envisioned cyberinfrastructures help students learn in out-of-school CS&E programs? Our systems will log students' reactions to in-app instruction to determine its effectiveness. Another strategy for evaluating the overall outcomes of in-app instruction is to utilize the natural cycle of product development. The development of instructional intelligence will be a gradual process. At the beginning, our systems will have limited intelligence. But they will become "smarter" after each iteration. It is, therefore, possible to measure the effect of new features added in an iteration based on comparing student data before and after that iteration.

THE EVALUATION PLAN

To complement the research as described above, Sun Associates will evaluate the project at individual, program, and community levels. At the individual level, evaluation will focus on **the extent to which the CS&E programs have successfully engaged students in out-of-school STEM learning**. The evaluators will use the data collected by the cyberinfrastructures developed in this project. Data from Google Analytics will also provide spatiotemporal information about student activities in the cyberinfrastructures. Participating teachers and out-of-school staff will provide inputs for evaluating the effectiveness of the professional development activities, the instructional materials, the supporting technologies, and the overall CS&E programs based on their experiences. Instruments including surveys, questionnaires, interview protocols, and observation protocols will also be developed and used to collect outcome data from a small number of students selected to best represent a population with diverse backgrounds. The results of these traditional instruments will be compared with those from mining cyberinfrastructure logs. To facilitate this comparison, CC and Sun Associates will establish a data sharing agreement, which will allow each side to access and analyze shared data independently. At the programmatic level, evaluation will focus on **the extent to which the project has attained its goals**. The evaluators will delineate a comprehensive set of project indicators and metrics, organized by best practices for evaluating the impacts of learning technologies in informal settings (Flagg, 2008). The primary goal of program evaluation is to monitor project progress and provide regular inputs on areas of possible improvements. In addition to formative reporting to project staff, Sun Associates will report summatively via an annual report submitted to the project, the Advisory Board, and NSF. The report will also include recommendations for improvements. At the community level, evaluation will analyze **the extent to which the project has successfully supported the communities of practice**. Much of this community context will be developed as the project unfolds through its design-based research process. As such, the community level evaluation is expected to be highly formative.

PROJECT TIMELINE AND MANAGEMENT

This project is scheduled as follows: **October 1, 2017-September 30, 2019** will be the pilot-test phase in which we will focus on developing and testing the CS&E programs and technologies with participants from 10 sites. We will hold the first Advisory Board meeting to help us steer the direction. **October 1, 2019-September 30, 2022** will be the expansion phase in which we will build capacity to support 20-30 sites annually and explore possibilities to serve an even larger number of participants within New England and beyond, while continuing our design-based research to improve our infrastructures. We will hold two Advisory Board meetings in this phase to review research outcomes and brainstorm development strategies.

PROJECT PERSONNEL

The Advisory Board

Dr. Ron Lasser is a Professor at Tufts University. He will bring his expertise in digital image processing and mobile medical devices and apps to help our technology development. **Michael Arquin** is Director of KidWind, a successful educational project on wind energy that will serve as a great model for this project. **David Bursell** is Vice President of FLIR Systems. His 12 years of experience as the Director of Science in FLIR will be a great resource to this project. **Emily Kemper** is Senior Engineering Manager at CLEAResult with 14 years of experience in building science, including smart and connected home technologies and integrated sustainable design. **Dr. Cathy Lachapelle** is Director of Research and Evaluation of the Engineering is Elementary Program at the Museum of Science. She will bring insights into research and evaluation to this project. **Dr. Janice Mokros** is the Principal Investigator of the AISL-funded STEM Guides project at the Maine Mathematics and Science Alliance that aims to support STEM learning in underserved rural areas. She will also share her experience in energy education with this project. **Carter Wall** is Managing Director of Franklin Beach Energy, which provides energy consulting services, including solar development advisory. She was formerly the Executive Director of the Massachusetts Renewable Energy Trust. She serves on the board of New England Women in Energy and the Environment and as an Ambassador to DOE's Clean Energy Education and Empowerment. **Dr. Peter Wong** is Director of Food STEM Initiative at the Museum of Science. His initiative focuses on STEM education using food as an accessible topic for all ages, which provides a model for our project that uses energy as another accessible topic.

