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Pecan Street Smart Grid Demonstration Program

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Abbreviation List

Acronym	Definition
AE	Austin Energy
AMI	Automated Meter Infrastructure
AMR	Automated Meter Read
ARRA	American Recovery and Reinvestment Act
ATI	Austin Technology Incubator
DOE	Department of Energy
EDF	Environmental Defense Fund
EV	electric vehicle
FTE	full time equivalent
HAN	home area network
HEMS	home energy management system
kV	kilovolt
kW	kilowatt
kWh	kilowatt hour
MWh	megawatt hour
NIST	National Institute of Standards and Technology
PV	photovoltaic
ROI	return on investment
RFI	Request for Information
SGDP	Smart Grid Demonstration Program
SIR	savings to investment ratio
SOC	state of charge
TOU	time-of-use pricing
TPR	Technology Performance Report
UT	The University of Texas
VArs	Volt Amperes reactive

I. Introduction

This document represents the final Regional Demonstration Project Technical Performance Report (TPR) for Pecan Street Inc.'s (Pecan Street) Smart Grid Demonstration Program, DE-OE-0000219. Pecan Street is a 501(c)(3) smart grid/clean energy research and development organization headquartered at The University of Texas at Austin (UT).

Pecan Street worked in collaboration with Austin Energy, UT, Environmental Defense Fund (EDF), the City of Austin, the Austin Chamber of Commerce and selected consultants, contractors, and vendors to take a more detailed look at the energy load of residential and small commercial properties while the power industry is undergoing modernization.

The Pecan Street Smart Grid Demonstration Program signed-up over 1,000 participants who are sharing their home or businesses's electricity consumption data with the project via green button protocols, smart meters, and/or a home energy monitoring system (HEMS). Pecan Street completed the installation of HEMS in 750 homes and 25 commercial properties. The program provided incentives to increase the installed base of roof-top solar photovoltaic (PV) systems, plug-in electric vehicles with Level 2 charging, and smart appliances.

Over 200 participants within a one square mile area took advantage of Austin Energy and Pecan Street's joint PV incentive program and installed roof-top PV as part of this project. Of these homes, 69 purchased or leased an electric vehicle through Pecan Street's PV rebate program and received a Level 2 charger from Pecan Street. Pecan Street studied the impacts of these technologies along with a variety of consumer behavior interventions, including pricing models, real-time feedback on energy use, incentive programs, and messaging, as well as the corresponding impacts on Austin Energy's distribution assets.

The primary demonstration site was the Mueller community in Austin, Texas. The Mueller development, located less than three miles from the Texas State Capitol, is a 711-acre LEED Neighborhood Development mixed-use, urban infill redevelopment on the site of Austin's former airport, currently under development through a public-private project between the City of Austin, and Catellus Austin LLC. Currently, Mueller is less than 50% complete and more than 3,500 people live or work at Mueller. At full build-out, the project will include more than 3 million square feet of commercial and institutional space, more than 13,000 residents from approximately 5,700 single-family and multi-family dwelling units.

Figure 1 shows a Google Map image of the Mueller community, zoomed in on the residential streets participating in the project.

