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Enabling Technologies Development Grant Program: Final Report

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ENABLING TECHNOLOGIES DEVELOPMENT GRANT PROGRAM

Final Report 2002–2015

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TAC Members (current):

- Mauro Dresti (Southern California Edison)
- John Holmes (Sempra Utilities)
- Belvin Louie (Consultant)
- Charlie Middleton (Pacific Gas & Electric)
- Larry Miller (California Institute for Energy and Environment)
- Mary Ann Piette (Lawrence Berkeley National Laboratory)
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TAC Members (posthumous):

- Don Pezzolo
- Don Aumann

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Enabling Technologies Development Grant Program: Final Report is the final report for the Enabling Technologies Development Grant Program project (contract number 500-01-043) conducted by the California Institute for Energy and Environment, University of California. The information from this project contributes to Energy Research and Development Division's Energy Systems Integration Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The Enabling Technologies Development Grant Program addressed 3–5 year and 5–8 year energy-related research objectives. To meet specific public interest goals, grant awardees developed enabling technologies that can:

- Improve the reliability and quality of California's electricity by reducing service interruptions through expanded service options and new system-wide capabilities.
- Maximize market connection by reducing the installed cost of energy-related information, communication, and control technologies.
- Improve the energy cost and value of California's electricity by providing real-time information and a means to respond automatically to supply-side problems.

The University of California's California Institute for Energy and Environment managed the program and was responsible for proposal solicitations, pre-proposal screening, organizing proposal technical reviews, and presenting selected proposals to the Energy Commission for approval. The California Institute for Energy and Environment was also responsible for awarding the grants, monitoring the grant awardees for compliance with grant terms, and providing all necessary technical and administrative support.

This final report is a compilation of 22 final reports from research projects completed between 2002 and 2015 by the grant awardees.

Keywords: Public Interest Energy Research program, PIER, demand response, enabling technologies, network security, privacy, sensor networks, agile radios, business network, business processes, information models, systems integration, field simulation, collaboration exchange, intelligent agents, service-oriented software, wireless sensors, middleware, development environment, operating system, application programming interface.

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Introduction

Shortly after the Western U.S. Energy Crisis of 2000–2001, the California Energy Commission sought to make the state's electricity grid more resilient by exploring demand response as a means of shifting peak load to improve grid reliability and stabilize prices. Disruptive enabling technologies are necessary for achieving low-cost, high functionality meters, thermostats, actuators and other products part of demand-response and energy-efficient systems envisioned by state policy; however, industry and federal government Research and Development (R&D) programs do not fund their development. To meet this need, the Energy Commission funded a the Demand Response Enabling Technology Development Program in 2002 to develop and implement disruptive enabling technologies with ten times the functionality of current technology and one-tenth of the installation cost within the next 5–8 years. This program was unique in the sense that many research programs typically fund projects with immediate demand and a 2–3 year timeline. In 2008, the Enabling Technology Development Program evolved into the Enabling Technology Program.

Project Purpose

The Enabling Technology Program's specific public interest goals were to develop enabling technologies that can:

- Improve the reliability and quality of California's electricity by reducing service interruptions through expanded service options and new system-wide capabilities.
- Maximize market connection by reducing the installed cost of energy-related information, communication, and control technologies.
- Improve the energy cost and value of California's electricity by providing real-time information and a means to respond automatically to supply-side problems.

The California Institute for Energy and Environment (CIEE) administered the program. With the advice of the Energy Commission, consultants and the Technical Advisory Committee (TAC), CIEE developed and administered several Research Opportunity Notices (RONs):

- Revenue Energy Metering (New Meter)
- Temperature Measurement (New Thermostat and New Temp Node)
- Network Management
- System Integration
- Control and Communications Integration
- Enabling Technologies for Legacy Buildings
- Transmission
- Distribution

- Smart Homes

Some RONs were open to entities with a presence in California while others were restricted to California state universities. The TAC reviewed and scored the proposals and forwarded the results and recommendations for funding to the Energy Commission for final selection and commissioner approval. Between 2002 and 2014, the Energy Commission awarded a total of $12.9 million in funding to 22 grants—ten of which were with the University of California, three with the California State University, two with the U.S. Department of Energy National Labs, and seven with private industry.

Project Results

The projects cover a wide variety of topics ranging from hardware (batteries, energy harvesters, thermostats, wireless technologies, arc fault interrupter for DC systems) to middleware (controls, power factor filter, inverter controls) and to systemic issues (evaluation of wireless communication, network architecture, privacy, networked electric vehicles, consumer engagement). Over the course of the program, researchers at the University of California, Berkeley developed small integrated sensor nodes with low powered radios using thermoelectric and vibration power generation, as well as printable storage devices. Researchers worked across campuses and between institutions to develop improved lithium battery technologies, inverter controls that improved grid stability, user interfaces and controls to enable acceptable electric vehicle charging in networks, and mobile apps to engage residential electricity consumers.

Project Benefits

The technologies resulting from these projects have benefited California in numerous ways. A residential gateway reference design paved the way toward commercial products. Research improved thermostats in multiple ways. Two advanced thermostats companies, EcoFactor and Nest Labs, benefited from the advanced thermostat research, which encompassed improved user interface design, machine learning, and occupant sensing. The Energy Commission formed the Universal Smart Network Access Port (USNAP) Alliance to promote, certify and advance a protocol independent modular communication interface standard, known as ANSI/CEA-2045, that enables any Home Area Network (HAN) or Demand Response (DR) standard, present and future, to use any energy services interface as a gateway, without adding additional protocol-specific hardware. In 2010, Golden Power introduced a sub-$100 Programmable Communicating Thermostat with 2-USNAP ports, and included a Wi-Fi communications module.

Utility Integration Solutions (UISOL) demonstrated the feasibility of automating demand response (DR) business networks end-to-end in the DRBizNet software. By late 2014, some 1,100+ registered users of DRBizNet in over 250 companies in 27 states were using DRBizNet; UISOL was 80 people strong, with 50 percent of its revenue coming from DRBizNet licenses and services. DRBizNet created about 40 new jobs.

In addition, many start-up companies developed both directly and indirectly as results of work from the program, including:

- Imprint Energy (printable batteries), founded by Christine Ho
- Adura Technology (wireless load controls, (acquired by Acuity Brands), co-founded by Charlie Huizenga)
- Sentilla (Information technology infrastructure intelligence software, [acquired by Ericsson], founded by Joe Polastre)
- Dust Networks (wireless mesh network of motes) acquired by Linear Technology), founded by Kris Pister
- Arch Rock (Internet Protocol-based wireless network technology, (acquired by Cisco), founded by David Culler
- Vigilent Corporation (formerly Federspiel Controls), founded by Cliff Federspiel

Dozens of graduate student researchers worked on the Demand Response Enabling Technology Development/Enabling Technology Development Program between 2003 and 2014. Many went onto private industry and universities and have become thought leaders and sources of authority in the energy field.

CHAPTER 1: Background

In 2002, the Energy Commission Public Interest Energy Research (PIER) Program awarded the Demand Response Enabling Technologies Development Grant Program (later renamed the Enabling Technologies Development Grant Program) (Program) to the University of California's California Institute for Energy and Environment (CIEE). CIEE possesses the technical, project management, and administrative expertise needed to implement the Program.

The initial purpose of the Program was to develop enabling technologies for establishing a real-time Demand Response (DR) infrastructure in California that addresses both Market DR and Contingency DR. To achieve this objective, it is anticipated that new interaction paradigms will have to be created between the electric transmission and distribution infrastructure and customer loads. These paradigms will require advanced *information*, *communication*, and *control* relationships and technologies creating a DR capability that executes customer preference automatically under a variety of market and contingency conditions. It is also anticipated that similar advanced *information*, *communication*, and *control* relationships and technologies can benefit other energy-related areas of research.

1.1 Project Objective

The Program addressed 3–5 year and 5–8 year energy-related research objectives. The technology development initially focused on large commercial, industrial and institutional facilities although it is expected that the results of the proposed research, development, and deployment (RD&D) may apply to smaller buildings. In addition, in the area of DR, it is expected that the development of DR enabling technologies (which are focused on peak-load reduction) will lead to enabling technologies that also reduce the base load through generic energy efficiency improvements.

The Program was expanded in 2008 to research areas beyond the originally targeted area of DR and was known as the Enabling Technologies Development (ETD) Grant Program. In particular, the research was extended, but not limited to, other PIER focus areas such as:

- Distributed Energy Resources Systems Integration (interconnection standards/technologies and market integration),
- Distribution (more flexible and responsive distribution solutions)
- Security (issues related to California's electric grid),
- Strategic and Enabling Technologies (storage, seismic, tools for market analysis)
- Transmission (enhancements of transmission capabilities), and
- Energy efficiency in buildings and the operation of Heating Ventilating and Air Conditioning (HVAC) equipment.

The specific public interest goals of the Program are to develop enabling technologies that can:

- Improve the reliability and quality of California's electricity by reducing service interruptions through expanded service options and new system-wide capabilities.
- Maximize market connection by reducing the installed cost of energy-related information, communication, and control technologies.
- Improve the energy cost and value of California's electricity by providing real-time information and a means to automatically respond to supply-side problems.

In order for the Energy Commission to develop, and help bring to market, energy technologies that provide increased environmental benefits and that provide tangible benefits to electric utility customers, there has to be a long-term strategy that fills the research and development (R&D) pipeline with enabling technologies that lead to useful products. The focus of the Program is to develop enabling technologies that dramatically reduce costs and increase functionality of controls- and communications-related products. Included in these enabling technologies are sensors, power supplies, and transceivers which are building blocks that are not being funded by industry and federal government R&D programs but are absolutely necessary for achieving low-cost, high functionality meters, thermostats, actuators and other products that are part of demand-response and energy-efficient systems envisioned by state policy.

A specific intent of the Program is to leverage on-going RD&D funded in communication, information, and control technologies by other agencies such as the Department of Defense. The Program will focus on specific energy-related tasks that can lead to dramatic decreases (by a factor of 10) in the installed cost of these technologies for energy-related applications. Technologies that are of particular interest to the Program are energy-related (a) microelectromechanical systems (MEMS) sensors and actuators, (b) open-system, mesh-architecture communication systems that can seamlessly share data, (c) real-time, distributed-intelligence device networks that are self-organizing, and (d) enterprise-wide, multilevel control strategies that can absorb legacy systems.

An additional unique area of emphasis under enabling technologies is control and communication integration (C^2I). Technology development is needed that specifically focuses on the C^2I issues associated with ubiquitous (widespread) communicating interval meter deployment; the potential for integration with dispatchable distributed energy resources (e.g., distributed generation), and the potential positive impact that a metering infrastructure might have on emerging distribution automation initiatives.

RD&D projects fell into the following categories:

- Building-block technologies that relate to a real-time communications infrastructure such as the DR signaling infrastructure.
- System architectures and topologies for deploying the building-block technologies.
- Legacy system and personnel issues with respect to adopting new technologies.

- Storage technologies for local, distribution, and transmission applications.
- Low cost and high quality power monitoring technologies.
- Smart devices in the distribution grid that can self-diagnose and self-heal the grid.
- Technologies that can automatically re-synch a power island with surrounding the power grid.
- Modeling and control algorithms to facilitate the integration of intermittent renewable energy resources.

1.2 Project Implementation

Specific areas of technology research of interest to the Program were documented in a series of Research Opportunity Notices (RON). The RON's were the bases of proposal solicitations issued by CIEE. CIEE was responsible for the administration of the proposal review/selection process, from pre-proposal screening, to proposal technical reviews, to presenting selected proposals to the Energy Commission for approval. CIEE was also responsible for awarding the grants, monitoring the grant awardees for compliance with grant terms, and providing all necessary technical and administrative support.

The RON topics included: Revenue Energy Metering (New Meter), Temperature Measurement (New Thermostat and New Temp Node), Network Management, System Integration, Control and Communications Integration, Enabling Technologies for Legacy Buildings, Transmission, Distribution, and Smart Homes.

The Program is supported by a volunteer Technical Advisory Committee (TAC) consisting of energy technology domain experts from the State's Investor Owned Utilities, private companies, and independent consultants. The TAC assists in the reviewing of proposals and provides technical guidance to the research conducted by the grant awardees in the Program.

Between 2002 and 2014, a total of $12.9M of funding were awarded to 22 grants, of which 10 were with the University of California, 3 with the California State University, 2 with the National Labs, and 7 with private industry.

1.3 Project Results

1.3.1 Thought Leaders

Dozens of graduate student researchers worked on the program between 2003 and 2014. Many went onto private industry and universities and have become thought leaders in the energy field. Some of the notable former graduate student researchers are:

Table 1: Thought Leaders

Therese Peffer	Nathan Ota
Program Director, Enabling Technologies Development Associate Director, i4Energy California Institute for Energy and Environment	CTO Radio Thermostat of America
Alex Do	Andrew Redfern
Senior Value Stream Manager Acuity Brands	Senior System Engineer Sentilla (Acquired by Ericsson)
Christine Ho	Joe Polastre
CTO and Co-Founder Imprint Energy, Inc.	Presidential Innovation Fellow Founder, Alkio Labs and Sentilla (Acquired by Ericsson)
Eli Leland	Michael Koplow
CTO and Co-Founder Subway Labs	Associate O'Melveny & Meyers LLP
Dan Steingart	Eric Carleton
Assistant Professor Princeton University	CTO & Vice President Engineering Prodigy Surface Technology
Will Watts	Jaehwi Jang
Sr. Software Engineer / Architect Vail Systems	Senior Manager Samsung Electronics (Korea)
Joel Wilson	Elizabeth Reilly
Senior Engineer Exponent Engineering and Scientific Consulting	Managing Engineer Exponent Engineering and Scientific Consulting

1.3.2 Standards and Consumer Products

1.3.2.1 PCT and USNAP

In 2006, a multi-phase project to develop a reference design and proof-of-concept prototype of a demand response (DR) capable programmable communicating thermostat (PCT) was started. The intent of the reference design was to assist with the development of wording for the 2008 Building Energy Efficiency Standards (codified in Title 24, Part 6 of the California Code of Regulations) for new and retrofit building thermostats to support DR signals.

In late 2007, the PCT reference design final report made recommendations that included the use of the 1-way RDS (Radio Data System) technology for broadcast DR signals and the use of an expansion I/O port to support for optional communications such as WiFi, Bluetooth, Zigbee, ZWave, etc. For the project, theSecure Digital Input Output- read/write SD flash memory cards standard was recommended.

During the project, companies such as Honeywell, White Rodgers, and Golden Power, were invited to participate in review sessions and workshops. Tim Simon of Golden Power was very interested in the expansion I/O port concept and adopted it for his thermostat product line. But instead of the SDIO standard, he created a new standard that was cheaper than SDIO.

In 2007, Barry Haaser with Tim Simon, formed the USNAP (Universal Smart Network Access Port) Alliance to promote the acceptance and commercialization of the standard. The mission of the Alliance is to promote, certify and advance a protocol independent modular communication interface standard, known as ANSI/CEA-2045, that enables any HAN (Home Area Network) or DR (Demand Response) standard, present and future, to use any energy services interface as a gateway, without adding additional protocol-specific hardware. The USNAP Alliance fosters collaboration and education among utilities, AMI suppliers, HAN vendors, industry consultants, academics and regulators who seek interoperable, secure and cost effective solutions for extending the Smart Grid to energy aware consumer products.

In 2010, Golden Power introduced a sub-$100 PCT with 2-USNAP ports and an included Wi-Fi communications module. This PCT was branded as a 3M-Filtrete product and sold through Home Depot stores.

1.3.2.2 Advanced Thermostats

In 2003, a team of UC Berkeley researchers, led by Therese Peffer, began research to develop the Demand Response Electrical Appliance Manager (DREAM). Part of the DREAM system is a thermostat that learns and adapts to the environment and the user's preferences. The goal of the DREAM thermostat was to learn about the house's HVAC system, climate, occupant's schedule and temperature preference, and then given electricity price data, optimize the performance of the HVAC system to minimize cost and maximize comfort.

Two advanced thermostats companies, EcoFactor and Nest Labs, benefited from the DREAM research. Founded in 2006, EcoFactor is a home energy management company based in Redwood City, California that has developed a cloud-based platform that provides energy-saving services while maintaining consumer comfort. EcoFactor supported two of the DREAM graduate students during their pilot phase in 2007, and incorporated elements of the learning algorithm into their system. EcoFactor is privately held and funded by Claremont Creek Ventures and RockPort Capital Partners. While EcoFactor works with utilities and telecommunication companies in promoting software as a service, Nest Labs targets consumers by manufacturing a smart thermostat retail product. Nest Labs is a home automation company headquartered in Palo Alto, California, that designs and manufactures sensor-driven, Wi-Fi-enabled, self-learning, programmable thermostats and smoke detectors. Co-founded by former Apple engineers Tony Fadell and Matt Rogers in 2010, the start-up company quickly grew to have more than 130 employees by the end of 2012. The company introduced its first product, the Nest Learning Thermostat, in 2011. In October 2013, Nest Labs announced the Nest Protect smoke and carbon monoxide detector. On January 14, 2014, Google acquired Nest Labs for US$3.2 billion and left Nest Labs to use its own brand. Nest Labs continues to grow quickly with more than 460 employees in mid-2014.[1] Although no researchers from the UC Berkeley team were directly involved in the formation of Nest Labs and its products, the UC Berkeley's idea and concept of an adaptive, learning thermostat clearly influenced the Nest Learning Thermostat and pre-dated the Nest product by 4-5 years. In fact, at the 2014 Indoor Air Quality conference, keynote speaker and noted researcher Dr. Shin-ichi Tanabe credited Therese Peffer's 2009 PhD thesis as instrumental in influencing smart residential controls, including Nest.

1.3.3 Commercial Product and Job Creation

1.3.3.1 DRBizNet

Between 2004-2006, Utility Integration Solutions (UISOL) received approximately $1M from PIER as cofunding to demonstrate the feasibility of automating demand response (DR) business networks end-to-end. As part of this research UISOL worked closely with the California ISO and the three investor owned utilities in California to define the requirements for a software package called "DRBizNet", developed an initial prototype of DRBizNet, and proved the concept of end-to-end automation of DR in California. The project was successfully completed in September of 2006.

While UISOL and its clients have made a 10X investment in DRBizNet software since the PIER project completed, DRBizNet would not have materialized without the initial $1M PIER funding. Some of the benefits to Californians are outlined below:

> In 2009-2010 UISOL implemented the current commercial version of DRBizNet at the California ISO, waiving the entire license fee. The software was put in production in the summer of 2010 by the California ISO and supports the entire Proxy Demand Response Market in California. While the details of this transaction are confidential, the waived license fee fully paid off the PIER investment.
>
> UISOL was a 2-person "Mom and Pop" startup in 2003 when the company received the PIER funding. DRBizNet boosted UISOL into one of the most successful companies in the utility industry (e.g., In 2009 UISOL was listed in the INC500 list of the fastest growing companies in the US, and ranked 15th in the energy category). Today UISOL is 80 people strong, with 50% of its revenue coming from DRBizNet licenses and services. The DRBizNet operation is all centered at the UISOL Solution Center in Silicon Valley. DRBizNet can therefore be credited for creating some 40 new jobs.
>
> DRBizNet has also tremendously improved the state of the art in energy efficiency and demand response. Implementation of DRBizNet at PJM Interconnection received the Project

[1] From Wikipedia

of the Year award in the Energy Efficiency and Demand Response category at DistribuTech 2010. The implementation at the California ISO is a finalist for the same award in 2011. The DRBizNet experts are leading the state of the art in DR. As an example, Dr. Scott Coe of UISOL now serves on the Board NAESB, defining measurement and verification standards for DR. DRBizNet team member Scott Neumann serves as the US Technical Advisor to the IEC helping define international standards for interoperability for AMI and smart grids.

But perhaps the most important value of DRBizNet is that it is an essential infrastructure to scale DR. Today, some 1100+ registered users of DRBizNet in 250+ companies in 27 states are using DRBizNet. Together, they are creating over 9000 MW of demand response—which is the size of several large power plants. Given that DR is significantly cheaper than central generation, is clean, and does not depend on foreign oil, DRBizNet is helping with cost savings, protecting our environment, and increasing the country's energy independence.

1.3.4 Startup Companies and Job Creation

1.3.4.1 Imprint Energy

Christine Ho started as an undergraduate student at UC Berkeley in 2001. In 2003, she began working with the DR MEMS research team, led by Prof. Paul Wright and Prof. Richard White. The DR MEMS research is funded by the Enabling Technologies Development Program, managed by the California Institute for Energy and Environment, with funds provided by the PIER program. In 2005, she continued her education at UC Berkeley as a graduate student under Prof. Jim Evans and her work on the DR MEMS research progressed, supporting the early conceptual ideas of printable batteries on printed circuit boards. Meaningful results appeared in 2007 when she became the lead graduate student researcher developing this new technology. Between 2007 and 2010, she continued the research and refined the technology.

In 2010, Christine participated in the UC Berkeley's Haas Business School's "Cleantech To Market" (C2M) Program. The C2M Program is a partnership between students, scientists, engineers, and professionals to translate cleantech research into market opportunities. There, she met MBA student Brooks Kincaid. For the C2M program, they developed an assessment of the printable battery technology, its market potential, and possible competitors.

Even before graduating with her PhD in December 2010, Christine and Brooks formed and incorporated their company, Imprint Technology, in November 2010 to further develop the technology and commercialize the technology. The formation of the company was aided by Christine's two professors, Paul Wright and Jim Evans, who each used their personal funds to pay for the business license and patent applications. Imprint Energy was also able to negotiate an exclusive license with UC Berkeley.

The new startup won five national and international business plan competitions to secure its early funding. A National Science Foundation SBIR (Small Business Innovation Research) Grant and a University of California Discovery Grant provided additional funding. UC also provided lab and office space for the startup company. Finally, Dow Chemical provided seed funding which allowed the company to move to its current Alameda, CA location in March 2012.

Their first product may be the power source for stickers to monitor food temperatures. In January 2012, the collaboration team began working with printed memory maker Thin Film Electronics of Oslo, Norway and printed transitor maker PARC of Palo Alto, California to develop a plastic temperature-recording sticker that could provide detailed histories of perishable items such as crates of food or bottles of vaccines. These stickers would be the first to be made of all-printed electronics components, including memory, logic, and battery. The cost per sticker could be only 30 cents or less. The company was awarded $6 million in Series A funding in June 2014 in order to accelerate their zincpoly™ chemistry and product design for the wearable electronics and internet-of-things markets. AME Cloud Ventures also provided funding.