Staff at the Concord Consortium

Dr. Charles Xie will serve as the PI. A physicist by training, he has 16 years of research and development experience in STEM education. As a developer, he has created several scientific simulation tools used by over a million students and numerous professionals. As a researcher, he has authored over 40 papers and is leading research on data mining for assessing project-based learning. He is the recipient of a 2011 SPORE Prize from *Science Magazine*, the winner of the 2016 DOE JUMP Smartphone Innovation Challenge, and a fellow of the International Society of Design and Development in Education. **Joyce Massicotte** will serve as the Project Manager. She has eight years of experience in energy education and program management in industry. She directed the award-winning Sustainable Energy Education Drive that mobilized afterschool environmental science clubs at 18 schools. She also managed a team of 40 members to engage communities with energy efficiency practices. She holds an M.S. in Resource and Administration from the University of New Hampshire and is a Building Performance Institute (BPI) certified analyst. **Dr. Saeid Nourian** will serve as a senior developer for the proposed cyberinfrastructures. He has done extensive research in virtual reality and computer graphics. He has created mathematics software used by more than 200,000 people. He holds a Ph.D. in computer science from the University of Ottawa. **Dr. Jie Chao** will serve as a learning scientist responsible for leading the research of the project. She works on learning analytics for assessing learning in student-centered and open-ended environments. Her research on technology-enhanced learning in out-of-school settings has reshaped the curriculum design for middle school girls to learn computer programming. As a former afterschool program director, she developed multiple summer enrichment programs that benefited over 2,000 students. She holds a Ph.D. in STEM education from the University of Virginia. **Dr. Corey Schimpf** will serve as a learning analytics scientist responsible for validating the proposed analytics and rubrics for assessing out-of-school learning. He has experience in structuring and overseeing several out-of-school programs involving middle school students and underprivileged college students. He holds a Ph.D. in engineering education from Purdue University.

Staff at the Alliance for Climate Education

Alan Palm will serve as the Co-PI. An informal science educator, Alan has over 10 years of experience communicating science concepts to youth and facilitating meaningful actions. He has delivered presentations on climate science to more than 80,000 students, led outreach efforts covering more than 360 schools in New England, and supported students to carry out dozens of sustainability projects. **Rebecca Anderson** is the Director of Education at ACE. She has over 10 years of experience in climate education, curriculum development, and teacher support. Rebecca develops ACE's science content and manages ACE's online resources and teacher networks. Rebecca holds a B.A. in Geosciences from Williams College and an M.S. in Geosciences from the University of Colorado. **Maayan Cohen** is ACE's Deputy Director of Partnerships. Maayan has nearly a decade of experience in environmental science education. She develops, manages, and supports strategic partnerships at all levels at ACE. She has presented the ACE Assembly to over 50,000 students and built partnerships from the New York Department of Education's Sustainability Office to the United Nations. She hold a B.A. in Environmental Studies from Bates College.

Industry Consultants

Engineers from Borrego Solar and Boston Solar will provide consulting services for the Virtual Solar Grid Program. As part of the JUMP Innovation Challenge Award (U.S. Department of Energy, 2016), scientists and engineers at the National Renewable Energy Laboratory (NREL) and CLEAResult will provide free technical assistance to incubate the Infrared Street View Program. Developers of the FLIR ONE thermal camera at FLIR Systems, our long-term partner in IR thermography, will also contribute to the development of the SmartIR app. In addition, FLIR will offer special discounts of their IR cameras to this project.

References

Afterschool Alliance. (n.d.). Afterschool in Your State: A clearing house of information on afterschool across the country. Retrieved from http://www.afterschoolalliance.org/policyStateFacts.cfm?state_abbr=MA

Barber, G. (2016, October 22). Three Ways to Bring Solar Power to the People Who Need It Most. *Wired*. Retrieved from https://www.wired.com/2016/10/how-to-bring-solar-energy-to-low-income-families/

Bienkowski, M., Feng, M., & Means, B. (2012). *Enhancing Teaching and Learning Through Educational Data Mining and Learning Analytics: An Issue Brief*. Retrieved from Washington, DC: https://tech.ed.gov/wp-content/uploads/2014/03/edm-la-brief.pdf

Bonney, R., Ballard, H., Jordan, R., McCallie, E., Phillips, T., Shirk, J., & Wilderman, C. C. (2009). *Public Participation in Scientific Research: Defining the Field and Assessing Its Potential for Informal Science Education*. Retrieved from http://www.informalscience.org/public-participation-scientific-research-defining-field-and-assessing-its-potential-informal-science

Brown, E., Sharples, M., Clough, G., Tangney, B., Wishart, J., Wijers, M., . . . Polmear, G. (2010). *Education in the wild: contextual and location-based mobile learning in action: A report from the STELLAR Alpine Rendez-Vous workshop series*. Retrieved from Nottingham, UK: http://oro.open.ac.uk/29882/4/ARV_Education_in_the_wild.pdf

Buchanan, B. G., & Shortliffe, E. H. (1984). *Rule Based Expert Systems: The Mycin Experiments of the Stanford Heuristic Programming Project* Boston, MA: Addison-Wesley Longman Publishing Co., Inc.

