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A Smart Home Test Bed for Undergraduate Education to Bridge the Curriculum Gap From Traditional Power Systems to Modernized Smart Grids

Qinran Hu, *Student Member, IEEE*, Fangxing Li, *Senior Member, IEEE*, and Chien-fei Chen

***Abstract*—There is a worldwide trend to modernize old power grid infrastructures to form future smart grids, which will achieve efficient, flexible energy consumption by using the latest technologies in communication, computing, and control. Smart grid initiatives are moving power systems curricula toward smart grids. Although the components of smart grids fall within the broader discipline of electrical and computer engineering, undergraduate students are rarely assigned single design projects that require classic power systems knowledge combined with communication, computing, and control. Therefore, as a significant step toward potential curriculum changes, this paper presents such a project, a smart home test bed based on the pedagogical model of project-based learning (PBL) for undergraduate education. The proposed test bed allows undergraduates to gain key knowledge in smart grid topics, such as flattening demand peaks, real-time price response, wireless sensor networks, machine learning, pattern recognition, embedded system programming, user interface design, circuit design, and databases. This is well aligned with smart grid initiatives and provides a platform for students to develop their creativity in engineering design. It also offers real-life examples to be used for raising general public awareness of energy conservation.**

***Index Terms*—Demand response, energy management system, power system education, project-based learning (PBL), research experience for undergraduates (REU), senior design, smart grids, smart home.**

I. Introduction

IN RECENT years, the electrical power industry has undergone a modernization, moving from traditional power systems toward smart grids. Efficient, flexible, and controllable energy consumption is one of the fundamental goals of smart grid initiatives. According to the U.S. Census Bureau, the American population will swell to 336 million by 2020, and 400 million by 2043 [1]. Due to the rapid growth of the US population, the demand for residential energy consumption will increase. Moreover, in the past few years, the availability of advanced metering infrastructures (AMIs) and communication technologies makes real-time pricing (RTP) technically feasible [2]. The application of RTP provides the chance for consumers and load serving entities (LSEs) to interact with each other, which creates an opportunity for consumers to play an increasingly active role from the demand side of the present electricity market with smart home energy management system (SHEMS). The broad benefits include peak-load shaving, energy consumption reduction, and electricity cost saving. In recent years, these have been hot topics both for technical papers and industrial products to build "smarter" homes [3]–[11].

Developing the "open" concept of a smart home will require the integration of various electrical and computer engineering (ECE) technologies, such as power, communication, computing, and control. More specifically, the technologies of demand response, electricity market operation, machine learning, pattern recognition, wireless sensor network (WSN), Web user interface (UI) design, circuit design, and database management will be needed to various extents for smart grids.

The evolution from power systems to smart grids has important implications for university education. Due to the nature of power systems that deal with large-scale infrastructures of electricity grids, traditional power system-related projects for undergraduate ECE students are usually based on simulation and seldom offer a hands-on laboratory learning and research experience. The smart home test bed, in contrast, offers the latest technologies in communication, computing, and control, and allows undergraduates to solve real-life issues that go beyond the conventional power systems curriculum.

To this end, this paper presents a platform of an SHEMS [12] on which undergraduates can extend their theoretical knowledge and apply it to practical applications. Initially, the SHEMS was designed as a Research Experience for Undergraduates (REU) program in the field of ECE, supported by National Science Foundation (NSF) Engineering Research Center (ERC) funding for the Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT). SHEMS gradually evolved into a platform for senior design projects, to benefit a broader range of ECE undergraduates, and became a significant milestone in bridging the gap between traditional power systems curriculum and smart grids.

The SHEMS test bed has a broader implication for ECE educators wishing to create an effective and innovative research and design project. Senior design projects based on this test bed could be a required curriculum module for smart grid concentrations, giving these students the opportunity to explore various

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The authors are with the Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, TN 37996 USA (e-mail: fli6@utk.edu).

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advanced technologies. They can creatively design and modify the existing system according to their interests, and their ideas and results can easily be verified through actual experiments on the test bed. By conducting the experiment and gathering the data, undergraduates can gain a better understanding of the mechanism of smart home design and an awareness of energy efficiency and conservation.

The pedagogical model of project-based learning (PBL) [20] was adopted for its ability to cultivate students' independent and creative thinking. The academic assessment results reported here indicate that the project participants not only showed considerable improvement in their research skills, research knowledge, research application, personal and professional development, and creativity in engineering, but also had increased interest in attending graduate school.