Since its founding, the company has grown to 11 employees in 2014.

1.3.4.2 Other Startups

Imprint Energy's technology was the direct result of research conducted on the Program. However, many other researchers on the Program went on to start new companies, although the technologies from these companies were not the direct results of work from the Program. A few of the most notable companies are:

- Adura Technologies (acquired by Acuity Brands), co-founded by Charlie Huizenga.
- Dust Networks (acquired by Linear Technology), founded by Kris Pister.
- Arch Rock (acquired by Cisco), founded by David Culler.
- Sentilla (acquired by Ericsson), founded by Joe Polastre.
- Vigilent Corporation (formerly Federspiel Controls), founded by Cliff Federspiel.

1.4 Report Structure

This final report presents the results of research conducted by grant awardees of the DRETD and ETD Program from 2002-2015. Each of the grant awardees prepared a final report at the conclusion of their project. Those individual project final reports are compiled into this final report of the program.

The next several chapters of this report present summaries of each of the projects. The complete project final reports are assembled as Appendices.

CHAPTER 2: Enabling Technology Development work at University of California, Berkeley

University of California, Berkeley

Full reports found in Appendices A–G.

The Enabling Technology Development Program began with a pilot research project at University of California, Berkeley with an innovative model that included principal investigators, faculty, and students from several disciplines across campus to conduct research on developing disruptive technologies. The research aimed to develop technologies that would enable Demand Response at the residential and small commercial electricity markets, and initially focused on thermostats, wireless sensor nodes, and meters. The team leveraged microcomputers and Microelectromechanical System (MEMS) technology in developing wireless communication and controls that could be installed at one tenth the cost with 10 times the functionality of existing technology. The wireless sensor and control development and integration is discussed in Subsection 2.1.

The latter years of the research focused on details of development: residential gateway, integration (printable energy harvesting and storage, network communication, and sensing), and integration of the platform with a current meter.

2.1 Sensor Development and Integration

For the first phase of the project, the team created early prototypes as enabling technologies for wireless meters, wireless thermostats and wireless temperature nodes. The second phase showed further development of these technologies, with lab- and field-testing. The next phases focused on just the nodes and meters, looking at energy harvesting and microintegration of sensors, wireless networks, and storage (sugar cube size), and then finally wafer-scale integration (head of a pencil eraser size and flexible "band-aid" size). When in final production by commercial entities (in the mid-to-late part of this decade) the OEM costs for the meters and thermostats should be in the "few-dollars" range and the cost for the nodes in the "sub-one-dollar" range.

2.1.1 New Thermostat, New Node, and New Meter

Principal Investigators: P. Wright, J. Rabaey, D. Culler, D. Auslander, E. Arens, D.White
2003-2007

Phase 1 report found in Appendix B; Phase 2 report found in Appendix C.

2.1.1.1 Introduction

Current electric meters are of either the electromechanical type or the solid state type. Neither type supports dynamic tariffs. Newer solid state meters with communications are too costly for wide spread deployment. Adding communications to existing solid state thermostats for receiving price signals and adjusting the setpoint also is too costly for wide spread deployment. Research is needed to develop new technologies that can support dynamic tariffs and make demand response implementation cost effective.

In addition to controlling air conditioning and heating, there would be further demand responsiveness benefits if the system had a broader scope, managing all significant electrical appliances in the house, and influencing the occupants to manage them in an appropriate manner. For example, pool pumps, electric hot water heaters, and even refrigerators do not run continuously and have some flexibility as to when or how often they come on. Start times could be delayed until the electricity price came down. Similarly, occupants may choose to postpone manually starting a load of laundry if they were aware that the electricity price was high at a particular time. The broadened scope implies multiple sensors and actuators, more than exist in normal residences today: relays to control on-times of HVAC and appliances, power sensors, temperature and occupancy sensors, and signaling devices to inform occupants about electricity prices and the consequences of decisions. They would be spread about the house, and many would not be where there is convenient access to mains power or communications cabling. It suggests a distributed system, with a low cost of purchase and installation and is simple and convenient to operate, if it is to achieve widespread market penetration and have a substantial impact on California's demand responsiveness.

Low cost necessitates the use of wireless devices to avoid the substantial cost of running power and communication wires. These devices would need to operate for a long time independently with infrequent battery changes. They should be available from a hardware store, and be installable by a homeowner. Simplicity of operation is essential for DR to work. Many people find today's programmable thermostats too complex to program. To be simple enough for most occupants to use, the new DR systems would have to behave autonomously based on effective initial defaults and machine learning; they need to work right out of the box; no programming required in order for it to operate well. The user interface would have to be concise and intuitive for nontechnical people. It should help them be effective at managing their home and appliances within a variable-price DR context, which will be a new concept for most people.

To achieve long life in building applications the myriad of networked devices must operate without replaceable batteries. Apart from battery cost, it would be impractical to expect building owners/users to frequently change batteries in many tiny distributed sensors and actuators. Thus this research includes the study of a variety of solar, vibration and flow methods for scavenging energy.

In 2003, an interdisciplinary group from UC Berkeley began a contract with the California Energy Commission to work on these issues under the Demand Response Enabling Technology Development (DRETD) program.

2.1.1.2 Project Purpose

The research objective of this project is to leverage existing research funded by the Department of Defense and private industry and to develop enabling technologies such as ad hoc wireless self organizing sensor networks, sensors utilizing Microelectromechanical Systems (MEMS) technology, and adaptive comfort control algorithms for the basis of new reference designs for sensors, meters and thermostats that will make the demand response (DR) infrastructure very cost-effective and compatible with legacy systems. The research has the potential of reducing statewide DR implementation costs by a factor of 10 while at the same time increasing functionality also by a factor of 10.

The goal was to develop early prototypes for the mesh networking of wireless thermostats, wireless meters, and wireless temperature nodes. The four groups consisted of:

- **Communications/Network** group, which undertook the development of an open source wireless network operating system (TinyOS), developing and testing microradio technology to characterize the performance of these radio networks in buildings, and extending the battery life of radio transmitters by reducing their size and power consumption

  Principal Investigators: David Culler, Jan Rabaey, Electrical Engineering Computer Science; Paul Wright, Mechanical Engineering

- **Metering/Sensors** group, who focused on voltage and current sensor development in pursuing low-cost designs for monitoring power in residential circuits using Microelectromechanical Systems (MEMS) technology

  Principal Investigator: Richard White, David Culler, Electrical Engineering Computer Science

- **Energy Scavenging** group, which looked at sourcing power from micro-scale ambient light and vibration to extend the battery life of radio transmitters

  Principal Investigator: Paul Wright, Mechanical Engineering; Jan Rabaey

- **Thermostat/Controls** group, which concentrated on developing controls and designing user interfaces, using the infrastructure above.

  Principal Investigator: Dave Auslander, Mechanical Engineering; Ed Arens, Architecture

2.1.1.3 Project Results

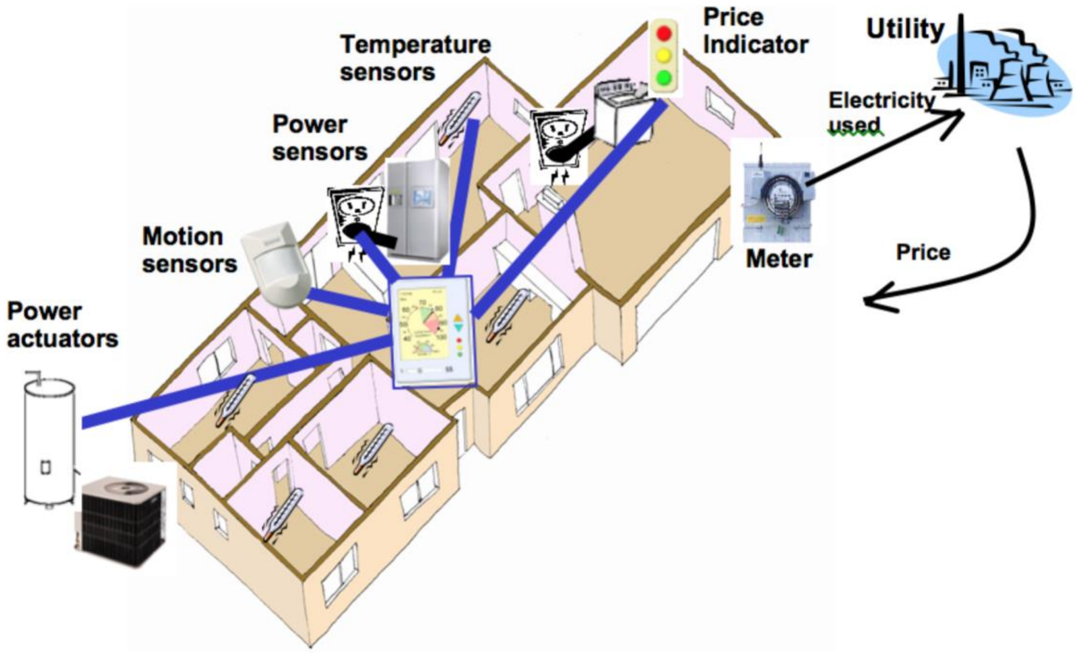
The research team has developed individual macro-level, proof-of-concept devices such as low-power radios, energy scavenging power supplies, and real-time operating systems for ad hoc self-organizing sensor networks. The team has also developed prototypes of residential real-time meters, demand response enabled thermostats, and remote wireless temperature sensors. Other developments include demand response related simulation software, adaptive control strategies, optimizing cost-to-comfort algorithms, and user interfaces. Research results were presented at formal annual public workshops.

The Communications/Network group looked to TinyOS as a mesh networking tool on small microcomputers called motes. PicoRadio and other low powered micro-scale radio communication formed the backbone of the wireless network of these motes. The Metering/Sensors group developed passive proximity voltage and current sensors, and tested an appliance outlet current sensor and actuator. The Energy Scavenging group developed and tested MEMS-scale vibration powered and solar powered motes. The Thermostat/Controls Group looked at the requirements of the new thermostat and problems with existing technology—the interface, control system, and sensors and actuators—to develop a smart, adaptive, integrated demand-responsive residential control system. The design of the new thermostat uses the platform of wireless technology for communication among the interface, controllers, sensors and actuators, and implements new smart control algorithms and a graphic engaging and useful user interface.

Figure 1: A Tmote Sky, by Moteiv, shown in a custom enclosure.

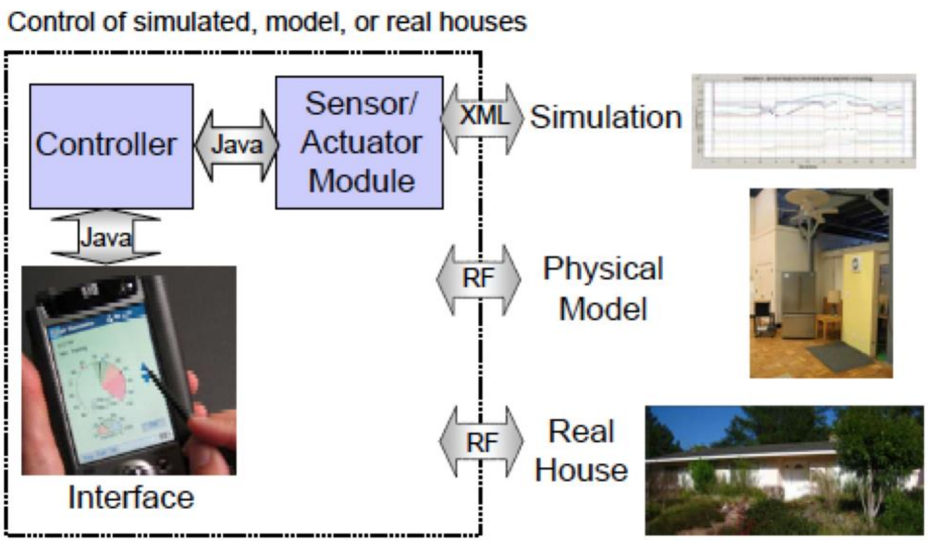
The design of the residential DR system itself — its interfaces, control system, and the nonelectricity-metering sensors and actuators — was carried out by the Thermostat Group. The system was termed DREAM--Demand Response Electrical Appliance Manager. DREAM is predicated on the home system receiving a price from the utility that varies over time based on overall demand and supply, and responding by reducing the heating or cooling load or the load of other appliances, as well as informing the occupants of the price and their current electricity consumption. The occupants determine their usage based on their economic, comfort, and convenience preferences. The electricity price and usage is monitored frequently and the accumulated cost transmitted to the utility at least monthly.

Figure 2: Schematic of Demand Response Electrical Appliance Manager (DREAM) system



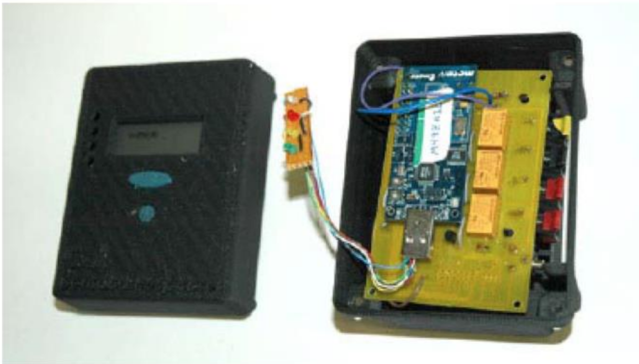
The DREAM platform was developed in a modular fashion to be able to test the system in simulated, bench-scale, or real houses.

Figure 3: Modular DREAM platform design



The team designed and built a prototype system complete with multiple sensors and an HVAC relay. The system was tested in a Plexiglas house, then in lab with a full-scale wall with fan, electrical subpanel and outlet. A user interface was developed on a Personal Digital Assistant as well as desktop computer. The system was initially deployed the system in an occupied house in 2005 for four months. The simple star network of sensors included: seven sets of indoor environmental sensors (globe and air temperature, occupancy, relative humidity), whole house power sensor, weather station measuring solar radiation, wind speed and direction, outdoor temperature and relative humidity. The controller and data was monitored remotely from our lab.

Figure 4: Wireless HVAC relays as a functional "thermostat"



A detailed model of the house (MZEST) was developed to create simulations. The revised system was deployed again in two houses for two months in 2007, this time with a Tablet computer to provide the user interface and multiple algorithms. An optimization algorithm changed the temperature set point to reduce cost and improve comfort. A learning algorithm uses the weather and HVAC cycling patterns to improve precooling times. The user interface provides a friendly and informative face to the system, allowing people full control over the system but also teaching and advising them how to save energy and money.

2.1.1.4 Project Benefits

This project supports California's goal to accelerate its implementation of demand response programs that signal the actual price of electricity to customers during peak demand periods per the Integrated Energy Policy Report 2004 Update; and to make progress achieving demand reduction and electricity savings per the Integrated Energy Policy Report 2003 by:

- Researching and developing new reference designs for sensors, meters and thermostats that will make the demand response infrastructure cost-effective in California.
- Researching and developing to increase functionality and reduce cost of the enabling technology components for the new reference designs.

Several of the ideas and prototypes developed in this project were later commercialized. For example, the learning and optimization algorithms were adopted and further developed by EcoFactor. NEST thermostats developed similar algorithms, especially including occupancy information. A large community of academics, professionals and industrial collaborators was created that transferred the technologies invented to (for example) smarter thermostats and building control methods. Many technical papers were published and inventions were disclosed at the UC Berkeley office of Intellectual Property and Industry Research Alliances

(IPIRA). The students involved with the project graduated and joined both large and small California clean-tech companies. Three start-ups were launched: *Imprint Energy; Wireless Industrial Technologies; Persistent Efficiency*. The project created Test Beds (Living Laboratories) that enabled (and will continue to enable) the research team to demonstrate the viability and performance of new IT methods for the energy sector. Please see Appendix A for the full report and list of students and papers.

2.1.2 Micro-Integrated Packaging of Low-power Radios, MEMS Sensors, MEMS Power Generation and Micro-Power Storage for Intelligent Electricity Systems

Principal Investigators: P. Wright, J. Rabaey, K. Pister, D. White, S. Sanders, J. Evans, 2007-2009

2.1.2.1 Introduction

In previous work under the Demand Response Enabling Technologies Development (DR-ETD) program, wireless prototypes at the "macro-scale" were demonstrated. The macro-scale temp-node (a wireless node self-powered by vibrations) had a size of 5.1cm x 5.1cm x 7.6cm and was demonstrated in February 2003. Collaborating with colleagues in the Dept. of Architecture at UC Berkeley, these "macro-scale" prototypes were "macro-integrated by hand-assembly" and installed in several California houses to demonstrate several milestones. These included: a disaggregated wireless thermostat, current sensors, a self-powered temp-node, and demand responsive control strategies.

In this third phase of the project, the team added material science professor Jim Evans, and two additional EECS professors (Sanders and Pister) and discontinued the application-based portion of the research (e.g., the Thermostat).

2.1.2.2 Project Purpose

The purpose of this phase of the project is to continue to develop smaller, cheaper and more functional enabling technologies for ultra-low cost, low-power wireless, sensor-based, completely self-powered, microintegrated packages.

2.1.2.3 Project Results

Continued effort pursued lower-power, inexpensive, reliable wireless communication. The Pico-radio project focused on the design and fabrication of inexpensive, miniaturized low-power radios, including an FBAR-MEMS resonator for transmission, and sensors for applications. New directions in this phase included dispenser printing storage devices and pursuing devices in the millimeter or micro scale with MicroElectrical Mechanical Systems (MEMS). The flexibility of dispenser printing allows room temperature processing of virtually any battery material. It is a process that speeds research development yet can be scaled for mass production. In this phase, the team created early prototypes of individual "micro" scale devices with modeling, design and prototyping of radios, scavengers, and sensors.[2] The team

2. Meter (m, little over a yard): Millimeter (mm, 10^{-3} meters, a grain of sand = 0.2 to 2 mm): Micrometer (μm, 10^{-3} mm, a human hair ~ 10-100 μm; domain of electronics and MEMS): Nanometer (nm, 10^{-3} μm, molecular bonds are tenths of nm).

prototyped MEMS-scale structures for scavenging (or harvesting) power from natural physical effects such as thermal gradients and a variety of ambient vibrations that naturally occur in all structures. The team also developed MEMS-scale power sensors (both current and voltage) that are proximity-based (nonintrusive to a wire or cable).

Table 2: Research topic areas with student and faculty leads.

Topic Area	Students	Brief Summary of Important Results
Low power wireless	Brian Otis, Ben Cook & Nate Pletcher	MEMS-FBAR[3]-based Pico-radios and other designs. Demonstrated low-power and low-duty cycle. Reactive radios further reduce power
Wireless networking	Joe Polastre & Nate Ota	Demonstrated that TinyOS is suitable tool in houses, for mesh-networking and disaggregated thermostats
Sensors for current and voltage	Jonathan Foster and Eli Leland	Macro-scale, self-powered, proximity-based, sensors for current and voltage measurement. Early modeling for MEMS scale and early design ideas
Energy scavenging	Beth Reilly & Lindsay Miller	Ambient vibrations can power nodes. MEMS-scale piezoelectric prototypes demonstrated
Energy storage	Dan Steingart and Christine Ho	Printable batteries atop circuit boards allow for: package reduction; matching chemistries and capacities for individual sub-systems

Micro-scale low-power wireless transceivers; micro-operating systems; MEMS[4]-sensors; micro-power scavenging; and micro-packaging/micro-manufacturing are key components of this effort. The ongoing research also an added focus on modeling, design and the prototyping of new materials for autonomous, micro-power storage and packaging.

The team continued improving the individual components as well as successfully integrated them into a standalone microintegrated node called the Pico-Cube. Phase 3 research has lead to reduction in the size and energy and power requirements of the components, improvements in the materials fabrication, and validation and perfection of new designs and the designs' fabrication processes.

2.1.2.4 Project Benefits

The benefits of this work support the goal of the Energy Commission to develop, and help bring to market, energy technologies that provide increased environmental benefits and that provide tangible benefits to electric utility customers.

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[3] FBAR: Film Bulk Acoustic Resonator

1. MEMS: Micro-electro-mechanical systems -- made with microfabrication technologies in the UC Berkeley "MicroLab"

2.1.3 Wafer-scale integration

Principal Investigators: P. Wright, J. Rabaey, K. Pister, D. White, S. Sanders, J. Evans, 2010-2012

2.1.3.1 Introduction

The enabling technology creates a basis for many new future prototypes and products for the "Smart Grid" such as low cost self-powered intelligent sensors for a wide variety of measurement, monitoring, diagnostics and control. Silicon wafer-scale integration represents an important step as it allows all of the components of the sensor node to be designed and fabricated in tandem, drastically decreasing component cost and increasing manufacturing throughput.

2.1.3.2 Project Purpose

The purpose of this next phase of the project was to further reduce the size and energy/power requirements of the sensor components and integrate them at the wafer scale, that is, a single Silicon platform.

2.1.3.3 Project Results

The accomplishments of the research team on micro-scale integration of the low power radios, current sensors, energy scavenging devices, and power storage components mark several key advancements in their individual fields, and allowed the researchers to be uniquely qualified to approach this new challenge. The goal in the first year was to refine the designs of the individual components and create a common fabrication process. The validation process included a number of wafer fabrication runs. In the second year, additional fabrication runs were primarily focused on improving device performance and increasing yields.