CAISE. (n.d.). Informal Science Education Research Agendas. Retrieved from http://www.informalscience.org/research/research-agendas

Chao, J., Xie, C., Nourian, S., Chen, G., Bailey, S., Goldstein, M., . . . Tutwiler, M. S. (2016). Bridging the design-science gap with tools: Science learning and design behaviors in a simulated engineering design environment. *Journal of Research in Science Teaching, Under review*.

Esling, P., & Agon, C. (2012). Time-series data mining. *ACM Computing Surveys (CSUR), 45*(1).

FitzGerald, E. (2012). Creating user-generated content for location-based learning: an authoring framework. *Journal of Computer Assisted Learning, 28*(3), 195–207.

Flagg, B. N. (2008). Evaluating Learning Technologies. In A. J. Friedman (Ed.), *Framework for Evaluating Impacts of Informal Science Education Projects*. Washington, DC: The National Science Foundation.

Gates, B. (2016). Two Superpowers We Wish We Had. Retrieved from https://www.gatesnotes.com/2016-Annual-Letter

Gellersen, H. W., Schmidt, A., & Beigl, M. (2002). Multi-sensor context-awareness in mobile devices and smart artifacts. *Mobile Networks and Applications, 7*(5), 341-351.

Gopsill, J., Snider, C., Shi, L., & Ben, H. (2016, May 16 - 19). *COMPUTER AIDED DESIGN USER INTERACTION AS A SENSOR FOR MONITORING ENGINEERS AND THE ENGINEERING DESIGN PROCESS.* Paper presented at the The DESIGN 2016 14th International Design Conference, Dubrovnik, Croatia.

Groom, N. (2016, October 26). Clouds gather in rooftop solar's biggest U.S. market. *Reuters*. Retrieved from http://www.reuters.com/article/us-usa-solar-rooftop-idUSKCN12Q0C1?feedType=RSS&feedName=technologyNews%3A+reuters%2FtechnologyNews+(Reuters+Technology+News)

Haglund, J., Jeppsson, F., Melander, E., Pendrill, A.-M., Xie, C., & Schönborn, K. (2016). Infrared Cameras in Science Education. *Infrared Physics and Technology, (accepted)*.

Harley, J. M., Poitras, E. G., Jarrell, A., Duffy, M. C., & Lajoie, S. P. (2016). Comparing virtual and location-based augmented reality mobile learning: emotions and learning outcomes. *Educational Technology Research and Development, 64*(3), 359-388.

Hartnett, K. (2016, October 2). Mobile data collection is so thermal right now. *Boston Globe*. Retrieved from https://www.bostonglobe.com/ideas/2016/10/01/mobile-data-collection-thermal-right-now/lG2WB9JrAFHbPcxsQeCBpO/story.html

Ishinoa, Y., & Jin, Y. (2006). An information value based approach to design procedure capture. *Advanced Engineering Informatics, 20*(1), 89-107.

Jacobsen, E. K., & Slocum, L. E. (2011). Summer Camps. *Journal of Chemical Education, 88*(7), 849-850.

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based science curricula for meaningful understanding. *Science Education, 94*(3), 525-551.

LaMonica, M. (2013). How to Create Thermal Images for Millions of Homes. *MIT Technology Review*. Retrieved from https://www.technologyreview.com/s/512611/how-to-create-thermal-images-for-millions-of-homes/

Lave, J., & Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. New York: Cambridge University Press.

Marshall, J. (2012). Online Gamers Achieve First Crowd-Sourced Redesign of Protein. *Scientic American*. Retrieved from https://www.scientificamerican.com/article/victory-for-crowdsourced-biomolecule2/

McSweeney, K. (2016, September 23). Drones and robots make solar panels more efficient. *ZDNet*. Retrieved from http://www.zdnet.com/article/drones-and-robots-make-solar-panels-more-efficient/

Melero, J., Hernández-Leo, D., Sun, J., Santos, P., & Blat, J. (2015). How was the activity? A visualization support for a case of location-based learning design. *British Journal of Educational Technology, 46*(2), 317–329.

National Research Council. (2009). *Learning Science in Informal Environments: People, Places, and Pursuits*. Washington, DC: National Academies Press.

National Research Council. (2015). *Identifying and Supporting Productive STEM Programs in Out-of-School Settings*. Washington, D.C.: National Academies Press.

Newbill, P. L., Drape, T. A., Schnittka, C., Baum, L., & Evans, M. A. (2015). Learning Across Space Instead of Over Time. *Afterschool Matters, 22*, 4-12.

NGSS Lead States. (2013). *The Next Generation Science Standards: For States, By States*. Washington, DC: The National Academies Press.