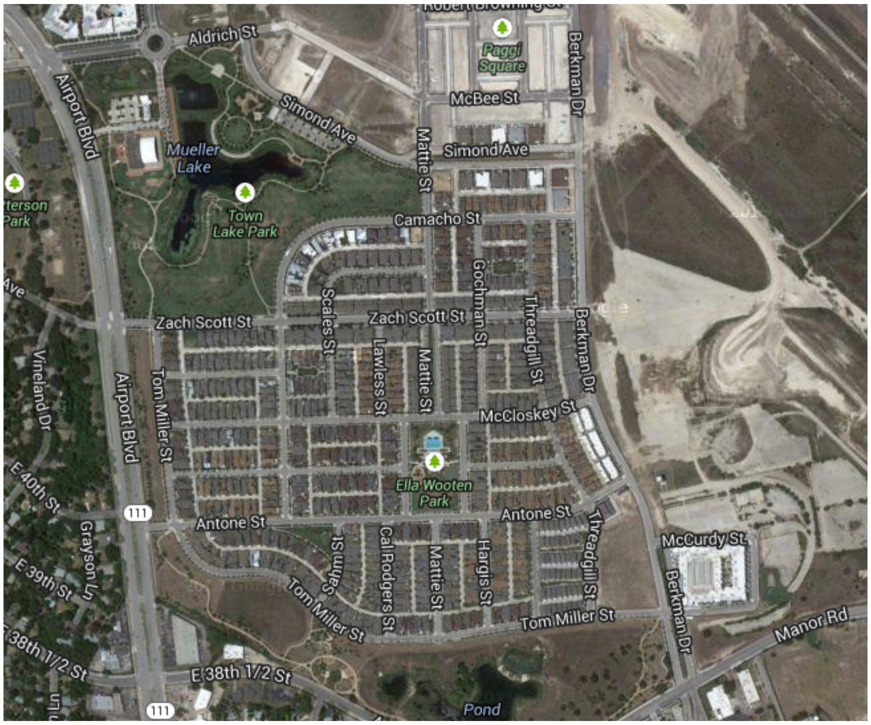

Figure 1. The Mueller community

Pecan Street constructed its lab, the Pike Powers Lab & Center for Commercialization, funded in part by this grant, in the Mueller community. The lab opened its doors in June 2013 and serves as a testing facility for products and services prior to deployment in the organization's field trials. Products are evaluated to ensure they perform as specified, can interoperate with other devices in the home, and that Pecan Street is able to get the required data from the device. Additionally, the installation process for each device that is to be field-deployed is tested at the lab. Pecan Street procured and installed a the lab a 30 kW lithium ion battery system, 5.5 kWh of roof-top mounted PV and a X natural gas generator to develop and test interconnection protocols for multi-fuel microgrids. The lab is used by Pecan Street's staff to undertake program-related research and development, and by companies interested in utilizing the lab for its affordable product testing services.

Overall, Pecan Street evaluated over 30 smart home technologies and collected over 200 billion data records during the project period.

II. Scope

Project Abstract

Pecan Street's goal is to develop and implement an open platform Energy Internet Demonstration in Austin, Texas. The Energy Internet is the smart grid of the future, in which information flows between the utility and its customers, a web of interconnection exists within the home or business though devices embedded with intelligence that enable real-time management of the home's consumption and that enable aggregated energy management by the utility, enabling utilities to more efficiently balance demand and supply with clean energy sources without disrupting their customer's quality of life. The Energy Internet enables distributed energy production and management, enabling residences and businesses to play a more proactive role in their relationship with utilities, often referred to now as 'prosumerism.'

The objective of this project is to develop and implement an open-platform Energy Internet, that uses open ADR communication standards rather than relying on proprietary standards or software. Establishing an open-platform Energy Internet is critical to accelerating innovation in the smart home and smart grid sectors. An open-platform approach allows for greater competition and reduces the cost barriers for new or small companies to enter the sector because they don't have to pay for or compete with proprietary software and standards.

The primary project location is the 711-acre Robert Mueller mixed-use redevelopment project in Austin, Texas. The project will leverage the significant green building penetration at Mueller along with Austin Energy's next generation Energy Internet-enabling systems (including 2-way meters, home Energy Control Gateways and smart thermostats).

Working with volunteer participants, the project team will use this technology platform to demonstrate and optimize grid integration of distributed clean energy generation, smart grid water systems, distributed storage, smart appliances, and plug-in electric vehicles. The project will also use these Energy Internet systems to compare different behavioral modification programs.

The ultimate purpose for this project is to develop energy and pricing systems that:

- Significantly reduce customers' and the electricity system's environmental impact
- Reduce per capita water usage
- Improve energy efficiency
- Provide greater value for customers
- Advance economic opportunities for the private sector
- Preserve the financial viability of utilities to carry out their grid management responsibilities. '

The Mueller community possesses utility interconnection, storage, distributed energy sources, critical loads, and conventional loads found in neighborhoods across the country. Every new building in Mueller is required to be green built, either certified through LEED or Austin Energy's nationally recognized Green Building program. The development is urban in-fill redevelopment, built on the site of Austin's former municipal airport. It is a prototypical urban infill development model, similar to hundreds like it across the United States. The Mueller development provides a dynamic platform on which to research, develop and demonstrate advances in home area networks, distributed energy generation and energy management techniques.