Specific research includes continued research on the radio in pursuit of ultra-low powered radio. The further development of the current sensor includes progress in the development of passive, proximity based MEMS sensors for AC electric current. These devices are comprised of a piezoelectric cantilever with a permanent magnet mounted to its free end. When placed near a wire carrying AC current, the magnet couples to the wire's alternating magnetic field, sinusoidally forcing the piezoelectric element and thus producing a voltage signal proportional to the current in the wire. Recent results include integration of dispenser-printed neodymium-based micro-magnets with aluminum nitride MEMS cantilevers, initial acquisition of a sensor signal from the MEMS devices, and development of signal amplification circuitry to improve device sensitivity. Another focus in this phase was MEMS-based proximity power sensors based on: 1) capacitive coupling to energized conductors, 2) electromechanical coupling to nearby conductors, and 3) both capacitive and electromechanical coupling. The research team has demonstrated the feasibility of a using the voltage sensor as a scavenger from zip-cord type power conductors, and have fabricated a MEMS proximity power sensor. The team developed power-conditioning and amplification circuitry that is necessary to amplify the small amount of charge stemming from these sensors, enabling them to be coupled to a wireless radio chip for ubiquitous mesh-networking applications. Previous advances in the MEMS piezoelectric energy-harvesting branch of the project include: a ~5 mV signal was recorded by plucking one of the first generation of energy harvesting devices. Second generation harvesting devices were then successfully fabricated with resonance frequencies in the tens of Hz in order to more closely match the frequencies present in the built environment (first generation devices resonated between 1000 and 7000 Hz). Additionally, the residual stress in the second-generation devices was balanced, allowing beams to lay in-plane rather than curling up. Finally, second generation harvesting devices were successfully actuated with an AC voltage. In this phase, integration of the energy harvesting, power conditioning, and printed energy storage components began. The team also worked on a simple post-processing technique for tuning the resonance frequency of the energy harvester by printing additional mass on the end of the beam during the same step that the energy storage component is printed on the chip.

2.1.3.4 Project Benefits

The benefits of this work support the goal of the Energy Commission to develop, and help bring to market, energy technologies that provide increased environmental benefits and that provide tangible benefits to electric utility customers. Wafer-scale integration continues the progress towards lowering cost.

2.2 Final Integration: Flexible printed sensor and GREEN node

Principal Investigator: P. Wright
2013-2015

In the final phase of the project, the team continued to focus on two fronts: the flexible printed thermoelectric generator and storage, and the GREEN node. These two form factors (flat thin "Band-Aid" shape and small cube shape) lend themselves to different applications.

2.2.1 Integrated, Printed, Self-Rechargeable Wireless Sensor Node for Condition Monitoring of High-Value Rotating Equipment

2.2.1.1 Introduction

A natural progression from dispenser printing research was to explore other means of printing as a low cost fabrication technique, such as rolling printing press types.

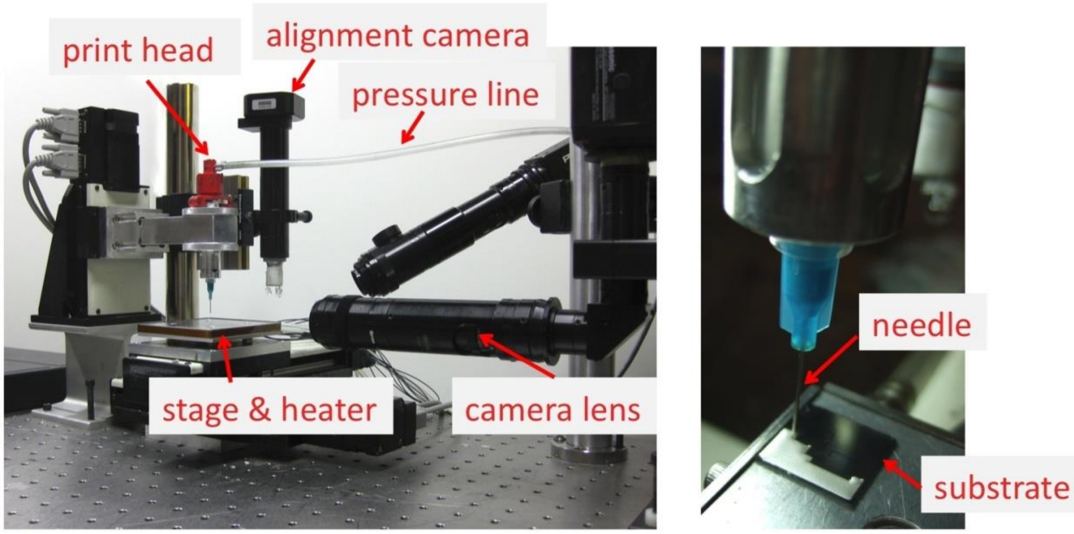
2.2.1.2 Project Purpose

The purpose of this final phase of the project was integration of technologies using printing techniques, especially low-cost printing on flexible substrates.

2.2.1.3 Project Results

To augment energy harvesting, the team invented new equipment for 3D printing of smart materials and new processes for energy storage. The computer controlled 3D printer is shown in Figure 5. Printed devices included batteries, capacitors, and thermoelectric generators.

Figure 5: 3D printing of batteries, capacitors, and thermoelectric generators



The experimental system in Figure 6 was also used to print thermoelectric generator (TEG) materials for energy harvesting. Harvesting from waste heat has many large- and small-scale applications, and our work focused on self-powered microelectronic systems for energy management. A TEG uses the well-known Seebeck effect when there is a temperature gradient across an array of side-by-side columns of n-type and p-type semiconductor materials. Figure 7 shows that the maximum power occurs with high-aspect-ratio thermo-element column (or leg) lengths of about 6.5mm. Our printing methods were able to provide these very high aspect ratios in dense arrays. For a modest temperature rise of 30^{o}C our completed TEG devices generated about 20 μW, which trickle charged the batteries described earlier (As an informal aside; an enlarged photograph of the printed TEG prototype was featured on the cover of the 2012, Volume 22 (9), edition of the *Journal of Micromechanics and Microengineering*).

Figure 6: 3D CNC dispenser printing (left) allows the prototyping of thermoelectric generators (center), batteries and capacitors (upper right).

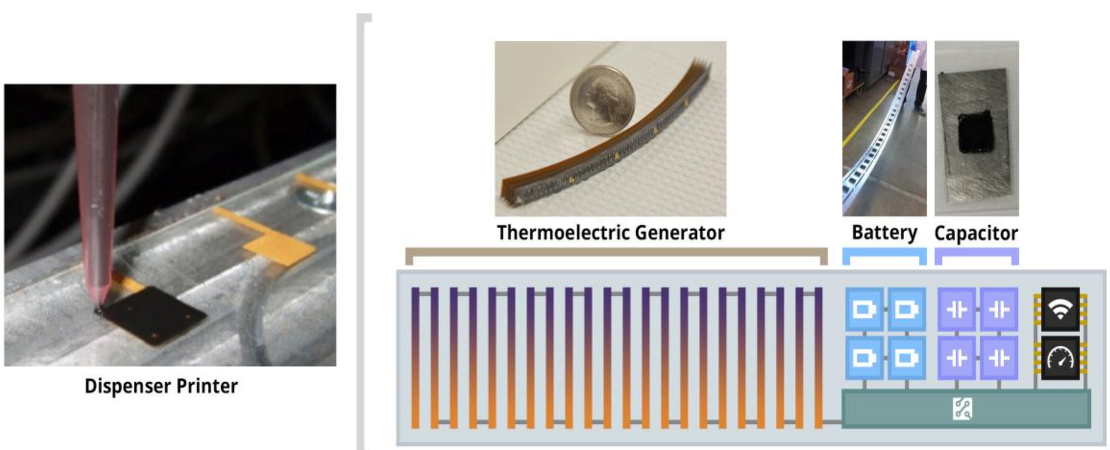
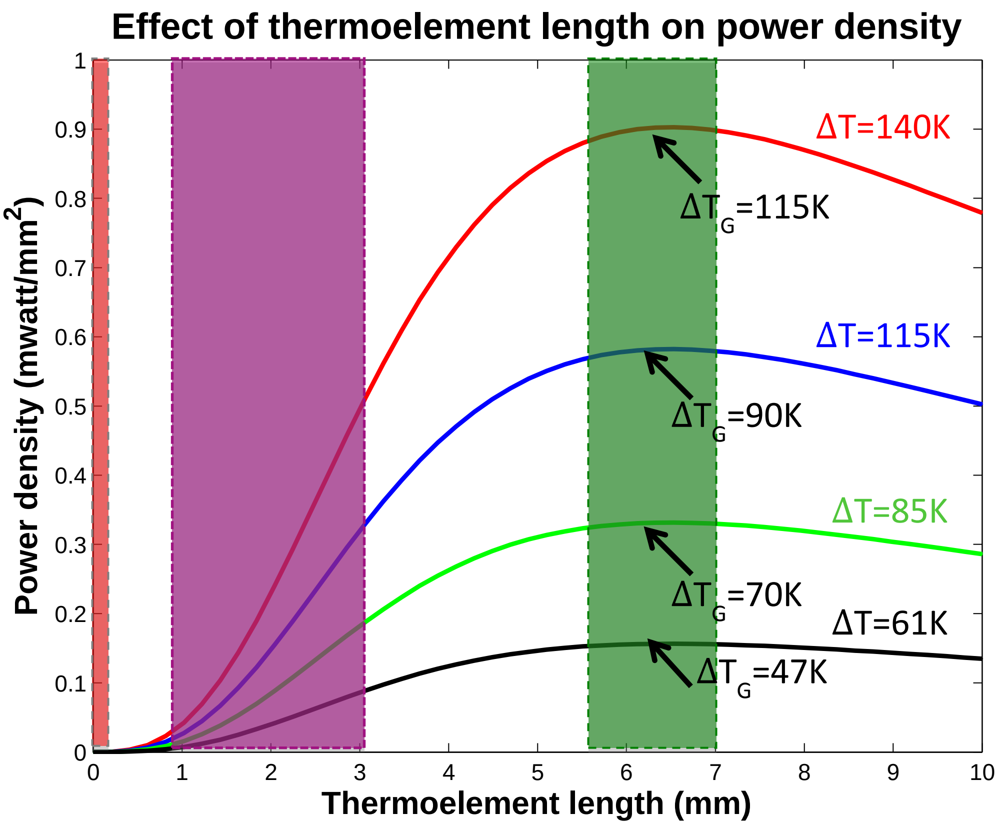


Figure 7: Influence of thermo-element column (leg) length on power output. Our 3D dispenser printing method creates devices with leg-length 5.5 to 7 mm and hence the best power density.



2.2.1.4 Project Benefits

The benefits of this work support the goal of the Energy Commission to develop, and help bring to market, energy technologies that provide increased environmental benefits and that provide tangible benefits to electric utility customers. Low-cost manufacturing techniques such as printing continues the progress towards lowering cost.

For more information, please see:

1. M. Cowell, R. Winslow, Q. Zhang, J. Ju, J. Evans, and P. Wright, "Composite carbon-based ionic liquid supercapacitor for high-current micro devices," *Journal of Physics Conference Series*, Volume 557, pp. 1-5, 2014, http://conferenceseries.iop.org/conferenceseries/issue/1742-6596/557/1

2. Winslow, R., Wu, C. H., Wang, Z., Kim, B., Evans, J., & Wright, P. K., "Development and manufacture of printable next-generation gel polymer ionic liquid electrolyte for Zn/MnO2 batteries," *J. Phys.: Conf. Ser*. 476, (*PowerMEMS 2013 (Dec 3-6), London, UK*), page 012085 – 012089.

2.2.2 Integrated Self-Powered Wireless Node for Nonintrusive Proximity-based Current Sensing

2.2.2.1 Introduction

Energy efficiency and Demand Response (DR) are the most effective when information about the energy usage in individual appliances becomes open and accessible to the Application Stack. Retrofitting existing systems and households requires that the sensing devices be as nonintrusive as possible for ease of integration and deployment.

2.2.2.2 Project Purpose

The purpose of this project is to continue progress towards small packages of integrated sensor components.

2.2.2.3 Project Results

A contactless submetering solution demonstrated that multipoint magnetic field measurements could accurately reconstruct electric currents. Called the Granular Radio EnErgy-sensing Node (GREEN), this platform contained an Atmel 2564RFR2 microcontroller with an internal ZigBee-compatible radio transceiver, a battery unit, and an integrated a GMR magnetic sensor to nonintrusively monitor loads on circuits such as the residential circuit breaker panel . To enable nonintrusive and low-cost installation, the GREEN node fits in a target design volume of less than 1 cm^3, including the power supply. The GREEN device was therefore smaller, installed at a lower cost than previously proposed solutions, and placed in a configuration that enabled self-calibration. Its small size allowed for more accurate placement, which in turn allowed for increased granularity of the reconstructed currents.

Figure 8: Granular Radio EnErgy Sensing Node (GREEN) – block diagram

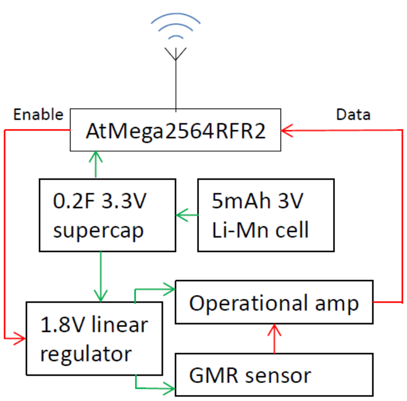
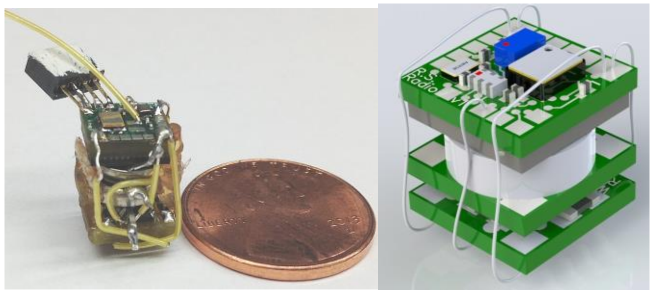


Figure 9: Granular Radio EnErgy Sensing Node (GREEN) - prototype



GREEN is currently the smallest ZigBee-compatible node in existence and this technology will enable the realization of ubiquitous sensing of a variety of data types, from current and voltage and environmental monitoring. The continuation of this work will include establishing a mapping between current and the ADC, resolving the linearity problems at low currents, as well as fully characterizing the achievable life span and integrating it with a larger network. The GREEN device is not limited to sensing magnetic fields and currents, although this is an excellent demonstration. Any sensor that interfaces via analog, serial, I2C, SPI or digital I/O can be connected to the controller / radio. The only requirement is that the sensors must be very low power so a battery (or harvester plus rechargeable storage) is able to provide a reasonable runtime. Even with this restriction the device has many potential applications, ranging from instrumenting a machine room to monitoring environmental conditions. The main advantage of the GREEN is that it presents a small mesh networkable radio platform, capable of interfacing with a wide variety of devices.

2.2.2.4 Project Benefits

This further development of sensor integration continued the progression toward smaller, more accurate, and lower cost prototypes.

For more information, please see:

Send, R., Q. Xu, W. Ku, I. Paprotny, R.M. White, P.K. Wright. Granular Radio EnErgy-sensing Node (GREEN): A 0.63cm3 wireless stick-on node for nonintrusive energy monitoring, Annual IEEE Conference on Sensors (IEEE SENSORS 2013), Baltimore, MD.

2.2.3 Residential Gateway

Principal Investigator: D. Auslander
2009-2014

Phase 1–4 Reports found in Appendices D–G.

2.2.3.1 Introduction

In order to enable demand response for the residential sector, technology was required to interface between the utility and the home, either through the interval meter or devices themselves, such as thermostats, pool pumps, or air conditioner compressors. These connected devices in the home became known as the Home Area Network.

2.2.3.2 Project Purpose

The Reference Design for Residential Energy Gateways (REG) project began in 2009 with the objective of developing an open-source software reference design for a system that could bridge the gap between emerging standards and protocols in the Home Area Network. Besides being an open platform, it was greatly desired that the system be highly modular and easily extensible.

2.2.3.3 Project Results

With these requirements in mind, the design team chose to develop the REG in the OSGi software framework for JAVA. OSGi, which previously stood for Open Services Gateway Initiative, has a modular architecture. Modules, or "bundles" in OSGi terminology, consist of JARs with additional metadata, where the metadata is used to define interactions between bundles. The OSGi framework is service oriented, whereby bundles provide and consume services within the OSGi framework. Within this environment, the REG team developed a data model, hardware abstraction layer, service application layer, and various applications which, taken all together, define the REG reference design. In the four years of the project, the REG design team has incorporated diverse functionality into the software suite, including:

- Web services
- MySQL database
- Embedded optimization solver
- Agent-based behavior (via Java Agent Development Framework – JADE)
- Calendar scheduling mechanism – to automate behaviors
- External gateway framework – to run the REG on an embedded compact platform
- Access to residential smart meters through the integration of ZigBee Smart Energy Profile (SEP) into the REG data model
- Supervisory control algorithms
- Analysis of power quality (i.e. investigate the effectiveness of a platform such as the REG in improving the operation of the local distribution system)

The REG software platform has been utilized for other research projects regarding commercial building energy management. This work has served to augment the REG with additional functionality (such as an embedded database and embedded optimization solver). Thus there is much overlap between versions of the Gateway for residential and commercial energy use.

2.2.3.4 Project Benefits

The REG reference design project has directly led to or contributed to seven conference publications three conference presentations, an industrial collaboration, and at least 10 seminars. In addition, the students working on this project were the 2011 DOW Sustainability Innovation Student Challenge Winners. While the two graduate students working on this project could never hope to create a software suite as sophisticated as a commercial entity, the

REG project demonstrated that a unified control framework within the home is possible and allowed the authors to investigate issues related to the abstraction of devices into a common information model (such as parent-child relationships).

When work on the REG project began in 2009, a literature search was conducted to see if any similar technologies existed or were being developed. None was found. However, recent searches for home energy management software suites now return information indicating many commercial entities are embracing many of the ideas put forth in this project. One notable example is Prosyst, who are developing an OSGi-based home energy management suite (http://www.prosyst.com/startseite/). It is encouraging to see many of the ideas explored as a part of this research project being embraced by industry.

For more information, please see:

Arnold, D., M Sankur, DM Auslander. 2013. An architecture for enabling distributed plug load control for commercial building demand response. Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES, 1-6.

Arnold, D., MD Sankur, DM Auslander. 2013. Optimal Control of Office Plug-loads for Commercial Building Demand Response. ASME 2013 Dynamic Systems and Control Conference, V001T13A001-V001T13A001

Arnold, D. , M Sankur, DM Auslander. 2013. The next generation energy information gateway for use in residential and commercial environments. Power and Energy Society General Meeting (PES), 2013 IEEE, 1-5

M Sankur, D Arnold, D Auslander. 2013. An architecture for integrated commercial building demand response, Power and Energy Society General Meeting (PES), 2013 IEEE, 1-5

MD Sankur, D Arnold, DM Auslander. 2014. Model Predictive Control of Commercial Office Plug-Loads and Battery Storage Systems. ASME 2014 Dynamic Systems and Control Conference, V001T07A001-V001T07A001.

2.2.4 A Demand Response Application of the Sensor Network Services Platform

University of California, Berkeley
Principal Investigator: J. Rabaey
January, 2007

Full report found in Appendix H.

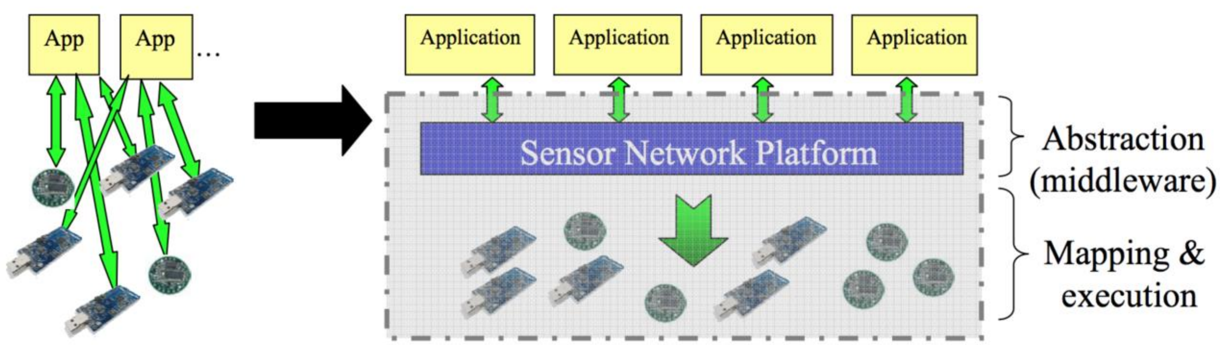
2.2.4.1 Introduction

Ad hoc wireless sensor and actuator networks may one day be a component of the California demand response infrastructure located on residential, commercial, or industrial premises. There is currently no standardized method to develop application software. Without standardized methods, application software will need costly rewrites for different hardware architectures.

2.2.4.2 Project Purpose

The research objective of this project is to develop and demonstrate an application software development environment for ad-hoc wireless sensor and actuator networks that will result in application software solutions that are easily portable over a variety of implementation platforms. The goal is to develop and demonstrate an application development environment for a scalable and extendible Demand Response system (DR-SNSP) using a universal application programming interface for ad hoc wireless sensor and actuator networks, called the Sensor Network Services Platform (SNSP). The Demand Response system will be portable over a variety of wireless sensor network hardware platforms and provide extendible functionality. In this way, cost and power efficient solutions can be introduced today without jeopardizing the potential introduction of new technologies and functionalities.

Figure 10: Write once, run everywhere applications enabled by a sensor network platform



One of the main objectives of the Sensor Network Services Platform (SNSP) is to provide a unifying framework that makes application programming and deployment easier. Applications should be agnostic of the underlying distributed hardware platform. Moreover, this framework should enable the creation of modular and reusable code that can be executed on a variety of different physical networks. The SNSP should shield the application from node failures and seamlessly integrate new nodes and software functionality as they are added to the sensor network.

2.2.4.3 Project Results

- Designed a services-oriented software architecture for programming wireless sensor network applications, called the Sensor Network Services Platform (SNSP).
- Implemented the SNSP software with application services that are portable across different wireless sensor network hardware platforms and reusable by multiple applications.
- Demonstrated seamless operation across multiple sensor node hardware platforms using a prototype Demand Response application (DR-SNSP).

2.2.4.4 Project Benefits

This project supports California's goal to accelerate its implementation of demand response programs that signal the actual price of electricity to customers during peak demand periods per the Integrated Energy Policy Report 2004 Update; and to make progress achieving demand reduction and electricity savings per the Integrated Energy Policy Report 2003 by:

- Developing a software interface that will reduce software development and maintenance costs of ad hoc wireless sensors and actuators networks deployed for demand response.

By standardizing the software and services that execute on a sensor network, the SNSP will enable large-scale sensor network deployment. Programmers will be able to create standard applications that are customized automatically at run-time to use the physical and software resources available in their particular network. These applications can then be reused on multiple platforms. Further, the SNSP future-proofs the sensor network by enabling applications to dynamically discover resources. When a new component (software or hardware) is added, it should be automatically incorporated into the system. This automatic integration eliminates tedious and costly manual configuration.