The remaining parts of this paper are organized as follows. Section II describes some previous works on SHEMS. Section III illustrates the pedagogical model and detailed project description. Section IV presents the contributions made by students from 2010 to 2014. Section V discusses the educational assessment, including a survey, an interview, and an assessment results analysis. Finally, Section VI shows the pedagogical importance of this work and presents suggestions for future work.

II. Previous Work on Smart Homes

Due to the increasing popularity of the smart home concept, a number of universities and companies have been conducting research in this area. Section II-A discusses the research and development of various aspects of this work. Section II-B goes on to describe the SHEMS prototype at The University of Tennessee, Knoxville (UTK).

A. Related Work

The broad range of previous works related to smart home and residential energy management systems includes hardware prototypes, appliance modeling, occupant activity recognition and prediction, load scheduling optimization, and communication security.

Various prototypes have been presented in recent years. A demonstration of an automatic appliance control design based on utility signal, customer preference, and load priority is given in [13]. A prototype of an intelligent metering, trading, and billing system with an implementation in demand-side management (DSM) is presented in [4]. The Georgia Tech Aware Home [14] is a prototype for researchers to simulate and evaluate user experience with off-the-shelf and state-of-the-art technologies. Other prototype SHEMS studies are documented in [3] and [15].

Occupant activity recognition and prediction are critical to optimize energy usage in smart homes. As WSN technology matures, researchers can take advantage of the data collected by sensors located throughout a house, in order to achieve better DSM. Several groups have been working in this area, a trend reflected in [3], [14], and [15]. The focus in [16] is on recognizing simple occupant activities by implementing the hidden Markov model (HMM) and conditional random field (CRF) to exploit human-centric appliances. In [17], an algorithm is described that automatically constructs individual models of normal activities within a home, using motion sensors. In [4] and [5], an agent-based smart home architectural model is proposed that considers and analyzes predictions of occupant activities and the related automated controls.

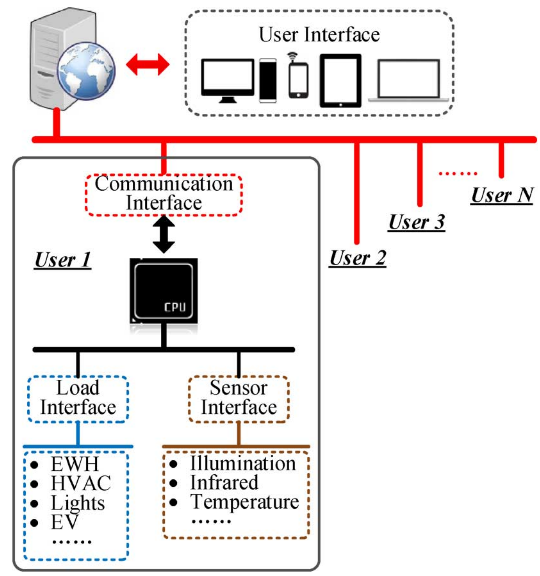

Fig. 1. Schematic diagram of SHEMS.

On the topic of load scheduling optimization, RTP-based residential energy consumption optimization is discussed in [7] and [18]. In [7], residentially distributed energy resources are considered collectively so as to generate coordinated scheduling. A dynamic price-responsive algorithm that leads to significant reductions in users' electricity payments is discussed in [18].

B. Overview of the SHEMS Test Bed

The SHEMS test bed [12] is a smart home prototype, developed in the Department of Electrical Engineering and Computer Science (EECS) at UTK. Integrating various ECE technologies, it constitutes an effective educational platform.

In contrast to previous hardware prototypes, the SHEMS test bed was designed to be easy to extend, and to be "open", in that students can enhance the system itself and explore areas relevant to the smart home concept. The test bed is able to: 1) read real-time prices (if a privilege to real data is granted); 2) provide optimal control strategy with automatically adjusted loads including electrical water heaters (EWHs), heating/ventilation air conditioning (HVAC) systems, electrical vehicle (EV) charging stations, dishwashers, washing machines, and dryers; 3) provide both local and Web-based user interfaces; and 4) upload log files to the server. The model platform of SHEMS is based on Stellaris LM3S9D96 MCU. Various protection systems, such as air switches, were included for safety and reliability. The platform is divided into several functional modules, which makes it easier for students to extend and upgrade the existing system.