Papert, S. (1991). Situating Constructionism. In I. Harel & S. Papert (Eds.), *Constructionism*. Norwood, NJ: Ablex Publishing Corporation.

Riedinger, K., & Taylor, A. (2016). "I Could See Myself as a Scientist": The Potential of Out-of-School Time Programs to Influence Girls' Identities in Science. *Afterschool Matters, 23*, 1-7.

Romero, C., Ventura, S., Pechenizkiy, M., & Baker, R. S. J. d. (2010). *Handbook of Educational Data Mining*: Chapman & Hall / CRC.

Sailer, C., Kiefer, P., Schito, J., & Raubal, M. (2015). *An evaluation method for location-based mobile learning based on spatio-temporal analysis of learner trajectories.* Paper presented at the the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct.

Schamper, A. (2012). collaboratat ion between afterschool practitioners and in-school teachers. *Afterschool Matters, 15*, 48-51.

Shute, V., & Ventura, M. (2013). *Stealth Assessment Measuring and Supporting Learning in Video Games*. Retrieved from Cambridge, Massachusetts: http://mitpress.mit.edu/sites/default/files/titles/free_download/9780262518819_Stealth_Assessment.pdf

Simonite, T. (2010). Seeing Infrared in Maps. *MIT Technology Review.* Retrieved from https://www.technologyreview.com/s/419785/seeing-infrared-in-maps/

Tan, Q., Chang, W., & Kinshuk. (2015). Location-Based Augmented Reality for Mobile Learning: Algorithm, System, and Implementation. *Electronic Journal of e-Learning, 13*(2), 138-148.

The Design-Based Research Collective. (2003). Design-Based Research: An Emerging Paradigm for Educational Inquiry. *Educational Researcher, 32*(1), 5-8.

Thomas, J. W. (2000). *A review of research on project-based learning*. Retrieved from http://www.bie.org/index.php/site/RE/pbl_research/29

U.S. Department of Energy. (2016). NREL Announces Innovation Challenge Winner for Crowdsourced Residential Buildings Energy-Efficiency Ideas [Press release]. Retrieved from http://www.nrel.gov/news/press/2016/38754

U.S. Energy Information Adminstration. (2016). What is U.S. electricity generation by energy source? Retrieved from https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

U.S. Environmental Protection Agency. (2011). *Energy Efficiency Programs in K-12 Schools: A Guide to Developing and Implementing Greenhouse Gas Reduction Programs*. US Environmental Protection Agency Retrieved from https://www.epa.gov/sites/production/files/2015-08/documents/k-12_guide.pdf.

Vollmer, M., & Möllmann, K.-P. (2010). *Infrared Thermal Imaging: Fundamentals, Research and Applications* (1st ed.). Berlin: Wiley-VCH.

Wenger, E. (1998). *Communities of Practice: Learning, Meaning adn Identity*. Cambridge: Cambridge University Press.

Wenger, E., McDermott, R., & Snyder, W. M. (2002). *Cultivating Communities of Practice: A Guide to Managing Knowledge*. Boston, MA: Harvard Business School Press.

Xie, C. (2011). Visualizing Chemistry with Infrared Imaging. *Journal of Chemical Education, 88*(7), 881-885.

Xie, C. (2012a). Interactive Heat Transfer Simulations for Everyone. *The Physics Teacher, 50*(4), 237-240.

Xie, C. (2012b). *Transforming Science Education with IR Imaging*. Paper presented at the InfraMation, Orlando, FL. http://energy.concord.org/publication/inframation2012.pdf

Xie, C. (2014). Visualizing Student Learning. *@Concord, 18*(1), 4-6.

Xie, C. (2015). Visual Process Analytics. *@Concord, 19*(2), 4-6.

Xie, C., & Hazzard, E. (2011). Infrared Imaging for Inquiry-Based Learning. *The Physics Teacher, 49*(September), 368-372.

Xie, C., Zhang, Z., Nourian, S., Pallant, A., & Bailey, S. (2014). On the Instructional Sensitivity of CAD Logs. *International Journal of Engineering Education, 30*(4), 760-778.

Xie, C., Zhang, Z., Nourian, S., Pallant, A., & Hazzard, E. (2014). A Time Series Analysis Method for Assessing Engineering Design Processes Using a CAD Tool. *International Journal of Engineering Education, 30*(1), 218-230.

Zapata-Rivera, D. (2012). *Embedded Assessment of Informal and Afterschool Science Learning*. NRC short thought paper. Board on Science Education, Division of Behavior and Social Sciences and Education, The National Research Council. Washington, DC. Retrieved from http://sites.nationalacademies.org/DBASSE/BOSE/DBASSE_071087#.UM-g5ba8FRw