CHAPTER 3: Network Security Architecture for Demand Response/Sensor Networks

CyberKnowledge and University of California
October, 2005

Full report found in Appendix I.

3.1 Introduction

Ongoing efforts aimed at developing technologies that will enable demand response benefits include advanced metering, sensors, and control technologies research and development. These will eventually be coupled with a communication and network infrastructure that supports the multicast of real-time pricing information, as well as the aggregation of energy usage and billing information.

One important issue with any future demand response infrastructure network is security. With the possibility that the network may be collecting a large amount of fine resolution data from energy consumers, another issue that must also be considered is privacy. However, sometimes, security issues and privacy concerns may be in conflict with each other. Security architecture design as well as the system architecture design of the demand response infrastructure must take into consideration privacy issues; otherwise, the infrastructure may require a costly redesign and/or redeployment if privacy concerns become a liability for the operation of the infrastructure.

3.2 Project Purpose

This project's research objective is to develop the basis for an overall network security architecture for demand response systems. The architecture will address all levels of a demand response network from the utility network, to the wide area network, and to the local area network located at the end-user location. This project will focus primarily at the local area network level and in particular focus on sensor networks; an area in which little security research has been conducted. Additionally, the research will take into account privacy issues in developing the architecture.

The goal of this project was to explore the privacy and security concerns that arise in the context of advanced metering and demand response infrastructures and propose general options for addressing them.

3.3 Project Results

The research team has studied likely implementations of advanced metering and demand response, investigated the privacy and security issues that will become important as the technology is deployed, and suggested both legal and technological solutions. Technological solutions have focused in particular on security and privacy in sensor networks and agile radio nodes, and the likely role of these technologies in a future demand response infrastructure.

The major accomplishment of this project was to develop an overall picture of the likely short, medium and long-term deployment scenarios for demand response, delineate the central design elements of each, identify the privacy and security issues of each, and recommend possible technical and legal solutions. By identifying opportunities to build privacy and security solutions into the demand response architecture, in addition to legal and regulatory solutions, this approach will aid developers and policy makers alike. Direction for future work is also suggested.

3.4 Project Benefits

The research supports California's goal to allocate and prioritize RD&D funding for energy efficiency and demand response, including new communication and control technologies, planning models, end-use technologies, and validation methodologies per the Energy Action Plan 2005; and to evaluate and, if appropriate, incorporate demand response technologies such as programmable communicating thermostats into the 2008 building standards per the Energy Action Plan 2005 by:

- Developing a cohesive network security architecture that will lead to demand response networks that are designed with consideration for security and privacy.
- Identifying and categorizing security concerns and threats that can arise in the context of sensor networks that consist of devices having limited power and computing power.
- Identifying and developing strategies, algorithms, and a roadmap to address the security concerns.

One of the goals of this project was to foster an increased awareness and deeper understanding of the security and privacy issues that exist in advanced metering and demand response systems among the technical designers who build the elements and infrastructures, and among the regulators and legislators who oversee or drive that process. This report will be useful to the energy industry, for helping identify areas where security and privacy issues may be important for both commercial or consumer protection. The recommendations may provide a starting point and framework for the development of solutions to network security, in particular in demand response networks that may employ emerging sensor and wireless technology. Attention to these problems benefits California utilities, as their networks are strengthened against attack, and their customers retain confidence in the companies' handling of their personal information. Attention to these problems benefits California's consumers, both in protection of their California Constitutional rights to privacy, and in the safety of their personal information from exploitation or theft. This report may also provide information useful to regulators and lawmakers that may need to enact new rules to enforce sound privacy and security choices.

CHAPTER 4: Network Agility and Management for Demand Response/Sensor Networks

CyberKnowledge and University of California
September, 2007

Full report found in Appendix J.

4.1 Introduction

In order for demand response to be successful, it is necessary to have an appropriate service, network management and communication infrastructure that enables communication with meters and other sensor nodes in the field in a scalable and reliable fashion.

Large investments are often made in legacy communications/networking infrastructure and back-end systems that support them; therefore, it is very attractive for the utilities to seek an architecture that allows them to maximize their return on investment. An ideal network vision should accommodate existing (legacy) infrastructure, while harvesting the benefits of evolving communications technologies for maximum cost-effectiveness. Often assets are stranded because the technologies are no longer up-to-date or compatible with the current architecture.

4.2 Project Purpose

The long-term research goal is to provide a basis for future-proofing the Demand Response network, minimize stranded assets, and preserve investment in software platforms, while enabling deployment of newer low cost hardware platforms in an incremental fashion. More specifically, this research is aimed at exploring emerging technologies in the domain of agile radios, with a view to leveraging these advances, as well as ongoing potentially disruptive changes in spectrum regulatory policy, in the context of the Demand Response network architecture.

The objectives were to:

- Identify the desired functionality related to network agility and sensor/device management that benefits Demand Response Networks,
- Develop a platform for implementing agile radio functionality, leveraging configurable building blocks, and that could be used as the basis for experimenting with agile networks,
- Define a mechanism for amalgamating agile nodes into the overall DR network architecture, and specifically, to articulate the functionality of interface to the Demand-response Services network on the one hand, and to the Sensors and sensor networks that may be deployed at home or in the business premises.

4.3 Project Results

The approach adopted in the project was to begin by developing representative scenarios that arise in different contexts related to Demand Response systems, and that can arguably benefit from agile functionality. These amalgamated scenarios identified a useful set of features in a system that supports network agility. The architecture of an agile radio node was developed. An experimentally designed and developed testbed served as a basis for prototyping potential implementations. This testbed is comprised of reconfigurable building blocks, along with associated methodologies that support rapid prototyping. Finally, mechanisms were delineated for interfacing agile radio nodes to sensor networks and network service delivery mechanisms.

Agile radio nodes constitute a key building block for agile networks. This research developed a platform for implementing Agile Radio functionality, leveraging configurable building blocks. The key components of an Agile radio node include: an antenna subsystem, an agile RF Front end, and a Base band processing engine.

4.4 Project Benefits

This project supports California's goal to implement ambitious demand response programs, through tariffs and control technology, and install advanced meters for all customers as soon as practically possible per the Integrated Energy Policy Report 2005 by:

- Researching the possible use of the agile radio concept to avoid asset stranding of radios used in DR networks as radio technologies evolve.

4.4.1 Operating Expenditure Savings

It is a well-established fact in the telecommunications community that a visit to a customer site by a maintenance/service professional for the purpose of installation or maintenance—sometimes referred to as a "truck roll"—entails a cost of $100-200+ per visit (depending on various associated costs and overhead). It has also been observed that for consumer related services such as DSL, Cable modems, etc.—and utility DR/programmable controlling thermostat/advanced metering infrastructure (AMI) deployments fall into this category for residences—operational costs that involve more than one site visit on average adversely impact the business case for such deployments, often to the point of making them infeasible in practice. The implication of this observation is that unless technology similar to that proposed in this project is leveraged in the context of DR/AMI, the business cases for deployments in the arenas of demand response and energy efficiency may be severely impacted, and impede a cost effective implementation of energy policy imperatives in the state.

4.4.2 Capital Expenditure Savings

The ability to remote provision services and upgrade capabilities after deployment avoids the expense inherent in procuring and provisioning new premises infrastructure equipment such as gateways and control thermostats. This ability can result in significant savings, which can again be passed through to the consumer.

4.4.3 Benefits for Demand-Response Networks

Thus, the use of agile, software-defined radio nodes can provide a superior ability to manage, upgrade, and provision new services. The advantages of establishing an open, modular, common service deployment platform include: broad acceptance of the technology, and potential standardization, resulting in lower development and acquisition costs. In addition, this technology can help reduce stranded assets by supporting legacy radio/sensor interfaces, while "future-proofing" deployments and reducing operational costs by enabling software download of new radio functionality, and enhanced services.

4.4.4 Potential Consumer Benefits

The potential impact of project to the electricity consumer is indirect, and projected to be along multiple dimensions. Based on initial estimations and empirical observations, the energy efficiency mechanisms deployed in this context can yield a potential savings ranging from 5 per cent to 30-49 per cent depending on energy consumption and conservation patterns and weather patterns. In addition, it is anticipate that the consumer will significantly benefit from the enabled energy information services and related services and that these will in turn engender improved energy efficiency and demand responsiveness. The consumer will have the freedom to purchase new home electronic gadgets and have the comfort of knowing that they can work with key parts of the installed infrastructure.

4.4.5 Benefit to the California electric market

It has been established that the California electric consumption patterns are such that there can be as much as a 50% spike in peak demand during the (relatively few) very hot days during summer. This spike in demand translates into a nominal load in the 30 Gigawatt range to peak loads in the range of 45 Gigawatts. Enablement of demand response capability will significantly assist in the reduction in capital and operating expenditure that is incurred by addressing the energy problem on the supply side to provide for peak capacity. It is also projected to dramatically improve the reliability of the grid.

In view of these figures, observations, and empirical evidence, the research team believes that the combined deployment of DR technology, energy efficiency, and energy information services that this project is intended to enable economically and environmentally both the end consumer at home and the enterprise, as well as to California.

4.4.6 General Benefits

The adaptability and future proofing of resulting systems will provide benefits for all of the stakeholders in the energy ecosystem: state policy making and regulatory agencies such as the California Energy Commission and Public Utilities Commission can legislate and implement policies designed to mitigate peak power requirements on the energy grid (thereby reducing capital expenditure for new power plants and ongoing operational expenditure associated with operating these plants); utilities and Independent System Operators will benefit by having technology that enables them to comply with regulatory requirements, support dynamic real time pricing and emergency curtailment signals, improve grid reliability, and bolster their existing business cases for advanced metering infrastructure; equipment vendors will benefit from a set of reusable platform components that can enable cost-effective products for their customers; and end consumers will benefit from reduced energy consumption (and therefore reduced energy bills) while maintaining desired comfort levels.

CHAPTER 5: California Demand Response Business Network (DRBizNet)

Utility Integration Solutions, Inc.
Sept 2006 - April, 2007

Full reports found in Appendices K and L.

5.1 Introduction

Demand response (DR) is a powerful strategy that can help mitigate heat storms, control peak load, and keep adequate grid safety margins. It differs from energy efficiency by being "time dependent," meaning it is called on when needed. An effective DR program would allow California's grid operator to reduce electricity load from participating customers instead of cutting power to entire neighborhoods. Customers are willing to respond to emergency episodes by voluntarily reducing load if offered financial incentives. Current processes to manage DR programs – from upfront customer enrollment, to real-time communications, to final financial settlements – have been cumbersome. Additionally, the grid operator's signal for DR currently must go through multiple channels, often not automated. All these processes have hindered the potential effectiveness of DR programs.

California is investing in Information Technology (IT) infrastructure for DR programs, but without a unifying architecture. To protect investments and enable more DR requires a suitable DR-IT architecture.

5.2 Project Purpose

The research objective of this project is to conceptualize, design, and demonstrate a suitable real-time DR business network for California to facilitate and maximize DR resources within the state. The project intends to utilize modern business process management and Internet technologies, and open system standards to achieve the research objective. This project is composed of two phases: a conceptual and design phase followed by a demonstration phase.

5.3 Project Results

The DR Business Network (DRBizNet), envisioned and architected as part of this R&D project, is a highly flexible, intelligent, distributed communications-coordination-control network that leverages modern distributed business process integration technologies and open interoperability standards to simplify and automate the California Demand Response value network (i.e., supply chain).

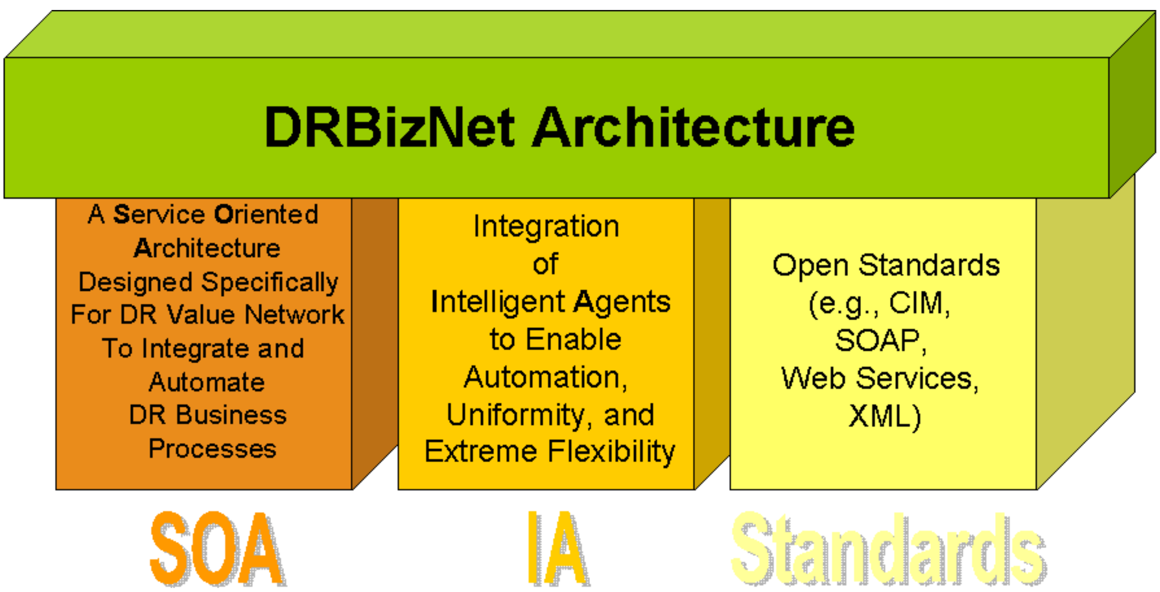
The initial conceptual and design phase was completed in May 2005. An architecture for the California DRBizNet was developed and documented. The concepts of the architecture were presented and demonstrated in a public workshop in April 2005. A field demonstration was conducted in August 2006. The architecture and demonstration were well-received by the

California Independent system operator (ISO) and the three California investor-owned utilities. Product commercialization discussion continued with Sempra and the California ISO.

5.3.1 Concept and Development Phase

The first report presents a high-level blueprint for constructing DRBizNet based on a Service Oriented Architecture, orchestrating standards-based Web services across a business network built on the Internet. The utility industry Common Information Model (CIM) is leveraged where applicable. DRBizNet includes distributed Registries, DR Collaboration Exchanges, Intelligent Agents (IA), and standardized Web services interface with DR participants. The Web services include the services that will be provided by utilities, customers, aggregators, and other service providers, using standardized, secure, protocols. Utilities can readily introduce new DR programs through DRBizNet. Participants can readily register and participate in various programs. Many of the participants' actions are automated through Intelligent Agents that can take actions on behalf of the participants based on the specifics of the DR programs obtained from the DR Collaboration Exchanges and the parameters specific to each participant. Implementation of each DR Program is highly automated through configuring Workflow Engines at DR Collaboration Exchanges, minimizing the need for inflexible and expensive- to-change, hard-coding of DR programs.

Figure 11: Foundation of DRBizNet Architecture



The DRBizNet can be implemented by the California DR stakeholders in a decentralized manner to the extent that their efforts are harmonized through a self-funding user group providing central support for 1) Architecture , 2) Buy-In from stakeholders, 3) Coordination of activities, and 4) Direction for evolution of DRBizNet.

As part of this project, the Project Team prototyped a software system that demonstrates the key innovations introduced in this DRBizNet R&D project. Additional field demonstrations are recommended as the next phase of the project to prove the novel concepts presented in this report and to gain DR marketplace participants' buy-in.

5.3.2 Proof of Concept Phase

The objective of this project phase is to refine the architecture and designs presented in the previous phase of DRBizNet, develop Proof of Concept (POC) system based on these designs, and conduct a Field Simulation with the marketplace participants to demonstrate this functionality to the stakeholders.

This report presents the results of the Proof of Concept (POC) phase of DRBizNet. In particular, the content and results of the successful August 11, 2006, Field Simulation involving market participants are discussed, as well as the development activities conducted during the POC phase that led up to the Field Simulation. The Field Simulation demonstrated the concepts presented in an earlier DRBizNet final report *California Demand Response Business Network*, and aimed at gaining DR marketplace participants' buy-in required for moving to the next phase of the project, DRBizNet Pilot.

5.4 Project Benefits

This project supports California's goal to vigorously pursue actions to ensure that the state's demand response goals are met per the Integrated Energy Policy Report 2005; and to allocate and prioritize RD&D funding for energy efficiency and demand response, including new communication and control technologies, planning models, end-use technologies, and validation methodologies per the Energy Action Plan 2005 by:

- Conceptualizing and designing a real-time demand response business network for California that will reduce integration cost of systems utilized for demand response.
- Demonstrating the demand response business network in a field simulation involving participation from the California ISO, the three major utilities, and select voluntary customers.

Wide-scale acceptance of the proposed DRBizNet architectural principals and standards will facilitate an efficient electronic collaboration, workflow, and transparent exchange of information among the participants in the California DR value network, enabling significant levels of DR at drastically reduced integration and operations costs.

This project produced a commercially available product that is still available in 2015 at http://uisol.com/new/demand-response/

CHAPTER 6: Barrier Immune Radio Communications for Demand Response

Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory
February, 2009

Full report found in Appendix M.

6.1 Introduction

Automated control of equipment has been shown to be much more reliable and effective in reducing energy use when needed than manual control. In existing commercial buildings, wireless communication to equipment is often more cost-effective than physical wired connections. In addition, the building materials vary tremendously, sometimes preventing communication signals from being transmitted and received successfully. There are currently no purely wireless technology platforms proven for demand response with commercial buildings. The lack of such a platform could jeopardize the financial viability of large-scale deployment of demand response in existing buildings.

6.2 Project Purpose

This project will investigate wireless technologies that can transmit and received through walls and floors, and be "bolted on" to new and multiple types of existing buildings regardless of energy management/control systems, Ethernet, available space in electrical conduits et cetera. These new systems must be backwards compatible with legacy systems. The report, under collaborative effort by Lawrence Berkeley National Laboratory (LBNL) and Lawrence Livermore National Laboratory (LLNL), concerns research in innovative and adaptive wireless technologies that are immune to communication barriers and scalable for cost-effective implementation of Demand Response (DR). The Barrier Immune Radio Communications (BIRC) project identifies essential technical elements in 900 MHz and 2,400 MHz narrowband, and Ultra-Wideband (UWB) frequencies.

6.3 Project Results

The characterization of wireless technologies was conducted through a series of product assessments, simulations, and field-tested deployment in a six-story laboratory building. The communications data that was generated during field testing was analyzed to identify wireless technologies that can scale for future DR applications through very low node density power consumption, and unit cost. Data analysis included analysis of the signal-to-noise ratio (SNR), packet loss, and link quality at varying power levels and node densities. Further analyses to benchmark and understand SNR characteristics in response to barriers and existing interferences were carried out using the rich data-set collected during the field tests. At the conclusion of the study LBNL and LLNL developed a set of recommendations for wireless DR strategies, and presented the research findings.

Technologies in the 900 MHz, 2.4 GHz, and UWB frequency ranges each met or exceeded performance expectations. Field testing was conducted in a 6-floor building with significant challenges to radio communications. Signal propagation was measured at varying power densities, and measurements were duplicated to test data validity. Narrowband technologies showed 100% penetration; with a maximum of one repeater node. 900 MHz technologies were able to provide coverage up to the fourth of sixth floors, at power levels as low as 100 mW. In general, the 900 MHz technologies showed better coverage than the 2.4 GHz technologies, and both of the narrowband solutions outperformed the UWB. A particularly impressive finding was that the 2.4 GHz technology was able to penetrate several steel decks. UWB radios are constrained to far less power than the narrowband transmitters, likely limiting its performance. Nonetheless, the UWB hardware performed much as expected, and offers 2 potential advantages in environments where the signal suffers multiple reflections and fading losses, where existing wireless networks and interference are an issue for narrowband systems, or where standard wireless technologies are not permitted.

Few BIRC technologies can be used in existing as well as new buildings, and in buildings both with and without energy managements control systems (EMCS). The ideal DR technology can be used in any facility, independent of the specific building characteristics. Since existing buildings vary extensively in terms of EMCS and Ethernet infrastructures, construction features, and layout, promising BIRC technologies must be further developed to ensure that they are applicable to any building type.

Barrier immunity need not be continuous. In this study packets were received or transmitted at a rate of 30 per second, with each packet consisting of 80 bits (or 10 bytes or characters) of data. Although this is not very fast for modern computer networks, it is more than sufficient for DR applications, which has a latency requirement on the order of minutes, rather than milliseconds. Furthermore, DR systems usually transmit small amounts of data, often just a few bytes.This suggests that for DR, a high degree of packet loss could be tolerated, provided that *ultimately* the message is received. Additional research could reveal whether coverage could be increased at lower power levels by leveraging this relaxed latency requirement. Alternately, multiple RF data bursts could be averaged in custom hardware to study the trade-offs between range of coverage and data rate.

6.4 Project Benefits

This project supports California's goal to implement ambitious demand response programs, through tariffs and control technology, and install advanced meters for all customers as soon as practically possible per the Integrated Energy Policy Report 2005 by:

- Discovering what types of demand response communications signaling technologies are compatible with various existing building types and construction materials.

The use of BIRC technologies has enormous potential for automating and scaling Demand Response. Study results indicate that with significant improvement in cost and key performance parameter, RF technologies are feasible for wide-scale commercial and industrial buildings, with or without Energy Management Control Systems. Further, the IEEE standard underlying the technologies in the study is compatible with concurrent developments in load management, such as residential Programmable Communicating Thermostats and Home Automation Networks, and the Automated Metering Infrastructure and Automated DR initiatives by California Energy Commission, utilities, and Independent Systems Operators.

The BIRC technologies that were identified show promise in meeting life-cycle cost requirements, encouraging higher participation in DR programs. BIRC reliability and scalability is unique compared to other wireless technologies in widespread use. For example, BIRC technologies are able to cover larger areas with fewer nodes than a barrier-prone wireless sensor network.

CHAPTER 7:
Demand Response Analysis and Control System

EnerNex Corporation
July, 2009

Full report found in Appendix N.