The schematic diagram of SHEMS used for this study, Fig. 1, shows the information flow within SHEMS.

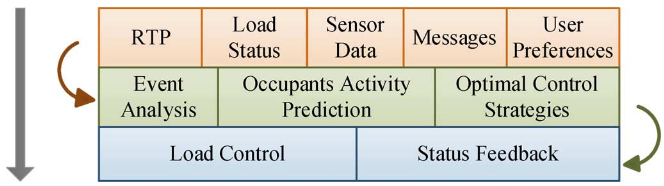

Fig. 2. Major directions for student projects.

III. Pedagogical Model and Project Description

In accordance with PBL and the findings in the engineering education literature, all the tasks in senior design projects evolve around SHEMS. Students are encouraged to use the test bed as an open platform to carry out a series of explorations to enhance performance in order to make a home smarter. The test bed can also be used to verify and assess the extent to which the updated hardware or software can improve the performance of SHEMS.

A. Pedagogical Model

PBL [20] is defined as "a systematic teaching method that engages students in learning knowledge and skills through an extended inquiry process structured around complex, authentic questions and carefully designed products and tasks" [21]. SHEMS incorporates two main themes of PBL: *design-oriented* projects and *problem-oriented* projects [22]. Design-oriented projects emphasize the concept of *know-how*, dealing with the practical problems of design. Meanwhile, problem-oriented projects focus on the concept of *know-why*, dealing with the solution of theoretical problems. Both types require relevant engineering knowledge. In addition, the specific aspects of the proposed project focus on the recognition of system context, reasoning about uncertainty, estimation, experimental design, and teamwork environment.

B. Main Directions for Student Projects

One of the eventual goals of SHEMS is to minimize a consumer's total electricity payment while satisfying his or her comfort needs, such as indoor temperature, hot water temperature, illumination, etc. SHEMS should be able to monitor and analyze the real-time status of a specific area or home. Furthermore, SHEMS should be able to identify optimal load control strategies in response to RTPs, the consumer's needs and habits, and any extreme scenarios.

With those objectives, undergraduates are encouraged to make the improvement of the existing SHEMS as test bed the theme of their senior design projects. To assist students in choosing a suitable senior design project task in the area of smart grids, they are supplied with a summary of possible SHEMS tasks, shown in Fig. 2. Reflecting the information flow, 10 tasks are divided into three layers. Input information to the test bed comprises RTP, load status, sensor data, messages, and user preferences; the data processing portion includes event analysis, occupant detection and prediction, and strategy optimizing; the successful delivery of the generated optimal control strategies requires load control and feedback. These 10 areas, and their potential for improvement by students, are now described in more detail.

1) RTP: To read RTP signals from the LSE, an Internet connection is required. Students could consider how to read RTP through the Internet and how to perform the preprocessing to avoid bad data.

2) Load Status: The system processor needs to obtain appliances' working status. Students could design load interface circuits to read data from appliances such as EWH, HVAC, EV, lights, dishwasher, and washing machine. The load interface design is expected to be efficient, reliable, and compact.

3) Sensor Data: Motion, flow, temperature, and illumination sensors need to be installed to monitor the environment, so as to predict occupants' activities. To keep the system efficient, the number of sensors and their locations should be studied to avoid redundancy. Students could perform simulations and experiments to find the optimal plan for deploying sensors to reduce total costs, and to increase efficiency without affecting the accuracy of machine learning and pattern recognition.

4) Messages: This function is designed to respond to extreme scenarios. For example, an LSE might send important messages to consumers about power outages, weather alerts, and similar situations. Since extreme scenarios are generally accompanied by accidents or other incidents, mobile communication should be considered in the design, either as the premium service or as a backup when a wired Internet connection is unavailable. Students could examine how to make the Ethernet and mobile communication cooperate to ensure efficient and reliable communication between consumers and the LSE.

5) User Preferences: To obtain consumers' preferences, SHEMS should include a touch screen UI for each consumer, so they can manually change the settings at home. Also, SHEMS should host a customized Web page to make remote controls available. Since a factor that discourages consumers from installing SHEMS is the complexity of a smart home's settings, a better UI design is vital to a successful SHEMS design. Students would analyze user requirements, and then design a concise UI offering a better user experience.