As part of the Smart Grid Demonstration, Pecan Street constructed and operates the Pike Powers Lab & Center for Commercialization located in the Mueller community. This lab opened its doors in June 2013 and serves two critical functions:

1. A testing laboratory for key technologies and systems that the Project team determines should first be tested in a carefully controlled setting on the distribution feeder serving Mueller prior to deploying in customer premises
2. A research facility for university faculty, graduate students and industry partners conducting research to improve understanding and develop impactful solutions in the areas of utility system operations, climate change, integration of distributed energy and storage, and customer needs and preferences

At Pecan Street's Pike Powers Commercialization Lab, companies test, commercialize, and verify performance of hardware and software that integrate smart grid, distributed generation (natural gas and solar PV), energy storage, building control, appliance control, algorithmic disaggregation, and wireless network technologies.

Designed and instrumented by a team composed of product development executives and researchers from The University of Texas, National Renewable Energy Laboratory and private industry, the lab is the only facility in the world where companies can test application performance under simulated conditions using actual customer electricity and gas use data. For example, developers of residential and small commercial natural gas fuel cells, disaggregation algorithms, electric and gas meter chipsets and home energy routers can test the performance of their products under second-to-second energy use simulations drawn from actual customer use.

Within the lab, Pecan Street can create a field-testing environment that allows for simulation of real-world conditions within a controlled system, enabling performance testing for specific variables. Lab testing of products prior to field deployment allows for troubleshooting in a controlled environment where installation, configuration, performance, and interoperability challenges can be identified, isolated, and fixed before installation in participants' homes or businesses. All products were tested in Pecan Street's lab prior to deployment in the field to avoid expensive and time-consuming troubleshooting within participant premises.

Product testing services at the lab include:

- Installation of products in real-world configurations, yielding step-by-step documentation for installers to ensure proper product installation and interoperability

- Documentation of the process for successfully pairing devices to meter and/or devices to gateway
- Testing for resiliency of data communications network
- Testing for adherence to device specifications, including up-time, data caching, product performance, and data quality

Prior to construction of the Pike Powers Lab & Center for Commercialization, Pecan Street rented a single-family home in Mueller that served as a temporary lab where products were tested prior to deploying systems within the broader base of participants. This home was prototypical for the Mueller neighborhood, and use of this space informed design of the Pike Powers Lab.

After technologies were deployed, the project collected and evaluated data in the areas of electricity generation, distribution, and consumption to determine the effects of integrating new technologies and controls in customer homes and the resulting impacts on distribution systems. Omnibus data on the participants is also collected for analysis through detailed online surveys. Throughout the project period, Pecan Street produced up-to-date analysis of on optimization of consumer-side smart grid technologies and the impacts of consumer behavior interventions on the residential demand for energy.

The dynamic impact of commercial energy management was also studied. Researchers used data from commercial buildings to examine changes in the electric system's performance with regard to reliability and power quality, environmental impact through reduced emissions and water use, and customers' experiences and preferences on the technology.

Smart grid systems utilized in this project include automated meter information, Automatic Meter Reading (AMR) and Advanced Metering Infrastructure (AMI) smart meters, HEMS, distributed generation systems, intelligent load control, and advanced billing platforms. These technologies were integrated with plug-in electric vehicles, smart appliances and solar PV in select homes to study the impacts and optimal configuration of distributed generation assets. The project also integrated smart water and natural gas technologies in a subset of participating homes. Finally, the Project team tested system integration requirements for energy storage.

Team Members

Pecan Street's project team was composed of Pecan Street's staff, partners providing cost share, grantee sub-recipients, and Pecan Street's Industry Advisory Council and Research Consortium members who provided valuable insights into the project design, implementation, and results analysis. Some organizations were involved in the project in multiple ways. Pecan Street's unique industry-university consortium approach to carrying out the research activities under this funding opportunity yielded unique project insights and benefits.

The functional work of the project was carried out by the following program teams, each of which was managed by a project executive:

- Utility-side of the meter systems: Pecan Street executive lead is the Lab Director. Team co-leads are with UT and Austin Energy.
- Customer-side of the meter systems: Pecan Street executive lead is the Project Manager. Team co-leads are with Austin Technology Incubator (ATI) and UT.
- Data Team: Pecan Street executive lead is the Data Group Director. Team co-leads are with Austin Energy, EDF and UT.
- Pricing and Commercialization: Pecan Street executive lead is the Chief Executive Officer. Team co-leads are ATI and Austin Energy.
- Interoperability and Cyber Security: Pecan Street executive lead is the Chief Technology Officer.