7.1 Introduction

Often "new" technologies can arise in one discipline from simply borrowing from another. In comparing a utility operation with military mission, military organizational requirements call for tight coordination of multiple command structures controlling individual resources and assets integrated in a coordinated action to achieve an objective in support of a mission. Similarly with a utility organization is the multiplicity of individual resources and assets controlled by individual departments. Unlike military organizations, a utility's mission is singular (lowest cost electricity at highest reliability) and non-changing although objectives are evolving and changing with the advent of new Smart Grid technologies. Classical military Command, Control, Communication, and Information (C^3I) systems have evolved that integrate real time data sources with behavior analysis and decision making toolsets. What constitutes C^3I in the military may apply to Command Control Information systems in the utility realm.

7.2 Project Purpose

The goal of the project was to address two research topics and questions identified in the research opportunity notice of the original proposal solicitation:

- Using a military (or another, such as air traffic control) C3I system as a model, adapt it to conceptually deal with C2I electricity applications such as dispatching DER (distributed energy resource) to keep the lights on. Compare and contrast the chosen C3I model with the requirements for implementing a C2I strategy for integrating utility control, communications and information systems. Are there analogies that indicate utilities can operate in a similar fashion? If not, what are the gaps that need to be filled and is it feasible to fill the gaps?

- Given current utility systems and assuming the systems are integrated, how would the California ISO or a Utility Distribution Company UDC operate its control centers in a military (or another) C3I style? With up-to-date real-time information and the ability to control all of its available assets, given a particular operational scenario, how would a plan to address the scenario be executed using strategies based on military (or another) C3I?

7.3 Project Results

What constitutes C3I in the military directly maps to C2I in the utility world dropping "Command" functionality, which is not applicable. This project has developed a C^2I system architecture that provides utilities the ability to identify, organize, analyze, forecast and execute demand response resources.

The first task involved the development of traceable and defensible requirements for command and control systems capable of operating systems with high penetrations of demand responsive load. This task utilized the use case based methodology for requirements capture developed by the EPRI IntelliGrid Consortium, the same methodology used at Southern California Edison (SCE) for the AMI requirements development. The EnerNex team conducted a workshop with utility and industry demand response stakeholders. Where possible, existing use cases, message traffic models, and related information developed for SCE's AMI project were utilized.

The second task utilized the same methods for requirements capture applied in the first task but for the purpose of determining what information, models, and algorithms are necessary to simulate the behavior of the Demand Response Aggregated Control System (DRACS). The platform is intended to be used to evaluate the overall stability of the power system when large amounts of demand responsive load change state in short time periods under the control of communication networks with large and highly variable latencies.

The third task involved the creation of an architecture and reference design for a generic DRACS based on the requirements captured in the first task. The reference design provides discussions of the Demand Response Management System (DRMS) parent system, DRACS design considerations, architectural strategies, the reference architecture and design, and architectural policies and tactics.

The last task developed the framework for a simulation and stability analysis platform suitable for testing a DRACS and evaluating its performance based on the requirements captured in the second task.

Classical military C^3I systems have evolved that integrate real-time data sources with behavior analysis and decision making toolsets. This capability is just now appearing in the utility industry. With real time up-to-date information available from all customers and across distribution grid and distributed resources, utilities can now use C^2I methodologies to develop operational strategies that are built upon high performance computational platforms.

Further research is needed around DRACS and the DRMS. Demand Response is still quite immature. This is evident in the various different ways that the California utility companies are approaching Demand Response deployments. Like many other Smart Grid technologies, California is out in the lead with Demand Response technologies. There is obviously risk associated with being the early adopter and trailblazer, but also opportunities to lead the industry, set a precedent, and help find solutions that not only work well in California, but also in the rest of the United States and beyond. This risk can be mitigated by using layered software technology and loose coupling, ensuring firmware is remote-upgradeable, and by objectively reviewing the DR landscape, standards development requirements and timelines, regulatory and policy inertia, and consumer products plans around Demand Resources and DERs. In fact, a comprehensive risk analysis may suggest that California closely track NIST Interoperability Standards adoption. Nevertheless, there are unique regulatory demands and critical peak power conditions experienced by California grid participants that require aggressive action. There is a critical need to perform additional technology, policy, risk, security, process, and peer analyses before DR strategies and systems are committed. California should invest in these types of studies and work to ensure that the large IOU utilities' DR systems can interoperate with each other and the California ISO for the overall benefit of the utilities and grid partners, and consumers.

7.4 Project Benefits

A Control Communication and Information (C2I) system architecture can provide utilities the ability to identify, organize, analyze, forecast and execute demand response resources. With real time up-to-date information available from all customers and across distribution grid and distributed resources, utilities can now use C2I methodologies to develop operational strategies that are built upon high performance computational platforms.

CHAPTER 8: Decision Support for Demand Response Triggers

Electric Power Research Institute
November, 2010

Full report found in Appendix O.

8.1 Introduction

The California Energy Crisis of Years 2000-2001 was a stark reminder of the perils of disconnected wholesale and retail markets. The crisis contributed to financial shock to net buyers of electricity, who incurred unprecedented wholesale charges revealed over a month after the fact— too late to take action. The California crisis highlighted the need for clarity on wholesale charges in time for the demand-side to act, and for a tool to inform energy retailers of wholesale settlement costs that demand response can help avoid.

This project developed a methodology and a prototype decision support tool to help electricity market participants understand and quantify the value of triggering demand response (DR) to avoid wholesale settlement costs. Project results bring California a step closer to realizing the benefits of DR, including the ability to manage customer load not only to reduce peak demand but as a dispatchable resource as though it were the output from a power plant.

With further refinements, the Demand Response Triggers Decision Support Tool could be used in operational timeframes (day-of and day-ahead) to establish a financial link between retail incentives for DR and actual wholesale market conditions. By clarifying the value of triggering DR to market participants, the decision support tool offers the potential to provide multiple benefits, such as:

- Clarify the financial impact of triggering demand response and resulting benefits to energy retailers that schedule load in wholesale markets.
- Enable market participants to quantify the impact of triggering DR on their wholesale settlements with an Independent System Operator (ISO).
- Allow energy retailers to mitigate wholesale market settlement charges.
- Inform energy retailers of estimated wholesale settlement costs that DR can help avoid.
- Offer the potential to enhance power system operational flexibility using demand response commensurate with financial impact.

The project addresses a persistent problem: the financial disconnect between wholesale electricity markets and retail electricity tariffs and rates. Although wholesale electricity costs vary with wholesale market and grid conditions, retail customers are generally disconnected from wholesale conditions and lack incentive to respond in a timely manner. Moreover, the wholesale market participants who schedule load lack timely (day-of and day-ahead) information to help them understand the financial consequences and impact of triggering DR on wholesale settlements.

The project begins to bridge the gap between wholesale and retail electricity markets by clarifying the financial value of triggering DR to help market participants make informed decisions about triggering DR in day-of and day-ahead operational timeframes.

8.2 Project Purpose

The project's objectives were to specify, develop, and demonstrate a methodology for energy retailers to trigger demand response in a fashion that financially links retail with wholesale electricity markets. The initial objective is to develop a methodology to form a basis for a decision support tool that can be used to inform energy retailers of the impact of triggering demand response on wholesale settlement costs, and charges that DR can help avoid. A subsequent project goal is to design the tool to be used in operational timeframes using latest information available on wholesale market conditions. The ultimate objective is to demonstrate the decision support tool and how it can capture value for market participants that schedule load.

8.3 Project Results

To bring a multifaceted perspective to bear on the project goals, EPRI assembled a cross-functional group of wholesale market participants, energy retailers, and information technologists including personnel from the four largest load-serving entities in California and the California Independent System Operator (California ISO). Engaging this array of industry experts with targeted expertise and information access proved critical to the project's success in bridging gaps between wholesale and retail market operations.

The project's first phase was to develop and prove feasibility of the concept. Major project stages included (1) DR Trigger Methodology Development, (2) Information Technology Specification, and (3) Proof-of-Concept Demonstration.

In Stage 1, DR Trigger Methodology Development, the project team identified and classified charge codes allocable to loads and relevant to DR. Charge codes were ranked based the combination of 1) relevance of DR and 2) significance of the charge code on actual settlements charged to market participants that schedule load.

In Stage 2, Information Technology Specification, the team specified and prioritized software requirements based on input from project participants and potential users of the DR Trigger Decision Support tool. Requirements were gathered on desired functionality and user interface contents. Sample input data was collected revealing useful data formats. Project participants also prioritized the resulting specified requirements.

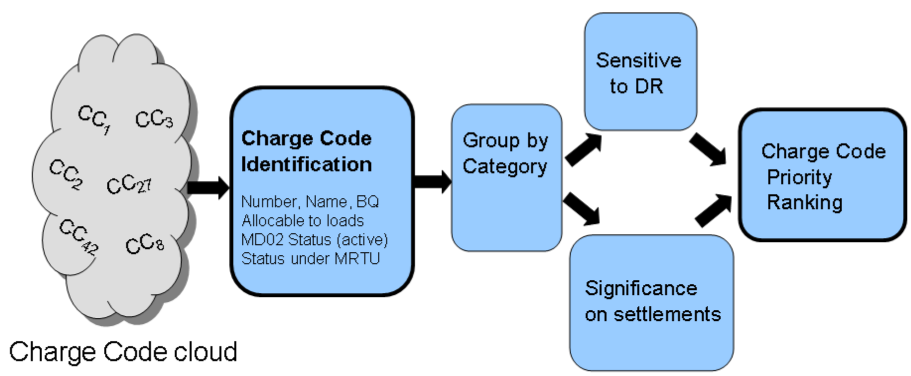
In Stage 3, Proof of Concept Demonstration, the project team conducted a live demonstration of the prototype decision support tool's value-added capabilities. The demonstration was given at a final project workshop held with project participants and funders at a face-to-face meeting hosted by the Energy Commission in Sacramento. The workshop presentation and demonstration were also shared through a live webcast that was open to public participation.

At the conclusion of the final workshop, EPRI led a meeting with the project participants to discuss next steps. The next steps form the basis for a detailed implementation plan being proposed for the project's second phase.

The project team developed an operational approach and tool to support value capture for energy retailers that schedule load and can trigger demand response in day-to-day operations. The tool's target users are short-term procurement personnel from day-of and day-ahead trading desks. By focusing on value-add for market participants on the demand-side of electricity markets, the approach has the potential of revealing value at any time during the year based on latest market conditions. In short, the approach helps market participants to determine the financial impact of applying a megawatt of demand response by resource and location at a given time.

In contrast to traditional DR programs that require an external source to fund incentive payments, this project's approach identifies market-based financial incentives for DR by clarifying wholesale settlement charges that DR can help reduce. Strategies with such a market connection are applicable on a persistent basis for revealing incentives for demand response. Such incentives are revealed in the project by carefully examining the settlement impact of metered load deviations from scheduled load.

Figure 12: DR trigger methodology



The project's approach focuses on the highest priority charge codes: those that are both most sensitive to DR and have the most impact on settlements. These codes—identified in the project's first stage through analysis of aggregated historic settlement data from market participants who schedule load—are the basis for the DR trigger methodology and the decision support tool.

8.4 Project Benefits

The decision support tool enables short-term procurement personnel to compare DR program resource costs with the impact of triggering each MW of demand response on wholesale settlements for the analyzed charge categories. In other words, the market participant representing load is empowered for the first time with information on charges that can be reduced on wholesale settlements from "self-supply" of procurement short-falls (below daily demand forecasts) using DR resources. The combination of equipping them with trigger impact information plus the ability to compare against DR program resource costs enhances day-ahead and day-of decision-making for triggering demand response. The Day-ahead and Day-of screens illustrate types of information that can be provided to support decision-making based on which resources, in what locations, how much is available, and when to trigger them.

The project team held a live demonstration of the proof-of-concept decision support tool in December 2009. The tool was explained in the context of the day in the life of short-term procurement personnel, beginning at the day-ahead desk, followed by the day-of desk. The demonstration highlighted information provided by the prototyped tool that supports decision-making beyond the status quo of information available to these users. In particular, the tool provides trigger impact information alongside program cost information, so that the market participant can readily discern time intervals when dispatching DR was estimated to "be in the money" (i.e., when the trigger impact is estimated to be greater than the cost of dispatching DR).

CHAPTER 9:
Privacy in the Smart Grid: An Information Flow Analysis

UC Berkeley School of Information, University of California, Berkeley
March, 2011

Full report found in Appendix P.

9.1 Introduction

The Smart Grid, by incorporating information technology into the electric grid, offers the promise of advancing several important energy policy goals: increasing efficiency, reducing peak demand, improving grid reliability and resiliency, and incorporating distributed and variable energy sources.

This same information technology, however, also creates privacy risks to residential electricity customers. Electricity meters are becoming information gateways that provide fine-grained details about home energy use. Whereas most customers are familiar with monthly meter readings, smart meters will provide hundreds of data points per month. These records alone can reveal a significant level of detail about what occurs within customers' homes—when they are awake or asleep, or when they are at home or away. The prospect of utilities or third parties controlling devices in customers' homes introduces a different kind of privacy issue: a remote entity (utility or third party) altering the behavior of appliances and other devices work inside customers' homes. This would represent a significant opening of the physical boundaries of the home.

Smart Grid data will not be confined to utilities. The California Public Utilities Commission (CPUC) is requiring utilities to honor customers' requests to make energy usage data available to third parties. Today, these third parties are not covered by the same regulatory or legislative privacy rules as utilities. The CPUC has also approved investments in devices, to be embedded in smart meters, which will allow utilities and third parties to communicate with appliances in customers' homes. Moreover, customers can purchase their own metering and control devices, opening the possibility that customers will rely on entities other than utilities to provide them with information about their energy use and to control their devices.

Unique privacy and security issues arise from the use of this two-way communication channel by utilities (or third parties) to control smart devices in customers' homes. Individuals will have incentives—financial or otherwise—to permit such remote control. This breaches a physical barrier that has protected individual decisions about how and when to use devices in the privacy of the home.

Decisions about Smart Grid architecture will have profound implications for privacy. These design choices will affect whether information leaves the home, where it goes, and who can access it. These same decisions will also influence grid cybersecurity. Finally, these architectural choices may profoundly influence how and where innovation and competition occur by expanding or limiting the freedom end-users have to choose the devices and services they use to connect their homes with the Smart Grid.

These issues transcend the geographic boundaries that dominate utility regulation and require immediate and ongoing attention at the national level. To be sure, utilities regulators have important roles to play in stating clear requirements for Smart Grid privacy, as well as protecting individuals by creating rules to govern data collection and use and to ensure that individuals have meaningful choices about whether and how to participate in Smart Grid initiatives. Supporting these policy goals through Smart Grid architecture would likely be done most efficiently at the national level. Unfortunately, the main source of federal guidance on Smart Grid data privacy takes it as a given that Smart Grid systems will generate, store, and use large amounts of sensitive information; and the guidance is largely limited to internal policy and data processing suggestions for utilities and other private firms.

9.2 Project Purpose

The purpose of the project is to assess the privacy risks in Smart Grid technologies that are in use, or may soon be in use, in the state and review both Smart Grid technologies, particularly those that are relevant to residential customers, and privacy laws and regulations, and interacting with relevant experts to identify threats that the Smart Grid presents to individual privacy. In addition, this project will determine gaps and inconsistencies in legal protections for Smart Grid data privacy.

9.3 Project Results

The project documented the Smart Grid information flows and considered the laws and agencies that protect, or could protect, privacy in this new technological landscape. Legal sources of privacy protection are highly varied, ranging from state public utilities commissions to the Federal Trade Commission. The extent and level of privacy protection depends critically upon the route information takes from source to destination. Though state utilities regulators have traditionally played a strong role in protecting customer privacy, like other regulators, their jurisdiction is limited. Changes in the architecture of the energy grid that create new data flows and empower new players to handle data threaten to render some privacy provisions obsolete and others ineffective. Given the proliferation of data, industry players, and usage models, new laws and privacy-protecting technical designs are necessary to afford privacy, comparable to that enjoyed today, to users of tomorrow’s energy network. Considering privacy upfront, rather than after technologies are deployed, will help build privacy protections into the Smart Grid while supporting other energy policy goals.

This project has met the objectives of comprehensively reviewing both Smart Grid technologies—particularly those that are relevant to residential customers—and privacy laws and regulations, and interacting with relevant experts to identify threats that the Smart Grid presents to individual privacy. Smart Grid technologies in or near deployment support a wide variety of electricity usage data flows, and the legal protections for the privacy interests in that data vary considerably depending on who obtains the data, and how. The report’s detailed analyses of eight salient information flows points to technical design choices that could mitigate privacy risks. This analysis also highlights gaps and inconsistencies in legal protections for Smart Grid data privacy.

Though the Smart Grid is in its early stages, its potential to lead to privacy intrusions by commercial entities, law enforcement agencies, parties to civil litigation, and criminals was well documented. Current federal and California laws address only a subset of Smart Grid privacy risks. The numerous Smart Grid components that affect privacy, the division of regulatory authorities and responsibilities between the state and federal levels, and the fact that Smart Grid policies are co-evolving with the grid itself all present challenges to setting privacy rules. Legal protection for Smart Grid data privacy changes as it travels among homes, utilities, and third parties.

Because the Smart Grid is early in its development, however, privacy risks can be efficiently addressed through a combination of sound technology choices and law. If regulators, utilities, and other Smart Grid players take privacy into account when choosing technologies, they will avoid costly retrofits and replacements of equipment and services. In addition, addressing privacy risks now will bolster public trust in this important publicly funded investment in the nation's energy future. Widely used privacy law frameworks, such as Fair Information Practices and privacy impact assessments, provide ready tools to identify privacy issues in this new technological environment.

Maintaining protections that are reasonably consistent with those that shielded customer privacy in the pre-Smart Grid electricity environment requires immediate action. The research team recommended the following steps:

- Privacy considerations must drive architectural and information flow design decisions within the network, as well as the policies that cover Smart Grid data held by the growing array of entities that will help reap the benefit of this investment. Because privacy must be embedded in technical design, it cannot be addressed adequately by policies created once technologies are designed and deployed.
- Because privacy risks are fairly consistent across jurisdictions, and the markets for Smart Grid technologies are national, federal policymakers should take the lead in setting legal and technical requirements to protect privacy. NIST, FERC, and the Department of Energy should recognize that the rules, standards, and guidance they develop will determine a great deal about how the Smart Grid develops. They should take advantage of this position to protect privacy.
- State utilities regulators (such as the California Public Utilities Commission) should use their institutional expertise in protecting consumer interests and their broad authority to protect privacy through administrative rules and technical requirements. Both regulatory mechanisms have roles to play in protecting privacy.
- Resolving privacy issues implicates grid cybersecurity, and innovation and competition in the devices and services that operate within the Smart Grid. Regulators at all levels

therefore should not consider them in isolation but rather use rulemakings and rate case proceedings to take the interdependencies among these issues fully into account.

- The utilities and technology firms that are building the Smart Grid should protect privacy through their design and implementation of hardware, software, and services.
- Widely accepted information privacy frameworks, such as the Fair Information Practices, combined with privacy-aware design, serve as a useful starting point and should provide the foundation for all Smart Grid players to engage on privacy issues.
- Regulators conducting federal and state Smart Grid policy proceedings as well as standard-setting bodies should continue to solicit input from privacy experts to ensure that the technical and policy blueprints for the Smart Grid attend to privacy issues.

9.4 Project Benefits

Supports the California's goal to research, develop and demonstrate technologies that will accelerate the transformation of the distribution grid into an intelligent and sustainable network per the Integrated Energy Policy Report 2007 by:

- Investigating the consequences to privacy as the result the Smart Grid due to the use of new technologies, data flows, and data handling.
- Providing an understanding of such consequences upfront, rather than after the technologies are deployed may prevent delays to the deployment due to legal obstacles caused by privacy concerns.

CHAPTER 10: People & energy at home: information display & thermal comfort development for residences

University of California, Berkeley
April, 2012

Full report found in Appendix Q.

10.1 Introduction

Residential buildings in California consume one third of the state's electricity and are responsible for about one fifth of the state's carbon emissions. However, residents typically have no feedback on their electrical consumption except for the monthly utility bill. Current sensors on appliances throughout the house can supply real-time energy usage information. This information, however, requires careful processing and management in order to be useful to people.

Heating and cooling homes consume a substantial portion of both fuel and electrical energy—9% of the total energy consumption in the U.S.; residential air conditioning alone accounts for 14% of the typical peak electrical load in California. Yet there is surprisingly little current research on residential thermal comfort. The Programmable Communicating Thermostat (PCT) and more recently the Upgradable Setback Thermostat (UST) was promoted for residential Demand Response programs, yet it is unclear what type of information—much less motivation—will encourage people to make better choices about their electricity consumption. Distributed temperature sensors and online weather forecasting information can provide better control over the heating, cooling, and ventilation systems in a house.

10.2 Project Purpose

This research covered two subjects: one study examined what types of information and motivation would encourage people to reduce their energy consumption using an information display and the other researched different thermostat control strategies to achieve an acceptable thermally comfortable home while also reducing energy used by heating and cooling systems. The impetus was to provide an application of distributed wireless sensors and microprocessors to provide a low-cost infrastructure towards improving residential thermal comfort and reducing electricity consumption through more detailed feedback, especially during peak times.

10.3 Project Results

The research regarding in-home energy displays involved exploring psychographic segmentation, reviewing existing displays, evaluating three displays in detail, and suggesting three types of display for three segments of the population. The various psychographic segmentations had commonalities—people motivated by money, the environment, and peers were the three targeted populations chosen. For each segment was described the type of information (e.g., cost, carbon emissions related to energy consumption) as well as the type of display (e.g., numeric versus graphic.) In addition, common attributes that all displays might share were discussed, such as more granular level of data (e.g., appliance level) and high latency.

The thermal comfort research included reviewing several existing surveys regarding how people use thermostats, developing and administering a separate survey, and developing and testing algorithms. Both surveys pointed out commonly used means of control that are outside the purview of typical thermostatic control, such as using the off switch, override, and hold modes. The open-ended questions of the survey created provided other insights into what people want and don't want in thermostatic control, as well as lent support to increasing thermal variability in the home. Respondents reported thermal comfort related to physical measures (e.g., house construction), certain behaviors, and especially social issues (age, gender, schedules). The functions reported not used fell in four general categories: those not used because not needed, because it was not applicable, because it didn't work well, and because the user did not know how to use it. The algorithm developed provided set points that adapt to outdoor air temperature and relative humidity; initial simulation testing showed that this has promise of providing the seasonal and daily variability that survey responders recognized—and save energy and money in the process. The algorithm could be improved in many ways, not the least would be to test in the field. Other issues of improving thermostats included more usable interfaces and other features such as timers and occupancy sensors.