6) Event Analysis: The processor reminds consumers about messages from the LSE through a specific UI. If messages could potentially affect the scheduling of home appliances, SHEMS should have the capability to analyze these events and provide related information, such as whether the room temperature still meets the consumer's preference. Therefore, students could design optimization algorithms to make SHEMS responsive to the messages from the LSE. For example, if there were to be a scheduled 1-h locational outage, SHEMS should update the control strategies for appliances, such as preheating the EWH and/or precooling the room, to accommodate the occupant's comfort level. Furthermore, SHEMS should alert consumers if the comfort level will be significantly impacted by any inclement event.

7) Occupant Activity Prediction: Machine learning and pattern recognition algorithms will be implemented to analyze and predict occupants' activities based on data collected by sensors; pattern recognition helps to identify activities, and machine learning trains the system to improve its prediction of consumers' habits. Here, students would not only improve the efficiency of the algorithm, but also modify it to fit various situations, such as single/multiple occupants and different lifestyles

TABLE I
STUDENT TEAMS AND THEIR ACHIEVEMENTS

Milestone	**Major Achievements**
2010 Summer	Hardware design_V1, Web UI_V1
2011 Summer	Implemented power usage monitoring
2011 Fall	Hardware design_V2
2012 Summer	Interface with air conditioner
2012 Fall	Hardware design_V3, Web UI_V2
2013 Summer	Compact design_V4, Load optimization algorithm
2014 Spring	Integrating geographic information, Web UI_V3

(e.g., profession, age, and gender), and to achieve better accuracy within a short training time.

8) Optimal Control Strategies: Since all the necessary information (i.e., RTP, consumer needs, emergency events, and occupants' activities) is available, the processor should be able to generate the optimal control strategies for each load based on appliance models. Students could update the appliance models to make them more realistic and improve the optimization algorithms in terms of both calculation time and performance.

9) Load Control: Appliances are expected to operate based on the generated control strategies. Students would design specific circuits for those appliances to communicate and realize complex settings, especially for the loads like HVAC and EV that have various control options.

10) Status Feedback: The status feedback module is to send information about the status of appliances, environmental parameters, and important events back to the LSE.

IV. ACHIEVED DEVELOPMENT

A. Students' Backgrounds

Typically, students work on the SHEMS-based design project during their senior year. Each student should be taking or have already taken the courses Power Systems Analysis I and II, and should have taken at least a senior-level course in communication, computing, or control. This "open" and "self-motivated" project provides opportunities for hands-on work and helps students to develop their individual interests, so it is a valuable exercise before being formally involved in a specific area of concentration. This is especially true for senior students who are at the point of deciding between attending graduate school and looking for a full-time job.

B. Project Achievements

From Summer 2010 to Spring 2014, seven groups of students, 23 in all, worked on this project. Their achievements are shown in Table I.

The first senior design project was the development of the SHEMS test bed itself in 2010. That design was able to connect to the Internet and read RTPs. A simple optimization method was implemented to reduce the total electricity payment based on RTPs. This first version was designed to control eight simple loads, but not appliances like AC units. Also, the remote control was available through a Web UI.

Since 2010, senior design students have been improving SHEMS by enhancing various functional modules, as described in Section III-B. The latest version of SHEMS, shown in Fig. 3, has several substantial improvements compared to the first version. In terms of hardware, it employs sensors to detect occupants' activities, Wi-Fi modules for wireless communication between appliances and sensors, and various load interfaces including a portable AC unit. Note that the AC unit can be wirelessly controlled not only with a simple on–off command, but also with complex settings like operating mode, fan speed, and expected temperature. In terms of the software, a compact and user-friendly Web UI has been developed. The implementation of sensors allows various proposed functions to be integrated in the test bed. The latest version incorporates machine learning and pattern recognition algorithms to predict occupants' activities. Also, it is now able—based on RTPs, messages from the administrator (i.e., the electricity supplier), appliance models, and occupant activities—to optimize appliances to save electricity costs without having much impact on user comfort. Furthermore, by predicting occupants' activities, the system can offer simple setting modes that allow users to avoid the complicated and time-consuming setting process.

Fig. 3. Latest version of the SHEMS platform.