Subrecipients

The sub recipients on Pecan Street's Smart Grid Demonstration Project include Austin Technology Incubator, The University of Texas at Austin, and the National Renewable Energy Laboratory.

Austin Technology Incubator

The Austin Technology Incubator (ATI) is the startup incubator of the University of Texas at Austin. A program of UT's IC^2 Institute, an interdisciplinary research unit that focuses on innovation, creativity and capital, ATI has a 25-year track record of helping start-up teams achieve success. ATI runs incubation programs in the Bio/Healthcare, Clean Energy, and IT/Wireless sectors. The Clean Energy incubator worked most closely with Pecan Street on implementation of the grant objectives, with the IT/Wireless team providing insight on selection and performance of IT technologies.

ATI provided valuable commercialization services in support of the project's required commercialization plan. The support provided by ATI included:

- Providing consulting to smart grid and clean energy-focused independent emerging technology firms and entrepreneurs licensing or developing University of Texas technology, in areas such as:
  - IP protection

  - Market identification
  - Technology testing
  - Management structure
  - Equity funding (venture, angel, bootstrap), grant funding and debt funding
- Hosting an annual Clean Energy Venture Summit, which merged with SXSW Eco in 2012, with a dedicated focus on smart grid and clean energy technologies.
- Creating and holding an annual smart grid/clean energy short course open to the community, held in partnership with Pecan Street Inc. and the Webber Energy Group.
- Managing a program through which selected emerging technology firms can beta test their systems at Pecan Street's lab and in its field trials.
- Providing insight into emerging technologies and start-up companies with technologies relevant for Pecan Street's research and development work.

The University of Texas at Austin

The University of Texas (UT) is the nation's second largest Tier 1 research institution, with a long track record of federally supported research. Pecan Street worked closely with UT's Engineering Department throughout the course of the project. The following faculty members and graduate researchers provided significant guidance, research, and analysis throughout the project period:

Dr. Thomas Edgar

Prof. Thomas Edgar, The George T. and Gladys H. Abell Chair in Engineering and Director of UT's Energy Institute, served as the project's Principal Investigator, responsible for the overall administration and direction of the project, including scientific focus, experimental design, and publication of research findings. Dr. Edgar has also served as an unpaid member of Pecan Street's board of directors since the organization's founding in 2009.

Dr. Michael Webber

Dr. Webber is head of the Webber Energy Group at UT, Assistant Director of the Energy Institute and host of PBS's Energy at the Movies. The Webber Energy Group includes approximately 30 student researchers and focuses on analyzing energy and environmental problems at the intersection of engineering, science and public policy. The Webber Energy Group's research is focused in four broad areas: the energy-water nexus, energy systems modeling, alternative transportation fuels, and the nexus of food, waste and energy. Dr. Webber also shared the responsibilities for the overall administration and direction of the project, including scientific focus, experimental design, and publication of research findings, he additionally served as the co-lead on the project team's data collection and evaluation program, and provided expertise in the area of water and energy interactions.

Through his various roles at UT, Dr. Webber and his students provided critical project guidance and support, including:

- Design of Pecan Street's annual sociodemographic survey
- Review of Pecan Street's field trials to ensure compliance with academic research standards
- Review of Pecan Street's energy audit template
- Analysis of over 5,000 energy audits performed and reported to Austin Energy as part of the City of Austin's Energy Conservation & Disclosure Ordinance
- Collaborate on design of the annual smart grid/clean energy course
- Provide project data review and analysis
- Publication of peer-reviewed articles that used project data to further public interest research in the areas of: electric grid resilience and reliability, climate change mitigation and adaptation, smart grid design, and behavioral economics

Dr. Webber and several of his students, along with members of Pecan Street's staff, produced a seminal article, "Experimental and Data Collection Methods for a Large-Scale Smart Grid Deployment," published in *Energy volume 65 (2014), 462–471,* DOI: 10.1016/j.energy.2013.11.004. This article documents Pecan Street's data collection methodologies and how these can be replicated for similar large-scale smart grid demonstrations.