10.4 Project Benefits

Understanding what motivates residential customers to reduce energy savings can help target utility programs and develop standards for feedback displays, including providing customer choice of types of data and graphic format, minimum latency (frequency) of data, and more granular data. Residential thermal comfort knowledge can guide Title 24 requirements for thermostat design, usability, and algorithms for improved comfort and energy savings.

CHAPTER 11: Self-Correcting Controls for VAV System: Filter/Fan/Coil and VAV Box Sections

Pacific Northwest National Laboratory
May, 2011

Full report found in Appendix R.

11.1 Introduction

Problems with the heating, cooling and ventilation (HVAC) systems in commercial buildings can cause occupant discomfort, reduce occupant productivity, produce safety hazards and require costly repairs. Thus much research has focused on predicting faults and reducing them by active detection, diagnosis, and prompt maintenance. The literature has generally focused on detection and diagnosis for a number of common faults (e.g., sensor biases and control logic errors). Little attention has been given to developing a comprehensive list of potential faults and the causes of those faults. In addition, fault detection and repair currently requires human observation and intervention, which takes time, can increase costs and introduce errors.

11.2 Project Purpose

The Pacific Northwest National Laboratory (PNNL) performed research for the California Energy Commission in self-correcting controls for commercial building Variable Air Volume (VAV) systems. The work included identification and analysis of fault modes and their symptoms, developing algorithms for the four steps of the process leading to automated correction of faults not requiring human intervention to physically repair or replace a system component, coding a selected subset of the algorithms in prototype laboratory-grade software, and laboratory testing. These steps in the process include training to capture relationships among key variables, fault detection, fault diagnosis (which is also known as fault isolation), and fault correction. The remainder of this executive summary briefly describes the work performed and key results and is organized in parallel to the chapter structure of the report.

11.3 Project Results

11.3.1 Identify Faults

A comprehensive list of faults that affect VAV systems was developed and mapped to their potential causes to facilitate the development of algorithms. The list of faults was developed in a brainstorming session that brought together several experts with experience in diagnosing faults in HVAC systems and developing automated HVAC control and fault detection and diagnostic (FDD) systems. The faults were categorized as hard (physical) or soft (software) component faults. The components for which faults were identified include temperature, pressure, and airflow rate sensors, valves, dampers, fans, filters, coils, economizers, VAV boxes, and supply-fan controls. Through a process called fault mode analysis, these faults were mapped to observable symptoms, which are indicators of deviations from expected system behavior. Some of these symptoms are easily observable (for example, if the measured supply air temperature is colder than the mixed-air temperature when the coiling-cool valve in an air handler has been commanded closed.) Other faults require the development of more complex models to empirically define normal operating conditions.

Twenty eight faults were identified that can be diagnosed in the airhandler (filter/fan/coil) and VAV-box sections of the air side of VAV systems in this set of algorithms. Of these faults, 18 are automatically correctable soft faults, and 10 are hard faults that require physical repair or replacement.

11.3.2 Development of Self-correction Methods and Algorithms

Based on physical principles, equipment design, and the insights gained from the fault-mode analysis, a set of rule-based algorithms was developed to facilitate automatic correction of the identified faults. The structure for these algorithms is the same structure used previously by PNNL in development of self-correcting controls for the mixing-box section of air handlers. This structure is a four-step process to fault correction. The first step, training, establishes the normal range for a set of variables and quantitative empirical relationships among some for later use in fault detection and diagnosis. The next step, passive fault detection (or passive diagnostics) uses observation of fault symptoms during ordinary operation to detect when a fault has occurred. After a fault is detected, proactive diagnostics (tests) are used to isolate which of potentially several possible faults was responsible for the observed symptom. This typically requires more information than is available from normal operation of the system, so specific diagnostic tests are run to create situations that provide additional data and information. After the fault has been isolated, the fault correction process characterizes the fault (e.g., the magnitude of a constant bias in a sensor output rather than erratic, constantly changing, sensor output), formulates a mathematical description of the fault, and then subtracts the fault to compensate the behavior of the faulty device. The correction is implemented via a virtual point (e.g., sensor output, control signal, etc.). The algorithms are documented in detail in a companion report identified in the reference list of the full report as Fernandez et al. 2011.

11.3.3 Implementation of Algorithms in Software Code and Integration with the Control System

The algorithms were successfully coded in prototype software using the Jython programming language (a hybrid of Java and Python). A subset of the full suite of algorithms was coded. Priority was given to the development of all four steps of the fault-correction process for two key soft faults: biased supply-air flow-rate sensors and biased supply-air temperature sensors. The software was integrated with a Johnson Metasys Building Automation System, using Factory Plant Management Interface (FPMI) software. The software uses two sets of virtual points for sensors. The first enables simulation of sensor faults through virtual sensor points that the control system reads in lieu of the direct sensor measurements. These virtual sensor points enable instigation of faults without damaging equipment and the outputs of these virtual sensors exhibit the characteristics of the fault of interest. The other virtual sensor points enable application of corrections developed by the self-correcting algorithms to the faulty sensor signals to create corrected sensor signals that replace erroneous values to the control algorithms.

11.3.4 Laboratory Testing of the Self-Correcting Software

Six laboratory tests were performed. Three tests of supply-air flow-rate sensor bias and three tests of biased supply-air temperature sensors were performed. The three tests for each fault were used to investigate differences in the outcome of the test as functions of fault severity and the values of key selectable thresholds for fault detection. The tests were each initiated with a 5-minute period of fault-free operation, during which no faults were detected. In all tests, the passive diagnostic tests successfully detected a fault soon after its instigation. In four tests, the fault was correctly diagnosed, and automatically corrected approximately to the level of the instigated bias. Faults with low severity and higher detection thresholds presented problems, which led to an inconclusive result for one test of the biased supply-air temperature sensor and an incorrect fault determination for one test for the biased supply-air flow-rate sensor. Modest changes in the algorithms are proposed to account for these issues. All methods for fault detection and diagnosis impose a tradeoff between sensitivity and false positive fault detection. Generally, as sensitivity is increased, the probability of false positives increases. Therefore, achieving the right balance between these behaviors is critical to successful deployment of the technology. Further laboratory testing will be used to "tune" the associated variables (e.g., detection thresholds and sensor tolerances).

11.4 Project Benefits

The targeted market for self-correcting controls in the short-term is built-up air systems, with a longer-term target of packaged HVAC systems. The benefits for self-correcting controls are estimated with PNNL's Building Energy Analysis Modeling System (BEAMS) using data for California. The market penetration over time is developed based on market diffusion curves, which are based on the Bass diffusion model. The analysis estimates 1.2 to 2.4 TBtu in annual energy savings for the State of California from built-up systems by the end of year 15 after commercial introduction to the market and 1.9 to 3.8 TBtu by the end of 15 years for packaged systems (but with a lower initial impact than built-up systems). Combining the two targeted markets, potential annual savings equal up to $160 million by year 15 with corresponding reductions in CO2 emissions of 130,000 metric tons.

11.4.1 The Path Forward

The final chapter of the report identifies specific proposed improvements to the algorithms to improve their performance, including:

- Piecewise empirical models to capture relationship between variables better when distinctly different behavior exist (e.g., a range of control commands for which no measurable response occurs compared to a range where the response monotonically increases with increasing control command).
- Use of cooling-coil effectiveness as the basis for relating the temperature change or air as it passes across the cooling coil to supply-fan speed and control signal to the chilled water valve.

Additional laboratory testing of the full suite of algorithms to better understand preferred values for selectable parameters (e.g., detection thresholds), to ensure that the algorithms minimize false fault detection, and prepare the full suite of self-correcting algorithms for VAV systems for field application.

The collective findings of the PNNL team in this project and prior work support development of a software module for self-correcting air-handler sensors, which would be suitable for use in field tests and early commercialization. Although the capabilities of this module would be limited in scope, they would address the important problems of out-of-calibration sensors in air-handling systems.

CHAPTER 12: Development and Demonstration of a JAVA OPC UA Web Service Client

System Integration Specialists Co., Inc. and Hypertek Co. Inc.
September, 2011

Full report found in Appendix S.

12.1 Introduction

Today, distribution assets are owned and operated by utilities. In tomorrow's distributed environment, information must flow beyond utility ownership boundaries. Frequently, information will be assembled and utilized from customer owned equipment, including Distributed Energy Resources (DER), and, customer owned facility management systems. In addition, information may flow across distribution companies and transmission company boundaries. Opening systems to go beyond utility boundaries will increase the need to join applications and networks that were never designed to work together. While information is available, proprietary walls inhibit data sharing. In order to take greatest advantage of the information in deployed assets, designers need to consider protocols and application models that can link and span heterogeneous systems.

12.2 Project Purpose

In order for information to flow beyond the utilities, what is needed is open standards-based connectivity between entities based on ubiquitously deployed and understood communication protocols and security profiles. This requirement can be satisfied by a set of Web Services called OPC Unified Architecture (UA). The acronym OPC stems from OLE (object linking and embedding) for Process Control; the OPC is the interoperability standard for the secure and reliable exchange of data in various industries. OPC UA specifications address the security and data modeling challenges introduces by service-oriented architectures and provide a feature-rich technology open-platform architecture that was future-proof, scalable and extensible. This open standard enables interoperability across platforms and different vendor products. OPC UA is on track to be standardized in IEC TC 57 WG 13, 10, and 17 as the Web Service Profile for exchanging device data. Companies that support OPC UA for communication with devices include Siemens and ABB. Additionally, Microsoft, OSIsoft, SAP, IBM, and GE support OPC UA in areas beyond device communication. While current OPC UA implementations support a variety of platforms, a Java implementation for Web Services is not available. Java has been chosen as the preferred development platform because of the many non-Microsoft based distribution devices in the market. It is expected that an open source implementation of OPC UA Web Services in Java will foster the adoption of open communication especially for DER devices.

12.3 Project Results

SISCO and Hypertek developed open source Java Open Platforms Communication Unified Architecture (OPC UA) Web Services communication software that can be used for data exchange with devices in the case where Web Services are preferred. SISCO and Hypertek delivered to the OPC Foundation fully tested and operational source code and compiled binaries as well as a Technical Report describing software build instruction and other documentation related to the stack (contained in the appendices of this document). SISCO and Hypertek successfully demonstrated the Java Stack to PJM ISO engineers. Because PJM is a transmission company, the research team decided to demonstrate how OPC UA can be used to exchange data about wind power rather than DER devices. Specifically, PJM was interested in how OPC UA can be used to hide the particulars of legacy wind farm data modeling and communication protocols. The purpose of the demo was to:

- Demonstrates access to wind power related devices over a WAN using secure reliable web services.
- Data accessed within the context of a device information model
- Device models standardized in IEC 61850/61400
- OPC UA Web Services support discovery and change notification to data and metadata

12.4 Project Benefits

Benefits include the development of Java UA Web Services stack within the existing OPC UA open source infrastructure provided by www.opcfoundation.org. The OPC Foundation is a nonprofit organization responsible for the development of the OPC specification and code base. OPC UA stack source code will be available royalty free for noncommercial use. For commercial use of the source code, companies will need to join the OPC Foundation

This software allows data exchange over different locations and technologies, between different companies and different business users, and is compatible with advance substation architectures.

CHAPTER 13: An Integrated and Cognitive Home Energy Management System for Demand Response

San Diego State University
November, 2011

Full report found in Appendix T.

13.1 Introduction

A customer's involvement in the smart grid is expected to help in shaping the load on existing grids by spreading the electricity demand uniformly over a period of one day which in turn helps the grid in guaranteeing a reliable energy supply. The technologies to enable customer engagement are emerging. A number of connected smart appliances has been already released by many manufacturers, however these solutions do not offer an integrated solution involving both utility company and the residential customer. In addition, existing home energy management systems may provide comfort and convenience, but do not take into account the utility data (such as load forecasts or TOU pricing) for the scheduling of appliances. There is also no coordination among multiple dwelling units to simultaneously manage DR in a residential community.

13.2 Project Purpose

The purpose of this project is to develop a turn-key solution to Demand Response (DR) for residential customers in order to address several of the shortcomings of current energy management systems and facilitate participation of residential customers in DR management.. The goal is to provide a one stop solution, bringing demand bidding to residential customers with aggregator bidding on power and offering incentives to residential customers to meet the conditions of the bid. This includes developing an algorithm for finding the optimum TOU electricity pricing in monopoly utility markets.

13.3 Project Results

The customer's daily tasks are scheduled according to user-specified constraints and the TOU pricing offered by the utility company to achieve cost savings and peak demand reduction. A cognitive residential adaptive neural fuzzy inference system (ANFIS) based master controller (MC) is developed for controlling appliances in the home and to forecast future power demand based on user's life style and environmental/social factors impacting power consumption. A self-organizing home energy management network is developed based on IEEE 802.15.4 to control appliances remotely. The appliance controllers developed here offer a zero configuration appliance network enabling the technology to be deployed in a home with no user configuration. An aggregator is developed to gather power consumption profiles from residential MCs to estimate the aggregated demand for energy in a region. A time-of-use (TOU) pricing algorithm is proposed to maximize the benefit to the user. The intelligent residential energy manager is implemented as a smart phone application.

The price elasticity based TOU pricing algorithm revealed that the price increase results in lowered demand. Simulations showed that DR is effective in maximizing the overall benefit to the customer. A self-organizing home energy network with appliances as the end nodes was successfully developed. The MC communicates with the appliance nodes via a home energy network gateway node developed as part of this study. A scheduling algorithm is developed for managing appliance schedules based on the branch and bound algorithm. Results show that this proposed system is an effective solution for home energy management.

13.4 Project Benefits

With a closed loop integrated solution, customer participation in DR programs can be increased; thus the cost of energy production can be controlled. The net result of this can be presented as a pricing policy that maximizes the benefit to the user. This solution:

(a) gives the utility the ability to predict and tailor the electricity demand in multiple dwelling units simultaneously in a given residential community:

   (i) by providing suitable incentives (such as differential TOU pricing) to customers, and

   (ii) by scheduling and controlling appliances to smooth the demand. The integrated solution presented here will enable the utility company in reducing and shifting the peak load, in providing a better forecast of electricity demand, thus avoiding load shedding during peak seasons.

(b) manages feeding the excess solar power to the electricity grid through the 'net metering' scheme. This will help in DR by reducing the load on the grid during peak load conditions. This will also reduce the need for the utility to buy electricity at higher rates during peak load conditions.

(c) provides an inexpensive, user-friendly, and easy to install/maintain architecture for both customer and utility provider.

The residential customer gets the following advantages:

(a) Improved energy efficiency for electricity usage, thus resulting in greater cost savings;

(b) Maximum usage of solar power locally within the home by shifting operation of certain appliances to times when solar generated power is available;

(c) Maximum user comfort by learning from user inputs, usage patterns and weather conditions.

CHAPTER 14: Feeder State Estimation with AMI and Advanced Sensors

EnerNex Corporation
February, 2012

Full report found in Appendix U.

14.1 Introduction

Transmission systems are well-instrumented, and state estimation algorithms for them are fairly robust. State estimation refers to the prediction of all voltages and currents in a power system, based on a set of measurements that might include missing or erroneous data. The conventional method of state estimation minimizes residuals (that is, the difference between measured and estimated value) of a measurement function, in which the state variables are node voltages (magnitude and angle), and a large number of real power and reactive power measurements are available. However, this classical method works poorly on distribution feeders for several reasons:

- Very few measurements are available, sometimes only the voltage and current at the substation.
- Switch states, capacitor bank states and transformer/regulator taps may not be directly monitored, as they typically are on transmission systems.
- Many of the feeder measurements are current, rather than power.
- Three-phase unbalances and low X/R ratios complicate the measurement function.

On the other hand, robust state estimation is a prerequisite for nearly any advanced control or automation concept on distribution systems. The challenges are obtaining enough measurements, and adapting state estimation to the unique characteristics of distribution systems.

14.2 Project Purpose

The project objective is to demonstrate practical state estimation of distribution feeders.

14.3 Project Results

A pilot project was conducted on a 12-kV feeder at City of Palo Alto Utilities (CPAU), using substation SCADA data and low-cost wireless current sensors deployed out on the feeder. A state estimation algorithm was tested using data collected from January through July, 2011. In parallel, extensions to the algorithm were developed at NC State University for detecting switching and capacitor bank topology changes, but these could not be tested on the selected pilot feeder.

Some fault current indicator events were detected at the sensor located just outside the substation, but these were not correlated to actual outages. There was not enough redundant data to fully test the state estimator; some of the sensor data exhibited gaps, and it was not sampled simultaneously. Some positive conclusions may still be drawn:

1. The state estimator can be run with a reduced circuit model derived from actual sensor locations, using an exact lumped model of the segment that reproduces power losses and voltage drops.
2. The tested feeder has low voltage drop and high power factor.
3. The data shows nonuniform distribution of loads among the monitored segments.
4. The tested feeder may have significant load unbalance among the phases. Improving the load balance would reduce losses and more importantly, reduce motor heating due to voltage unbalance.

Recommendations for future development include the following:

1. The wireless current sensors should have open access to data in real time; the web service interface should be completed and provide access to RMS current values, waveforms, etc. Interoperability between systems is very important for state estimation and other smart gird applications.
2. The sensor's fault current indicator report should include automatic waveform capture and notification by pager and/or email.
3. Simultaneous, or near-simultaneous, data acquisition seems to be important. This will be problematic for AMI, low-cost sensor, and other non-SCADA devices. More effort is needed to develop SCADA-quality measurement sources out on the feeder.

14.4 Project Benefits

State estimation will be a key enabling factor of smart grid concepts, including demand response, reactive power control, asset management, self-healing, and many more.

CHAPTER 15: Arc-fault circuit interrupter development for residential DC electricity

California Polytechnic State University, San Luis Obispo
Principal Investigators: A. Kean and Taufik
March 2015

15.1 Introduction

The use of direct current (DC) electricity in California homes will likely increase in the future due to greater adoption of residential photovoltaics and increasing use of electric (and plug-in hybrid) vehicles. While less certain to occur, there are also a lot of benefits to powering entire homes on direct current. A "DC house" has direct benefits like reduced energy consumption due to fewer conversions from alternating current (AC) to DC, and secondary benefits like potential increase of photovoltaic panel and electrical vehicle sales due to higher overall system efficiencies and shorter payback times. Perhaps the home of the future will be a "hybrid", with some loads served by alternating current and others direct current.

An Arc Fault Circuit Interrupter (AFCI) is a special circuit breaker that detects and eliminates unintended electrical arcs, which can cause a fire. Electrical arcs, also known as arc faults, occur when current jumps from one conductor across an air gap to another conductor. The high temperatures generated by an electrical arc are a fire safety concern, regardless of whether AC or DC electricity is being used. The U.S. Consumer Product Safety Commission estimates roughly 18,000 residential fires are started each year due to electrical wiring, with some indication that one-third of those are specifically due to electrical arcing. While these statistics relate to the standard AC electricity available in most residences, as the use of DC electricity increases, the risk of fire due to arcing of DC electricity also increases. Unfortunately, reliable detection of arc faults and determining the appropriate response is particularly difficult in DC circuits. Because DC does not pass through a zero-current state like AC, a DC arc is more likely to maintain itself.

The National Electric Code (NEC) and Underwriters Laboratories (UL) have recently developed requirements for AFCIs for photovoltaic systems with DC circuits operating at 80 volts or greater. Despite these adopted specifications, these AFCIs are still in development for many manufacturers and there is little consensus on the best approach. Virtually no research has occurred on protecting household DC circuits from arcing. These circuits are likely to be at voltages less than 80 volts, but still at a high enough voltage to cause significant fire risk if arcing were to occur.

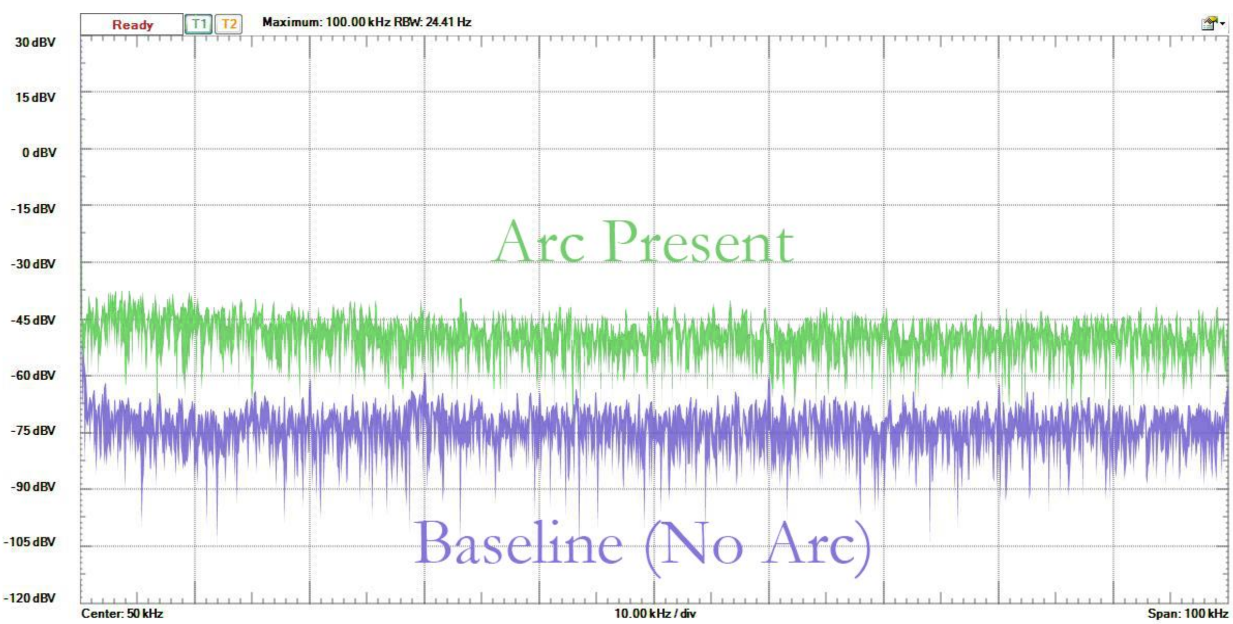
15.2 Project Purpose

Our research program focused on developing an Arc Fault Circuit Interrupter for a DC-powered house. See Appendix V for the full final report. In the context of increasing the efficiency of California's electric power supply, safety is the primary objective of this research project. Arcing events in electrical circuits are a major fire risk, and AFCIs can significantly reduce this risk. Arc Fault Circuit Interrupters are currently in development for 80 volts or higher photovoltaic circuits, but the research team developed a prototype AFCI for DC household plug circuits operating at primarily 24-48 volts. This new application of the AFCI has its own unique challenges due to the diversity of loads that may be present in household plug circuits.