V. EDUCATIONAL ASSESSMENT

This study proposes the following hypotheses: After completing this research project, students will have increased interests in choosing smart grids or power systems for their career, increased interests in attending graduate school, and enhanced research knowledge, research application, and creativity. Also, they will have a more positive attitude toward engineering. Based on these hypotheses, the assessment was designed in two parts: an online survey and a semi-structured interview.

A. Survey Design

For the survey assessment, a letter containing an introduction to this study, an informed consent form, and a Web link to the survey was e-mailed to 14 REU students who had participated in this project from 2011 to 2013. To ensure anonymity and reduce the chance of socially undesirable responses, personal identifiers were not collected. Additionally, to protect personal privacy, this project used secure software and encrypted Web links and did not collect subjects' Internet Protocol (IP) address.

The survey instructed the students to read a series of questions and rate each question based on a 5-point Likert-type scale

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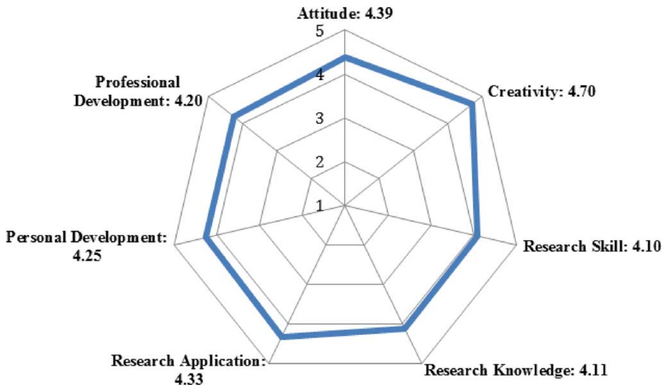

Fig. 4. Survey results showing the means of the major variables.

($1 = \text{no gain}$, $3 = \text{neutral}$, and $5 = \text{great gain}$) to indicate their levels of gain in various areas as a result of participating in this smart home design project. Furthermore, this survey instrument was designed to measure overall satisfaction, interest in engineering career, intention to attend graduate school, research training (skill, application, and knowledge), personal and professional development, attitude toward engineering, and creativity.

For specific measurements, scales from The Undergraduate Research Student Self-Assessment (URSSA) were adopted and modified to measure all the important concepts [19]. These five measurements are described as follows.

Research Training was measured by 10 questions covering the concepts of research knowledge, application, and skills. (These three subareas are shown individually in Fig. 4.) Sample questions include: "Describe how much you gained in the following areas as a result of your participation in this Smart Home Design Project: formulating a research question that could be answered, identifying limitations of research methods and designs, or understanding the bigger picture of research in power systems."

Personal Development was measured by six statements including: "developing patience with the slow pace of research," "managing my time efficiently," "ability to work independently," "confidence in my ability to contribute to the engineering field," "comfort in working collaboratively with others," and "confidence in my ability to do well in future engineering courses."

Professional Development in engineering was measured by seven statements regarding individuals' gain in the following areas including: "defending an argument when asked questions," "comfort in discussing engineering concepts with others," "explaining research to people outside my field," "preparing an engineering poster," "making oral presentations," "understanding what everyday research is like," and "taking greater care in conducting procedures in the lab or field."

Attitude Towards Engineering was measured by four statements including: "engage in real-world engineering research," "feel like an engineer," "feel like a part of an engineering community," and "networking with other researchers."

Creativity in Engineering was measured by four statements including: "thinking creatively about the project," "trying out new ideas or procedures on your own," "feeling responsible for the project," and "working extra hours because you were excited about the research."

TABLE II
MEAN AND STANDARD DEVIATION FOR THE THREE RESEARCH TRAINING SUBAREAS OF KNOWLEDGE, SKILL, AND APPLICATION

Variables	Items	Mean	S.D.
Knowledge	Formulate a research question	4.33	0.71
	Theory & concepts of guiding research project	4.00	0.71
	Bigger picture of research in power systems	4.00	0.71
Skill	Understand how data are collected	3.78	1.20
	How to deal with setback or negative results	4.38	0.52
	Problem-solving in general	4.67	0.50
Application	Identify limitations of methods and designs	3.56	0.88
	Figure out the next step in a research project	4.33	0.87
	Understand the relevance of research to coursework	4.11	0.78
	Understand how to apply concepts to practice	4.56	0.53

For each measurement, the scores for all question items were summed and averaged to obtain overall students' gains in that measurement.