Additional publications and conference presentations that Dr. Webber produced using data generated by Pecan Street:

- C.M. Meehan and M.E. Webber, "Using A Novel Unit Commitment and Dispatch Model to Estimate Bulk Power System Emissions Impacts from Increased Electric Vehicle and Renewable Energy Usage," Energy Policy (In Review).
- C.B. Harris and M.E. Webber, "An empirically-validated methodology to simulate electricity demand for electric vehicle charging," Applied Energy, 126, pp. 172{181 (2014).
- C.B. Harris and M.E. Webber, "A temporal assessment of vehicle use patterns and their impact on the provision of vehicle-to-grid services," Environmental Research Letters 7 034033(9pp) (2012).
- C.B. Harris, J.P. Meyers, and M.E. Webber, "A unit commitment study of the application of energy storage toward the integration of renewable generation," Journal of Renewable and Sustainable Energy, Volume 4, Issue 1 (20pp) (2012).

- B.C. Roberts, M.E. Webber and O.A. Ezekoye, "A Multi-objective Fire Safety and Sustainability Screening Tool for Specifying Insulation Materials," ASME 2014 International Mechanical Engineering Congress & Exposition, November 1420, 2014. Montreal, Quebec, Canada.
- C.B. Harris and M.E. Webber, "The Sensitivity of Vehicle-To-Grid Revenues to Plug-In Electric Vehicle Battery Size and EVSE Power Rating," Proceedings of the IEEE Power and Energy Society (PES) General Meeting, National Harbor, MD, July 27-31, 2014.
- E.M. Keys and M.E. Webber, "Variable Speed Drives for Power Factor Correction in the Water Sector," The 5th International Symposium on Power Electronics for Distributed Generation (PEDG) Systems, IEEE, June 24-27, 2014, Galway, Ireland.
- W.J. Cole, K.X. Perez, J.D. Rhodes, M.E.Webber, M. Baldea, and T.F. Edgar, "Community-Scale Air Conditioning Control for High Penetration of Rooftop Photovoltaics," 2014 American Control Conference, IEEE Control Systems Society, Portland, Oregon, June 4, 2014.
- C.B. Harris and M.E. Webber, "The impact of vehicle charging loads on frequency regulation procurements in ERCOT," Proceedings of the 2014 IEEE Power & Energy Society (PES) Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, February19-22, 2014.
- C.B. Harris and M.E. Webber, "Quantifying the Effect of Plug-In Electric Vehicles on Future Grid Operations and Ancillary Service Procurement Requirements," ASME 2013 International Mechanical Engineering Congress & Exposition, November 13-21, 2013, San Diego, CA, USA.
- J.B. Kjellsson, David Greene, Raj Bhattarai, and M.E. Webber, "Energy Benchmarking of Water and Wastewater Treatment, Distribution and Collection: Case Study of Austin Water Utility," ASME 2013 International Mechanical Engineering Congress & Exposition, November 13-21, 2013, San Diego, CA, USA.
- J.D. Rhodes and M.E. Webber, "Smart Grid, Smart Water: Real-Time Water Use Data From a Community in Austin, Texas," ASME 2011 International Mechanical Engineering Congress & Exposition, November 11-17, 2011, Denver, CO, USA.
- J.D. Rhodes and M.E.Webber, "Smart Grid in Texas, What's Happening?" 2012 ASHRAE Annual Conference, San Antonio, TX, June 27, 2012.

Dr. Alexis Kwasinski

Dr. Kwasinski shared the responsibilities for the overall administration and direction of the project, including scientific focus, experimental design, and publication of research findings. Dr.

Kwasinski provided expertise to the project on power system performance, design, and operation of smart grids.

Dr. Kwasinksi's provided specific project guidance on microgrid design, ultra-reliable and fault-tolerant power systems, efficient electrical energy conversion and storage, and electric grid resiliency following natural disasters. Along with his student, Harsha Kumar, Dr. Kwasinski also oversaw performance testing of home energy monitoring systems in his lab at UT and oversaw procurement and use of equipment purchased for UT's use through this DOE grant. In 2014, Dr. Kwasinski moved to the University of Pittsburgh.