15.3 Project Results

Change to the frequency spectrum of the DC electricity was chosen as the marker of an arc occurring. Consequently, the frequency response due to a DC electrical arc was studied carefully. Each experiment varied the parameters of the components used to ensure likely variations were accounted for in the spectral response characterization. Series arcing and parallel load arcing were tested in this manner. The impedance and characteristics (passive and active) of the loads were varied as well as the models and manufacturers of each component and device used (power supply, current transformer, spectrum analyzer, cables, and contacts). The DC power supply voltage was varied between the minimum voltage required to create an arc, and 80 volts. The contacts used in the Arcing Device were interchanged with various materials, contact shape, and size. Results showed that if an arc is occurring, it will create noise content at every frequency within the observed range (244 Hz-100 kHz), though the amplitude distribution may vary depending on components used.

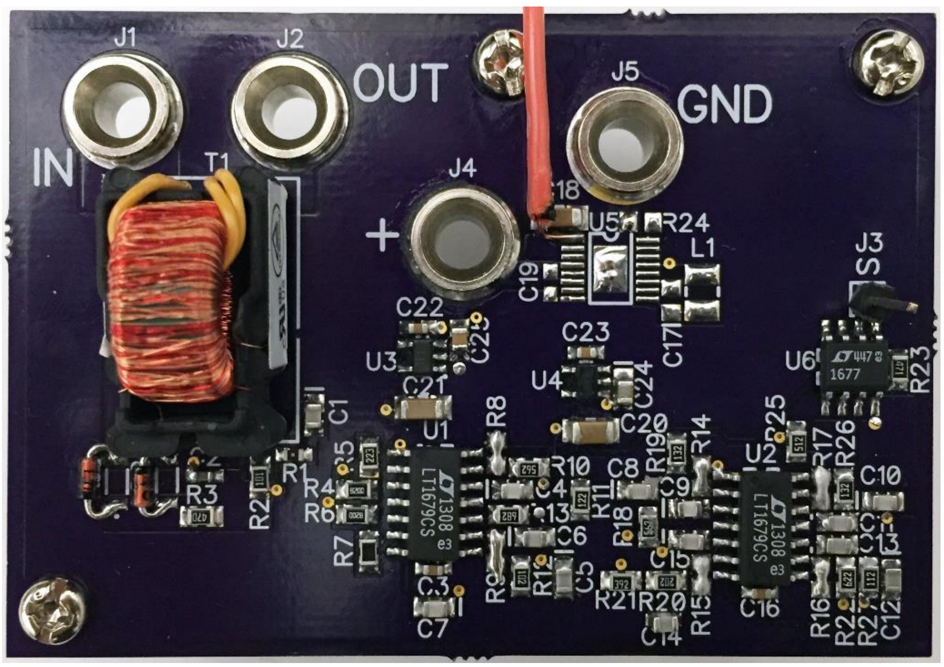
Figure 13: Arcing Test (244 Hz-100 kHz)



To provide a robust system, a predictable shape in the frequency response during an arc is needed; having a predictable shape will allow a microprocessor to compare and map several sample points to an arcing "signature" and, upon a successful match, send a shutoff signal to a current controller. To accomplish a reliable and repeatable response despite differing system parameters and components, an analog gain and filter system was designed to achieve a specific response by forcing the arcing noise to a predefined shape.

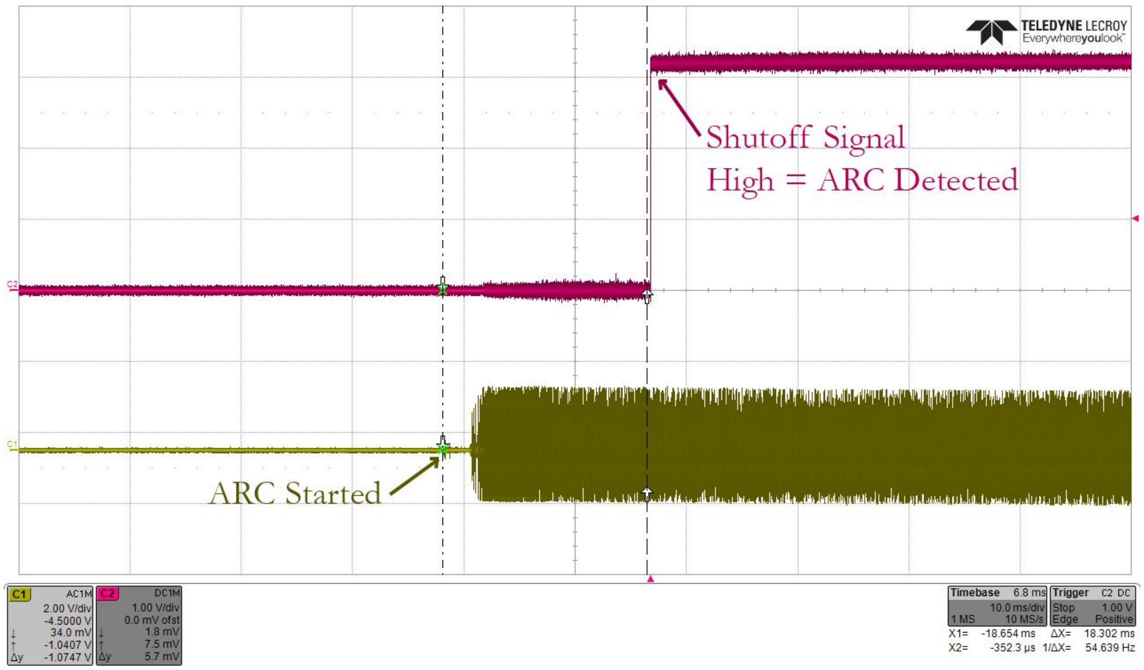
A full-featured spectrum analyzer will not be available for use in a low-cost AFCI. Instead, a microprocessor from Microchip is used for analysis and logic. The on-chip analog-to-digital converter was used with a sampling rate of 250 kHz, satisfying Nyquist criterion up to 125 kHz. Once the entire design of the AFCI was finalized and tested, it was then implemented on a printed circuit board to demonstrate its low-cost reproducibility.

Figure 14: Populated AFCI Board



The UL standard for DC arc fault circuit interrupters requires a shutoff signal to be sent within 2 seconds of an arc occurring. During testing, the AFCI design detailed in this report had a response time between 8 ms and 54 ms, which is well within the requirement (see Figure 4 below). With that significant of a margin, several improvements can be made in the software to prevent false positive detections (nuisance trips) by utilizing averages across more sample sets, and performing more complex processing.

Figure 15: AFCI Response Time (Test 1)



15.4 Project Benefits

A DC-powered (or partially DC-powered) home could become a component of a future, smart electrical network that increases the security, quality, reliability, and affordability of the electric power system. Safety is paramount with these systems, which is why there is a need for a low-cost Arc Fault Circuit Interrupter (AFCI) for residential direct current electricity. The DC AFCI is a technology that will enable better energy efficiency, accelerate adoption of electric vehicles, enhance service reliability, and of course, increase safety.

CHAPTER 16: Repetitive & adaptive control of distributed generation for seamless transition between grid tied & off-grid modes

University of California, Los Angeles
Principal Investigators: T. C. Tsao and L. Vandenberghe
March 2015

16.1 Introduction

According to International Energy Agency, global electricity demand increases every year from 117,687 TWh in 2000 to 143,851 TWh in 2008. As the energy consumption keeps climbing, concerns about transmission costs, power quality, and the lack of power generations for localized demand are crucial for the future power distribution system. Researchers strive to find alternatives to typical radial form power distribution systems, and the deployment of Distributed Generation (DG) across the grid seems to be a logical and reasonable solution to the aforementioned issues. Those DGs are usually small in size and adapt to local resources, they utilize renewable energy and provide an alternative means of power production than traditional centralized power systems.

Microgrids are systems that contain at least one Distributed Energy Resource (DER) and local loads. The islanding of a microgrid can be formed intentionally in the power distribution system. There are two types of DER in a microgrid: one is DG and the other is Distributed Storage (DS). Most of the microgrid systems use both of them to provide energy. Interconnection switches are used to disconnect and reconnect DERs between the main grid and microgrid but the transition has to be smooth or with minimal disruption to the local loads. Also, microgrid system relies heavily on PWM inverters to transfer power from the DERs to the loads; therefore, the inverters must be able to output harmonic free power to increase efficiency.

16.2 Project Purpose

The purpose of the project is to develop algorithms that can prove to efficiently and safely transfer power from DERs to loads using a microgrid. The major objectives can be stated as:

- Simulate a microgrid system that can be used to predict the microgrid power transfer using different control algorthms.
- Develop a repetitive control algorthm for the PWM converters and analyze the harmonic content produced versus typical control algorthms. Increased harmonic content reduces the power transfer efficiency which is a major issue using PWM converters.
- Most of the power converter control algorithm for DER in the literature has the capability to work smoothly in both grid -tied and off-grid modes, but they do not consider the issue of a smooth transition from one mode to another. Another objective is

to verify with the simulation that the transition from grid-connected to island mode is smooth or with minimal disruption to the local loads.

- In order to asses the viability of the controls developed, a Hardware-In-the-Loop (HIL) simulation with the control and the models running on different platforms is investigated and compared against the overall simulation
- Lastly, a high level model predictive controller is developed and implemented. The high level control satisfies the load's power needs while minimizing the cost. A cost is associated with running the microturbine, storing energy, and shedding noncritical load. So, the high level controller will decide which DERs to use given a certain power output from the photovoltaics and windmill. Also, the high level controller will take into account the forecasted load demand for the day.

16.3 Project Results

In this research, a control system that contains Model Predictive Adaptive Control and Repetitive Control is implemented on the microgrid simulation. The controllers provide superior power quality and maintain the safety of the microgrid during grid transition. The following results of the project can be summarized relative to the objectives:

The simulation of the microgrid has detailed models of the power converter, microturbine, windmill, and photovoltaic array. Having such a detailed model enables both transient and steady state power flow in the microgrid. Also, different control algorithms can be implemented in the simulation.

The power spectrum from Hardware-In-the-Loop simulation shows that repetitive control is able to effectively suppress the third harmonic in the output current. So it can transfer power more efficiently than traditional methods.

Using repetitive control and aligning the reference with the grid, it was also observed a smoother grid transition from both grid-connected to island and vice versa.

The proposed Model Predictive Control is able to utilize the predicted renewable energy production and predicted critical load demand to make optimal decision for controllable DERs.

To summarize, the repetitive controller can output a high power quality in a microgrid while minimizing unwanted grid transition fluctuations. Also, the high-level model predictive controller can minimize microgrid costs by minimizing the usage of high cost DERs.

16.4 Project Benefits

The benefits of the project can help in the development of microgrids, which will result in more renewable and alternative forms of energy integrated into the grid. Firstly, the detailed simulation developed can predict the transient behavior and control algorithm changes without having to invest in costly hardware. The benefits of a simulation can greatly reduce iterations and trial errors.

Moreover, a repetitive control in the inverters can deliver high quality power, while minimizing grid fluctuations. The results clearly show that a simple control algorithm can result in large fluctuations during transition and that an advanced controller can be minimize these fluctuations. A repetitive controller can track commands from a high level controller, so it is very advantageous when used in conjunction with one.

Also since the microgrid can have many DERs, the model predictive controller developed can make automated decisions about which DERs to turn on and off. In the current research, the primary objective was to minimize the cost; however, pollution and other factors can be added into the formulation. Overall, a repetitive and model predictive controller used together is a viable control strategy for the microgrid.

CHAPTER 17:
Porous silicon-based lithium ion anodes for secondary batteries

University of California, San Diego
Principal Investigators: M. Sailor and S. Meng
March 2015

17.1 Introduction

The automotive industry's pathway to commercially viable long-range electric vehicles (EVs), including plug-in hybrids, extended range electric, and all-electric vehicles depends on high capacity batteries. Lithium-ion batteries (LIBs) are of special interest as power sources for EVs due to their reliability, but they currently don't hold enough energy, limiting the number of miles that can be travelled between charging. Replacing the carbon-based (graphite) electrode that is currently used with silicon promises to increase the capacity by a factor of ten or more, which would significantly increase the range of EVs. However, silicon is currently not sufficiently stable to be used in rechargeable batteries—it can only be recharged a few times before it must be replaced. The main reason for this short life is that silicon expands and contracts each time it undergoes a charge/discharge cycle in the battery. The silicon material forms cracks after a few cycles and these cracks destroy its ability to be charged again. Carbon is less susceptible to this cracking process, which is one main reason carbon works so well in the current generation of lithium-ion batteries.

Carbon-based materials (e.g. graphite) that are currently used as lithium ion anodes have a theoretical maximum gravimetric capacity for intercalation of lithium of 372 mAh g^{-1} with a practical limit of 300-330 mAh g^{-1}. Electrode design and materials improvements that can increase the mass capacity, energy density, and the performance of Li-ion batteries are crucial. [3] Silicon has recently emerged as a promising candidate anode material, because it has one of the largest known theoretical specific capacities of 4200 mAh g^{-1}, more than an order of magnitude larger than carbon-based materials. [4] However, the large volume expansion of Si upon Li intercalation leads to loss of mechanical integrity during the charge/discharge cycle, resulting in rapid capacity fade from electrical isolation of the porous silicon material. To mitigate the effects of this volume change, the use of nano-sized, or nano-structured silicon particles has been explored with some success.

17.2 Project Purpose

The research team prepared a sponge-like form of silicon that allows more charge/discharge cycles. The spongy silicon is prepared by using an electrochemical process to drill microscopic holes into silicon crystals. These nano-holes accommodate the swelling of the silicon when it is charged with lithium. In addition, added chemical binders that tie the pore walls of the sponge together, to prevent cracking when discharging lithium. The pores, and the chemical binders that hold them together, combine to give a silicon material that can be charged and discharged through more than 400 cycles, a significant improvement compared to the pristine Si crystals. This report also illustrates that the modified material still has a capacity that is greater than carbon by a factor of 5.

The objectives of this project were to optimize the silicon etching conditions and carbonization chemistry to yield a manufacturable and scalable process that yields cycle life in excess of 3000 and capacity in excess of 1500 mAh g^{-1}. By tailoring the porous silicon etch process to the optimal void space, pore wall thickness, and spacing of perforations, the structure was expected to withstand the repeated volume changes and stresses associated with Li insertion/deinsertion. Also, the research team aimed to develop new chemistry to tailor the carbon coating on the porous silicon for optimal electrical conductivity and enhanced structural stability. The final step was then to test the performance of the anode materials in standard lithium ion half-cells and evaluate their behavior in solid and polymer electrolyte junctions.

17.3 Project Results

The team has successfully fabricated various desired morphologies (5 μm perforated pristine particles, 5 μm perforated rugate particles, and 150 nm perforated particles) of porous silicon (PSi) with corresponding successful implementation as lithium ion anodes using both polyacrylonitrile (PAN) binder [2], and carboxymethyl cellulose (CMC) binder. In addition, the research team successfully demonstrated various methods to carbonize the porous silicon active material: acetylene coating (ACE), Polyfurfuryl alcohol coating (PFA), and in-situ PAN coating. The formulation of the in-situ PAN carbonization coating has been the first of its kind to be demonstrated for porous silicon-based anodes. However, due to time constraints, only electrochemical cycling data for carbonized PSi electrodes made with PAN binder has been gathered. The electrochemical data for pristine, noncarbonized PSi using PAN binder yielded an average stable cycling specific capacity of around 600 mAh g^{-1}. Using again PAN binder, the various carbonization techniques previously mentioned yielded an average stable capacity of around 850 mAh g^{-1}. All electrochemical data collected for PSi electrodes made with PAN binder showed stable cycling capacities in excess of 400 cycles. However, due to time constraints and issues with first-cycle Coulombic efficiencies (CE) of the reported electrodes, the time spent to test whether the batteries showed stable cycling in excess of 3000 cycles was deferred for time spent testing different particle morphologies to address the issues faced with first-cycle CE capacity drops and specific capacity cycling of less than 1500 mAh g^{-1}.

For pristine, noncarbonized PSi using CMC binder, the average stable specific capacity cycling obtained was around 1000 mAh g^{-1}. For the 5 μm perforated rugate particle using CMC binder, the average cycling capacity was around 1200 mAh g^{-1}. Lastly, for the 150 nm perforated PSI using CMC binder the average cycling capacity was 1800 mAh g^{-1} with respect to active mass loading (near 6 times more than that of the standard graphite battery). However, due to time constraints the electrochemical data available for the 5 μm perforated rugate, and 150 nm perforated batteries are only available using the CMC binder. Also, due to time constraints, for batteries fabricated using CMC binder, only cycling data of up to 350 cycles are provided for the 5 μm pristine PSi electrode, and only cycling data up to 30 cycles are provided for the 5 μm rugate and 150 nm PSi electrodes.

17.4 Project Benefits

This project illustrates the successful fabrication of porous silicon-based lithium ion anodes that demonstrate higher, more stable specific capacity cycling than the current standard graphite battery. The ramifications of such an improvement can mean higher energy density, up to 15%. This can enable even smaller and lighter electronic devices and since the same type of battery is used in some of today’s EVs, it could mean an increase in maximum distance on a single charge by the same percentage so the range could increase from 300 to 345 miles per charge. Such improvements can make EVs more attractive to consumers and spur forward the renewable energy movement.

CHAPTER 18:
Smart Power For The Smart Home: Inverter Controls, Power Factor Corrections, And Peak Demand

University of California, Irvine and University of California, Davis
Principal Investigators: G. P. Li and M. Modera
March 2015

18.1 Introduction

The integration of renewables adds to the wide variability of household electricity energy consumption and creates challenges for power quality and electric grid reliability. The power quality of typical American households varies from 0.8 to 0.95 depending on the type and time of appliance used. For example, appliances such as heating, ventilation, and air conditioning (HVAC) equipment, motors, and lighting generate reactive and harmonic power, which is typically about 20% of the power consumption. Photovoltaic (PV) modules supply mostly real power to homes through an inverter, so the reactive power consumed by the loads would need to come from the electric grid. This decreases the energy efficiency of the total system. Surging demand on reactive power during hours of peak consumption further induces instability to the grid.

The shape of the sine wave of household electricity (current and voltage) can be altered by using an active power filter system that corrects the power factor to near unity (1.0). In addition, whole house electricity consumption can be monitored to disaggregate load profiles of individual devices; this data in turn can be used to develop strategies to reduce energy consumption and improve power quality.

18.2 Project Purpose

The project explored several means of improving power quality and thus grid stability and efficiency: design of an active power filter, development of a appliance signature disaggregation system including user interface display, development of a model and simulation tools, and field testing the filter and disaggregation systems.

18.3 Project Results

The project developed load signature disaggregation and Active Power Filter (APF) prototype devices to restore the sine wave of electricity at a household level.

The power monitor involved the development of printed circuit boards (PCB) and algorithms to capture and disaggregate plug load devices. In addition, a server end protocol was defined to establish a communicational channel between the PCB and a mobile friendly interface. The prototype also provided an easy to understand viewing feature by directly displaying users' devices energy consumption information at their fingertips.

A 1.5 kVA one-cycle controlled active power filter was prototyped.

A field test of the prototype devices was conducted at a smart home. The demonstration of the system showed that the power factor was corrected to greater than 0.98 for all types of loads in the house including Lights, Electronics, Vehicle Charging, Kitchen Appliances, Vacuum & Air Compressor, Whole House Fan, Water Heater & Vacuum, and Washer & Dryer.

The project developed a simulation model with different parameters to assess various scenarios to optimize the overall system. These modeling and simulation scenarios were developed to capture the varying consumption levels of energy and take into consideration the unpredictability of behaviors to produce a better understanding of integration of device and behavior in optimal energy savings and efficiency. The parameters that had the biggest impact on the load profile were the energy source (gas or electric) of equipment and appliances, the level of onsite solar generation, and the capacity and operation strategy of onsite electric storage.

18.4 Project Benefits

The active power filter could be integrated with inverter hardware at a relatively low cost. This would allow solar homes to provide a benefit for power quality on the grid, by correcting power factor for all loads in a home during all hours.

The prototype device that captured load signatures of multiple devices could be extended to monitor the entire house to monitor, record, and disaggregate devices' power consumption. Data gathered could provide utilities a better understanding of consumer energy consumption to promote energy savings and efficiency programs.

Modeling and simulations lend to a more precise identification and consideration of integrating renewable energy and household electricity consumption. For the utilities and stakeholders, this allows the exploration of the best solutions that will lead to better energy management.

Better understanding of loads as well as consumer behaviors and usage patterns can ultimately improve measures via incentives and/or regulations to achieve energy savings and efficiency.

The next potential applications include:

- Implement APF with solar panel inverters (and batteries if available, for the best results), to achieve near zero reactive power draw while consuming zero energy from the grid generation.
- Dynamically upscale APF to be multi-house level power-factor correction. By doing this, the static power consumption of APF is reduced to one of N houses. If this were to be taken to the next step, the utilities has the opportunity to implement the APF with a solar panel before distributing the electricity to each house, to even further reduce the burden on the grid.

CHAPTER 19: Control of Networked Electric Vehicles (NEVs) to Enable a Smart Grid with Renewable Resources

University of California, Los Angeles and University of California, San Diego
Principal Investigators: R. Gadh and R. Gupta
March 2015

19.1 Introduction

The rising fuel prices and greenhouse gases have spurred growing interest in transportation, electrification and in generation of electric power from renewable energy resources. Environmental concerns, due to global warming and increasing demand loads, have caused a pressing need to develop a smart power grid that can integrate renewable energy resources and store the energy for addressing the peak demand loads. A smart grid is a key technology for meeting the challenges faced by conventional grids. A smart grid is a power grid where generators, energy storage, and loads are monitored through an intelligent control system and communication network that supports various protocols. Utilities face the complex problems of peak demand and intermittent supply, which are made more pressing by the need to integrate large electric vehicle (EV) loads and distributed generation. The flexibility of EV loads, which can charge at varying rates, together with forecasts of renewable energy availability can be used to reduce integration costs.