B. Survey Results

Eleven out of 14 students (78.57%) completed this survey. The survey results indicated that every student (100%) was satisfied with this research experience. Also, 89% of the participants reported that this REU/design experience had increased their interest in choosing engineering as their career, and 78% of the students showed interest in attending graduate school. In terms of research training, students showed an increase in their level of research knowledge ($\text{mean} = 4.11$, *standard deviation*, $\text{S.D.} = 0.47$), research skill ($\text{mean} = 4.10$, $\text{S.D.} = 0.40$) and research application ($\text{mean} = 4.33$, $\text{S.D.} = 0.53$) (see Fig. 4). Table II presents the mean and S.D. of each item in the Research Training measurements of research knowledge, skill, and application.

In addition, the majority of the students reported an increase in professional development ($\text{mean} = 4.26$, $\text{S.D.} = 1.32$) and an increase in personal development ($\text{mean} = 4.25$, $\text{S.D.} = 1.86$). Figs. 5 and 6 report the mean for each item in the measurement of professional and personal developments, respectively.

Students' attitude towards engineering also increased ($\text{mean} = 4.39$, $\text{S.D.} = 1.64$). Furthermore, students expressed that this project helped increase their creativity in engineering ($\text{mean} = 4.70$, $\text{S.D.} = 2.85$). As shown in Fig. 4, the measure of creativity was rated the highest gain followed by attitude and research application. Among all the questions, the item of "discussing engineering concepts with others" was rated the highest in terms of students' perceived gains.

Although the mean score is considered to be very favorable (between 3.78 and 3.89), the survey results show that future improvements can be accomplished via aspects such as defending arguments, preparing engineering posters, and working independently. Future projects can therefore be designed to enhance students' knowledge of these aspects.

C. Interview Results

Besides the quantitative measures, a semi-structured interview was conducted. This 1-h-long interview included questions related to overall satisfaction, career choices (attending

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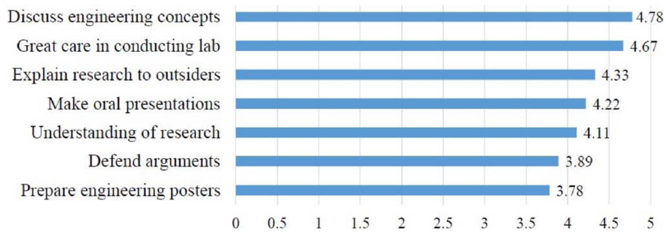

Fig. 5. Mean of each item for the measurement of professional development.

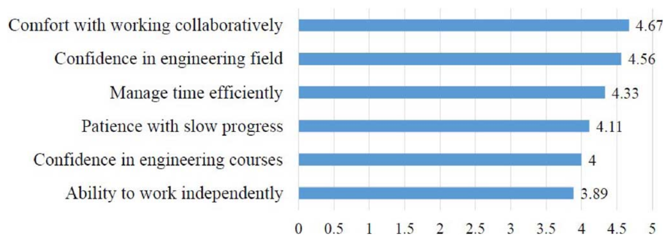

Fig. 6. Mean of each item for the measurement of personal development.

graduate schools or working in engineering companies), understanding of power system concepts, feelings of being an engineer, new ideas about research, teamwork and leadership, and research values. Space constraints mean the overall satisfaction and career choices reported in Section V-B will not be discussed again here. For power system concepts, students expressed a better understanding in the area of peak load shaving. As one student stated [sic]:

> "We definitely learned a lot about the daily load curve and that sort of things, because the whole basis behind the project is how to reduce the residential energy consumption during the peak load hours of a day and help people save money. Especially, since it gonna get that time of the day pricing, it is gonna get very expensive to people. I think it definitely help us understand how to shave off that peak over there."

Students also indicated this project had helped them think about new ideas about SHEMS. As one student pointed out [sic]:

> "There are a lot of similar products on the market. They are all focusing on convenience. If we can commercialize ours with emphasizing on time of day pricing, we can get really good edge on the market. Because everything else is just smart phone applications, website design and all the sort of stuff. Let's focus on ease of use far more than they are doing. If we also can focus on saving people money, it will really differentiate us."

This hands-on project had achieved the goal of teamwork and some leadership. In addition, students expressed that this project had made them feel good about being engineers. As two students stated [sic]:

> "I would say we all play a little bit leadership as a project leader, kind of role, during the different time of our project."

> "I feel like it was always interesting. Sometimes it might not be easy, but you know, who wants a job, the choice gonna to be easier if that work won't make you feel bored. It is always a challenge for me anyway."

Overall this project was perceived to have a put a positive value on attending graduate school and to have gone beyond classroom learning. Two students addressed this [sic]:

> "I think the project really related with research, let us worked more on academia side of engineering, and knew new technologies. This project definitely helps, at least for me. I didn't want to just go into industry and sit on the desk in the rest of my life."

> "We definitely need to do some research for a project. It was fun. The overall project is definitely fun, and more than other courses we had. Not like we just go to lectures and take tests. It was a lot more fun and a lot more hands on and will meet a lot more questions you will see maybe in the real world when actually do go to work. I think it gives us a good insight into what occurred."

VI. Conclusion and Future Work

The power industry paradigm has shifted from traditional power systems to modernized smart grids. University education needs to respond to this change by modernizing the existing power systems curriculum to cover smart grids. In this paper, a senior design project based on a smart home test bed is discussed as a potential education tool to bridge the curriculum gap from power systems to smart grids.

This paper presented a smart home test bed, called SHEMS, with "open" and extendable structure used for educational purposes. Various electrical engineering-related technologies can be integrated into the test bed, such as demand response, electricity market, machine learning, pattern recognition, wireless sensor networks, Web UI design, circuit design, and databases.

The SHEMS test bed is a viable platform for smart grid educators to teach undergraduates both theoretical knowledge and practical applications. It offers undergraduate students not only valuable research and design experience, but also an understanding of how smart homes work. In addition, the test bed promotes public awareness of energy efficiency and conservation. Most importantly, it helps raise students' interest in undertaking research as well as being power professionals. The observations and results from the comprehensive survey and interview show that the project was a successful experience, indicating that the students considered the hands-on experience of improving the SHEMS to be very useful for their future both personal and professional development.

Most importantly, it will be interesting and exciting to observe what other students can accomplish to improve the future versions of the smart home test bed.

Acknowledgment

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Qinran Hu (S'11) received the B.S.E.E. degree from Southeast University, Nanjing, China, in 2010, and the M.S.E.E. degree from The University of Tennessee, Knoxville, TN, USA, in 2013, and is currently pursuing the Ph.D. degree in electrical engineering at The University of Tennessee.

His research interests include power system optimization, smart energy management system, and renewable energy integration.

Fangxing (Fran) Li (M'01–SM'05) received the B.S.E.E. and M.S.E.E. degrees from Southeast University, Nanjing, China, in 1994 and 1997, respectively, and the Ph.D. degree from Virginia Tech, Blacksburg, VA, USA, in 2001.

He is presently an Associate Professor in electrical engineering with The University of Tennessee, Knoxville (UTK), TN, USA, as well as the Director of the education and diversity program of the Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT). He had been a Senior and then a Principal Engineer with ABB Electrical System Consulting (ESC), Raleigh, NC, USA, from 2001 to 2005, prior to joining UTK in 2005. His current interests include renewable energy integration, smart grid, power markets, and distributed energy resource.

Dr. Li is a Fellow of IET, a registered Professional Engineer (P.E.) in the state of North Carolina, and an Editor of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY.

Chien-fei Chen received the B.S. degree in English language and literature from National Cheng Kung University, Taiwan, and the M.S. degree in communication and Ph.D. degree in sociology from Washington State University, Pullman, WA, USA, in 1995 and 2009, respectively.

She is a Research Professor and Co-Director of the education and diversity program at the NSF-DOE engineering research center, Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT), and an adjunct faculty with the Department of Sociology, University of Tennessee, Knoxville (UTK), TN, USA. Her previous experience includes Public Television Service (PTS), Taipei, Taiwan; Vision Communication Public Relation Company, Taipei, Taiwan; KSPS, Spokane Public Station, Spokane, WA, USA; KCTS, Seattle Public Television, Seattle, WA, USA; Seattle Chinese Television Station, Seattle, WA, USA, Washington State University; and Virginia Tech, Blacksburg, VA, USA. Her current research interests include social-psychological factors of grid technology acceptance, renewable energy and energy conservation, and engineering education (K–12 and university).