Vehicle-to-Grid (V2G) technology offers a promising opportunity for increasing EV adoption. V2G provides reactive power compensation, active power control, tracking of renewable energy resources, load balancing, and smooth bidirectional power flow, which can increase the efficiency and reliability of the grid. V2G allows an EV fleet to feed energy directly back into the power grid or use this energy to partially feed connected loads in the distribution system. An efficient power transaction between an EV or plug-in electric vehicle (PHEV) and the grid requires exchanging much information among the EV/PHEV, charging station, renewable energy generation, and connected loads. This information includes technical data (such as the battery's state of charge), economic data about the price of energy, and statistical information about the energy's availability.

According to a 2011 study by Pike Research, it is predicted that by 2020, one in four EVs purchased in the U.S. will be in California, which makes the state potentially have a networked electric vehicle (NEV) capacity of 10 GW to use for enhancing power quality and reducing the cost of electricity. The actual available capacity will depend on technology and regulations. Another study shows that a combination of renewable resources and energy storage from NEVs could supply 99.9 percent of the electricity by 2030, while maintaining the present cost of supply. Various studies have shown that utilities will be able to cope with the increased load of EVs using coordinated or smart charging. The main barrier in the uptake of EVs by consumers seems to be the initial cost. An incentive to purchase EVs can be the return on the investment by selling NEV services to the grid. There are many services which NEVs can sell: electric energy time shift, electric supply capacity, load following, area regulation, voltage support, time-of-use energy cost management, renewable energy time shift, renewable energy capacity firming, and integration of wind generation into the grid.

This project has developed the enabling technologies for NEVs to maximize the EV potential for owners and utilities. To ensure reliable grid operation, every distributed energy resource (DER) has to be controlled to satisfy some technical requirements. In this situation it is desirable to develop unified standards and protocols for all DERs using NEV as a bidirectional DER.

In the NEV environment, each EV can charge and discharge or have bidirectional power flow through electric vehicle service equipment (EVSE). An EV functions as a mobile energy storage system that has the flexibility to move across time and across stations. This mobile energy storage is useful for optimizing the power flow in the network and compensating for the reactive power required by some renewable sources and the power generation ramps that occur across time slots from generators.

Integration of EVs into the power distribution network leads to solving the optimal power flow (OPF) problem across time, i.e., multiple period OPF. Although the original formulations are mixed-integer nonconvex mathematical programs, semi-definite relaxations were suggested to put computational bounds on voltage and link flow variables.

The current project report presents research and technology that mitigate the impact of photovoltaic (PV) penetration and minimize grid losses using a coordinated approach for unified control of DERs, NEVs, and available communication, computing, and control technologies. The use of NEVs can alleviate the impact of PVs and provide other services to improve the reliability of the electricity supply. This report summarizes the enabling technologies that form a network of electric vehicles (EVs) and provide a coordinated support for increasing power quality and reliability.

19.2 Project Purpose

The objective of this research project is to develop innovative technologies for creating a smart network of EVs that: (a) absorb the variability of DERs, (b) support isolated distributed system operation, and (c) supply peak load demands and ancillary support to the grid. Electrical characteristics of NEVs are similar to other stationary energy storage devices, but the consumer behavior and mobility aspect makes a considerable difference on the overall impact of NEVs on the grid. Within residential settings, a single NEV can influence power quality and this influence increases as more NEVs are aggregated into the system. A key objective in this project is to enable aggregation of NEVs to utilize the available NEV capacity by dynamically networking their charging stations. The network will be both physical – through distribution lines – and logical – through communication networks. The purpose of organizing NEVs into networks is to maximally exploit the capacity of the NEVs. Peak power support is an important application and the use of an NEV as a DER to provide real power can be achieved using signals from an independent system operator (ISO). The purpose of forming a network of EVs is to have decentralized feedback control that is based on set-point information, which derives from a coordinated optimal power flow application for real power and reactive power support.

To fully exploit the potential of NEVs, coordinating each NEV's behavior as a node in a network of EVs (and other DERs) is essential and this project addresses this technical need. The research project leverages the open-architecture technology for smart charging of EVs. In short, the objective is to develop communication, computing, and control for a unified management of renewable resources, energy storage units, and NEVs to enable a smart grid with renewable resources. The project will provide a proof of concept demonstration of the unified control and management of NEVs and PV solar.

The various objectives of the project include:

To develop a vehicle-to-grid system using CHAdeMO protocol

- Vehicle-to-Grid (V2G) is a combination of both power flow and signal flow that uses the communication between Electrical Vehicle Supply Equipment (EVSE) and EV to activate the discharging of vehicle battery using (i) SAE J1772 and (ii) CHAdeMO, SAE J1772.

To develop a communication network for NEVs

- Existing research and standardization have primarily considered wired connection for V2G communication, but wireless communications is preferred today for such communication. One of the common wireless communications standards is ZigBee, which is a widely accepted, low power and low data rate protocol; however, it has some limitations. Wi-Fi is more ubiquitous and has advanced encryption techniques such as Wi-Fi Protected Access 2 (WPA2); however, traditional Wi-Fi uses much energy. Low Power Wi-Fi (LP-Wi-Fi) has been developed, which decreases the power consumption through both hardware and software optimization, and presents an alternative to ZigBee. 3G has been designed for long distance communication using moderate data rates, but fading reduces the reliability of the network; Long Term Evolution- Advanced (LTE-A) Device-to-Device (D2D) communication has the potential for higher data rates. There are also other wireless technologies, such as RFID and near field communication (NFC) that may only be used for auxiliary functions such as authentication in V2G. This research project will design an interoperable and scalable communication infrastructure for NEVs.

To develop standards and protocols for NEVs as DER

- This project will represent an NEV as a DER unit within IEC 61850. This will be achieved by mapping between the existing ISO/IEC 15118 for the V2G communication interface with IEC 61850-7-420. IEC 61850 provides a standardized framework for substation integration that specifies communication protocols and system operation requirements. Its advantages include interoperability, free configuration and long-term stability.

To develop smart charging and discharging algorithms

- This research project aims to develop a fundamentally novel and innovative NEV environment where each EV can charge and discharge or have a bidirectional power flow through the EVSE. This research will involve designing a scheme that is flexible enough for the demands of the mobile energy unit's service and palatable enough to attract large shares of vehicle owners to ensure feasibility. A smart power flow schedule will be developed for the NEVs. Smart power flow algorithms are key to garnering user acceptance of the new technology and realizing the full potential of NEVs. In the smart NEV power flow algorithms the foremost consideration is the user's preference and the battery's lifetime.

Reactive Power Control, Optimum Power Flow, and Distributed Control

- Optimum voltage levels will be calculated based on optimum power flow that incorporates the prediction of renewable resources and system constraints. These forecasts, which are based on the measurements sent from DERs and California ISO ancillary requests, enable optimal power flow by enabling system-wide energy shifting and peak shaving. Distributed control algorithms will be developed to achieve the calculated optimum voltage levels at the controlled nodes that will absorb the variability of DERs using regulated NEVs and enable a smart grid with renewable resources based on this regulation.

19.3 Project Results

The project has several outcomes. The first outcome is a standardized communication network from NEV to EVSE and Control Center that uses widely adopted universal standards and protocols. The V2G increases the efficiency and reliability of the grid by enabling reactive power compensation, active power control, tracking of solar photovoltaic (SPV) energy, and load balancing and leveling. Another outcome of the project is the bidirectional power flow from EV to grid and grid to EV, using the CHAdeMO and SAE J1772 connector and protocols; key data are also recorded, such as voltage, current, frequency, active and apparent power, and power factor.

Next, this project enables reliable communication for remote monitoring and control of networked EVs using various wireless communication technologies that include 3G/4G, Wi-Fi, ZigBee, NFC and RFID. In addition, an approach is proposed to apply IEC 61850 and ISO 15118 into the V2G system in order to provide a standardized communication network. An explicit procedure for integrating IEC 61850 into the applicable V2G system is explained and demonstrated step by step, with results showing the data set specification, SCL file documentation and IEC 61850 Gateway and Client communication implementation in tables and figures; similarly, the integration of ISO 15118 is discussed and demonstrated with results. To evaluate the approach, a simulated V2G system with NEVs is developed that showcases the integration of IEC 61850 and ISO 15118 into the communication network.

To handle the charging and discharging of NEVs, the project also develops various smart algorithms such as smart multiple-power-source round robin, energy price generation, prediction of energy supply, and dynamic scheduling. As a test bed, a PV solar unit is integrated into the grid. Communication and control is established using the new DER object module that is integrated with the NEV controller. The UCSD team has also presented algorithms for integrating EVs into the smart grid that use charging/discharging reservation information and task deferrals, while mitigating the variation of renewable power generation. The UCSD team has also demonstrated how EVs can be used to balance power flow while regulating the voltage in the distribution network.

19.4 Project Benefits

The primary, direct quantitative benefits of the proposed projects are reductions in greenhouse gas emissions and air emissions (e.g., oxides of nitrogen) resulting from the deployment of DERs and PEVs. Smart charging holds the promise to enhance charging opportunities for customers, improve grid integration, efficiently use the charging infrastructure, and potentially enable cost recovery for public charging. Smart charging, although not yet commercialized, should cost no more than current EVSEs and, with the potential for multiplexing, should actually reduce the installation costs of the EVSE. Potential benefits include: (i) load smoothing, which would help avoid demand charges; (ii) smaller local loads, which would reduce installation costs; (iii) capability for each charger to support more vehicles through multiplexing; and; (iv) capability for power quality support.

This project moves smart charging capabilities forward by including bidirectional charging that enable V2G and integration of battery energy storage systems to provide additional distributed energy resources to the grid. The added benefits to smart charging include: (i) access to PEV BESS to provide emergency power for buildings and grid support; and (ii) enabling rate incentives.

A Vehicle-to-Grid (V2G) system, which is composed of these NEVs, can mitigate the impact of renewable penetration, minimize grid losses and improve the reliability of the electricity supply. In addition, a standardized communication network for NEVs will certainly enhance the system's reliability and provide the end user with benefits.

Employing the techniques of smart charging algorithms and renewable integration, the power demand for EVs can be reduced by 20-30% with a savings of 600-700 million dollars per year.

CHAPTER 20:
Enabling Real-Time Residential Pricing with Closed Loop Consumer Feedback

San Diego State University
Principal Investigators: Y. Ozturk and G. Lee
March 2015

20.1 Introduction

Demand response is a program that offers rewards for consumers who are willing to participate in demand rescheduling during peak energy demand periods. In price based demand response programs, energy pricing can be an effective control signal for utility companies to reschedule electricity demand during peak hours. In this project, a real-time residential electricity pricing system with closed-loop consumer feedback is proposed. The peak load shifting will benefit both utility companies as well as residential consumers for reduced energy production cost, reduced carbon emission, increased power system reliability, and optimized energy consumption pattern.

20.2 Project Purpose

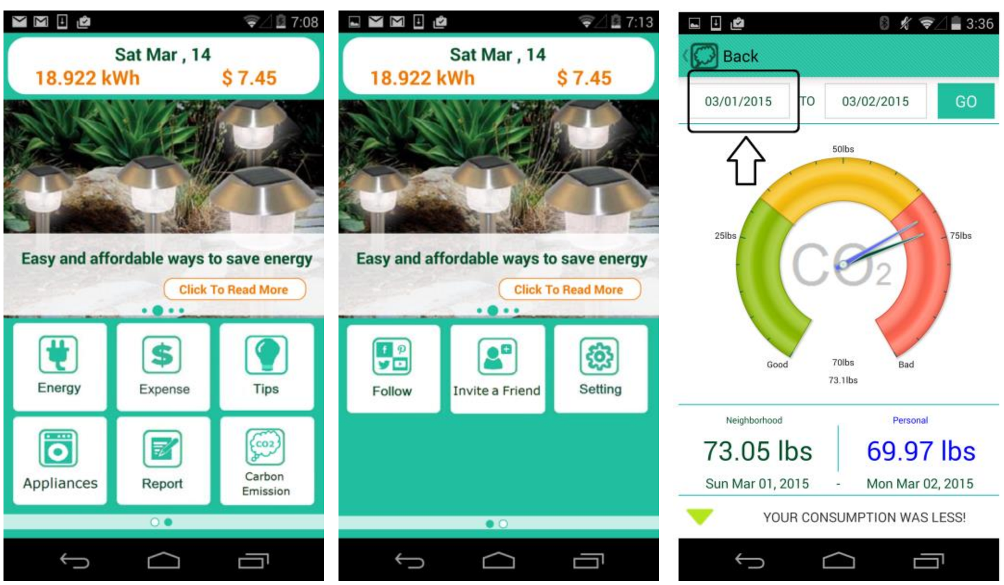
The purpose of this project is to develop a closed loop system for modification of consumer behavior through real time pricing of energy and encourage residential consumers to shift part or all of their energy consumptions from peak hours into off-peak hours.

20.3 Project Results

A closed-loop system is developed to acquire residential energy consumption data via the Green Button API, forecast future demand for energy, and display the price of energy to encourage a certain percentage of consumers to shift their energy consumption from on-peak hours to off-peak hours. An aggregator is employed to accumulate the predicted demand for a local micro-grid (25 residential households in this project). Once the forecasted demand is aggregated, the amount of peak demand which needs to be rescheduled within the proposed microgrid is determined. Based on the historical price, the: a) amount of demand needed to be rescheduled during peak hours, b) percentage saving for the consumers, and percentage profit for the utility company, and c) corresponding hourly electricity TOU prices are estimated. The real-time price information is communicated to the consumer on his/her smart phone application. Energy consumption, measured by smart meters installed on consumer premises, is acquired via an API (application programming interface) defined by the local utility company. The meter readings are used to estimate the error between the forecasted demand and real-time power consumption, as well as for assessing the consumers’ behavior change in response to energy price changes in real time. A Support Vector Machine (SVM) is used to forecast the individual household demand in the proposed system. A PID controller is utilized to train the SVM for fast training and to estimate the TOU price threshold values. Based on the historical price elasticity and amount of peak demand that is needed to be rescheduled, corresponding hourly electricity prices are estimated using two different approaches (price elasticity of demand approach and expense approach) and presented to consumers to affect their electricity usage during peak hours.

The real-time price information is communicated to consumers via a mobile application developed in this study. The mobile application developed in this study, EnergyElastics, is available on Google Play Store. Finally the success of the suggestions given to the consumer in the closed-loop system is assessed through smart meter energy consumption data reported by Green Button Connect program. The system is currently deployed on Amazon Cloud and Android platform. The project results showed that both a price elasticity of demand approach and an expense approach can capture the electricity peak prices using estimated 3-tier prices. The purpose of 3-tier prices is to generate a price-based demand response so that utility companies can reduce the peak demand load and in turn maximize the social welfare. The 3-tier estimated electricity prices are available for the consumers on their energy monitoring applications running on the consumers' smartphones. The consumers can adjust their electricity usage based on these price signals. The corresponding changes on their electricity usage patterns are recorded dynamically and modified accordingly in the next 24-hour cycle through the Green Button API.

Figure 16: Main Pages and Sample Page of Mobile Interface



20.4 Project Benefits

The project benefits include a mobile application that enables improved utility and consumer interaction to reduce peak demand and encourage energy savings. A cloud application that provides forecasts of future energy demand by a particular user also provides the user with daily and monthly energy consumption forecasts as well as provides the user with feedback on the CO_2 emissions due to energy consumption at on-peak hours versus off-peak hours. Finally the application computes and communicates an estimated 3-tier electricity price as control signal to consumers to change their energy consumption from peak hours to off-peak hours. While some parts of California are already using a time-of-use pricing program and it is expected by 2018 that the TOU pricing program will be uniformly used in the State of California, the proposed project can provide benefits in energy saving in peoples' everyday lives. With peak load shifting, utility companies and consumers will also benefit in the long-term with reduced energy production cost, reduced carbon emissions, and improved power system reliability.

GLOSSARY

Term	Definition
AMI	Advanced Meter Initiative, interval or smart meters
API	Application Programming Interface
CIEE	California Institute for Energy and Environment
DER	Distributed Energy Resource
DG	Distributed Generation
DR	Demand Response
DRETD	Demand Response Enabling Technology Development
EPIC	Electric Program Investment Charge
ETD	Enabling Technology Development
EV	Electric Vehicle
HAN	Home Area Network
MEMS	Micro-electrical-mechanical systems
NEV	Networked Electric Vehicle
PV	Photovoltaic
RON	Research Opportunity Notice
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
TAC	Technical Advisory Committee
TOU	Time of Use
UISOL	Utility Integration Solutions
USNAP	Universal Smart Network Access Port

APPENDICES

Appendix A: New Thermostat, New Temperature Node, and New Meter (Previously 2A)

Wright, Paul K. University of California, Berkeley. 2015. *New Thermostat, New Temperature Node, and New Meter.*

Appendix B: Demand Response Enabling Technology Development, Phase 1 Report (Report 2B)

Arens, E., et. al. 2006. *Demand Response Enabling Technology Development, Phase I Report: June 2003-November 2005, Overview and Reports from the Four Project Groups*, Report to Energy Commission Public Interest Energy Research (PIER) Program, Center for the Built Environment, University of California, Berkeley. April 4.

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Appendix C: Demand Response Enabling Technology Development, Phase 2 Report (Previously 2C)

Arens, E., D. Auslander, and C. Huizenga. 2008. *Demand Response Enabling Technology Development*, *Phase II Report from the Thermostat Controls Group: December 2005-December 2007*, Report to Energy Commission Public Interest Energy Research (PIER) Program, Center for the Built Environment, University of California, Berkeley. March 11.

Appendix D: Reference Design for Residential Energy Gateways: Phase 1 Draft Design Report (Previously 2D)

Auslander, D., and D. Arnold. 2009. *Reference Design for Residential Energy Gateways: Phase 1 Draft Design.* Report to Energy Commission Public Interest Energy Research (PIER) Program, Mechanical Engineering, University of California, Berkeley. Dec 28.

Appendix E: Reference Design for Residential Energy Gateways: Phase 2 Report (Previously 2E)

Auslander, D., and D. Arnold. 2010. *Reference Design for Residential Energy Gateways: Phase 2*. Report to Energy Commission Public Interest Energy Research (PIER) Program, Mechanical Engineering, University of California, Berkeley. Oct 4.

Appendix F: Reference Design for Residential Energy Gateways: Phase 2 Report (Previously 2F)

Auslander, D., and D. Arnold. 2012. *Reference Design for Residential Energy Gateways: Phase 2*. Report to Energy Commission Public Interest Energy Research (PIER) Program, Mechanical Engineering, University of California, Berkeley. May 23.

Appendix G: Reference Design for Residential Energy Gateways: Phase 4 Report (Previously 2G)

Auslander, D., and D. Arnold. 2014. *Reference Design for Residential Energy Gateways: Phase 2*. Report to Energy Commission Public Interest Energy Research (PIER) Program, Mechanical Engineering, University of California, Berkeley.

Appendix H: A Demand Response Application of the Sensor Network Services Platform (Previously 2H)

Appendix I: Network Security Architecture for Demand Response/Sensor Networks (Previously 3)

Appendix J: Network Agility and Management for Demand Response/Sensor Networks (Previously 4)

CyberKnowledge and University of California September, 2007

Appendix K: California Demand Response Business Network (DRBiznet) (Previously 5A)

Utility Integration Solutions, Inc. Sept 2006

Appendix L: California Demand Response Business Network (DRBizNet) (Previously 5B)

Utility Integration Solutions, Inc. April, 2007

Appendix M: Barrier Immune Radio Communications for Demand Response (Previously 6)

Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory February, 2009

Appendix N: Demand Response Analysis and Control System (Previously 7)

EnerNex Corporation July, 2009

Appendix O: Decision Support for Demand Response Triggers (Previously 8)

Electric Power Research Institute November, 2010

Appendix P: Privacy in the Smart Grid: An Information Flow Analysis (Previously 9)

UC Berkeley School of Information, University of California, Berkeley March, 2011

Appendix Q: People & Energy at Home: Information Display & Thermal Comfort Development for Residences (Previously 10)

University of California, Berkeley April, 2012

Appendix R: Self-Correcting Controls for VAV System: Filter/Fan/Coil and VAV Box Sections (Previously 11)

Pacific Northwest National Laboratory May, 2011

Appendix S: Development and Demonstration of a JAVA OPC UA Web Service Client (Previously 12)

System Integration Specialists Co., Inc. and Hypertek Co. Inc. September, 2011

Appendix T: An Integrated and Cognitive Home energy Management System for Demand Response (Previously 13)

San Diego State University November, 2011

Appendix U: Feeder State Estimation with AMI and Advanced Sensors (Previously 14)

EnerNex Corporation February, 2012

Appendix V: Arc-fault Circuit Interrupter Development for Residential DC Electricity (Previously 15)

California Polytechnic State University, San Luis Obispo Principal Investigators: A. Kean and Taufik March 2015

Appendix W: Repetitive & Adaptive Control of Distributed Generation for Seamless Transition Between Grid Tied & Off-Grid Modes (Previously 16)

University of California, Los Angeles Principal Investigators: T. C. Tsao and L. Vandenberghe March 2015

Appendix X: Porous Silicon-Based Lithium Ion Anodes for Secondary Batteries (Previously 17)

University of California, San Diego Principal Investigators: M. Sailor and S. Meng March 2015

Appendix Y: Smart Power for the Smart Home: Inverter Controls, Power Factor Corrections, and Peak Demand (Previously 18)

University of California, Irvine and University of California, Davis Principal Investigators: G. P. Li and M. Modera March 2015

Appendix Z: Control of Networked Electric Vehiclse (NEVs) to Enable a smart Grid with Renewable Resources (Previously19)

University of California, Irvine and University of California, Davis Principal Investigators: G. P. Li and M. Modera March 2015

Appendix Z2: Enabling Real-Time Residential Pricing with Closed Loop Consumer Feedback (Previously 20)

These appendices are available as separate volumes, publication numbers CEC-500-2016-011-APA-D, CEC-500-2016-011-APE-I, CEC-500-2016-011-APJ, CEC-500-2016-011-APK-M, CEC-500-2016-011-APN-R, CEC-500-2016-011-APS-W, and CEC-500-2016-011-APX-Z2.