Dr. Ulrich Dangel

Professor Dangel's research and teaching focuses on embedding the application of technology into the design process, advancing design-based learning approaches in technology courses, and educating students on the importance of architectural detailing. He is the recipient of the 2005-2006 School of Architecture Teaching Award for outstanding teacher, the 2007 Texas Exes Teaching Award, the 2007-2008 ACSA/AIAS New Faculty Teaching Award, the 2007-2008 School of Architecture Teaching Award for outstanding teacher, and the 2008-2009 Regents' Outstanding Teaching Award. Ulrich Dangel's book "Sustainable Architecture in Vorarlberg: Energy Concepts and Construction System" was published by Birkhäuser Basel in December 2009.

Professor Dangel provided design services for Pecan Street's lab and insights into innovative building attributes for energy efficiency.

Dr. Matt Fajkus

Professor Fajkus, a Fellow of the Center for Sustainable Development at UT, is co-director of the University of Texas School of Architecture's state-of-the-art Thermal Lab, an interdisciplinary design tool that tests the thermal and light properties of full-scale facade mock-ups as part of a larger body of building envelope research. He is a co-principal investigator and has received grant funding for the Smart Building Initiative, an innovative program designed to perform energy analysis and maintain a direct user interface in Sutton Hall on the UT campus.

In a collaborative effort with Dr. Ulrich Dangel, Dr. Tamie Glass and Dr. Atila Novoselac, Dr. Fajkus helped design the Pike Powers Commercialization Lab.

Dr. Robert Hebner

Dr. Hebner serves as Director of UT's Center for Electromechanics (CEM), a leading applied research unit. Researchers at the Center are recognized for expertise in advanced energy storage and power generation rotating machines for both intermittent and continuous duty applications. For the past four decades, CEM has served as a key contributor to the University's success in research, education, and service to the community.

CEM researcher Dr. Fabian Uriarte provided support to this project through creation of distribution system modeling concepts and by supporting interaction with industry. CEM also provided guidance on configuration options for energy storage integration and analysis of community energy storage costs and benefits.

Graduate Student Researchers

In addition to providing support for UT faculty students, Pecan Street provided funding to support 4 graduate students in each year of the study period. The following PhD candidates worked closely with the project team throughout the project performance period and actively participated in analysis and publication of project results:

Dr. Joshua Rhodes

Dr. Rhodes received his Doctorate degree in Civil, Architectural, and Environmental Engineering from the University of Texas at Austin in 2014. Beginning in 2011, he worked closely with the project team on characterization of project data quality, analysis and reporting. Dr. Rhodes is currently a post-doctoral fellow at the Energy Institute where he continues his research is in the area of residential smart grid applications, including system-level applications of energy efficiency and distributed generation.

Dr. Rhodes produced a large body of research utilizing Pecan Street's data throughout the project period including:

Papers submitted or in preparation:

- Upshaw, C.R., Joshua D. Rhodes, and Michael E. Webber, "Modeling peak load reduction and energy consumption for an integrated thermal energy and rainwater storage system for residential air conditioning systems in Austin, Texas," *Under review at Energy and Buildings.*
- Rhodes, J.D., Nour-El Imane Bouhou, Charles R. Upshaw, Michael F. Blackhurst, and Michael E. Webber, "The measured effect of residential energy retrofits in a cooling climate," *In prep.*
- Harris, C.B., Joshua D. Rhodes, and Michael E. Webber, "Quantifying the effect of geographic distribution for mitigating variability from high penetrations of renewable generation," *Abstract accepted to ASME 2014 International Mechanical Engineering Congress and Exposition,* November 14-20, 2014, Montreal, QC, Canada.
- Rhodes, J.D., Chioke B. Harris, Charles R. Upshaw, and Michael E. Webber, "Using multiple fixed solar arrays to mimic the output of tracking arrays" *In prep.*

Published peer-reviewed journal articles:

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- Cole, W.J., Joshua D. Rhodes, Krystian X. Pereza, Michael E. Webber, Michael Baldea, and Thomas F. Edgar, "Community-scale Air Conditioning Control for High Penetration of Rooftop Photovoltaics," *The 2014 American Control Conference,* June 04-June 06, 2014, Portland, Oregon, USA.
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- Rhodes, J.D, Brent Stephens, Michael E. Webber, Energy audit analysis of residential air-conditioning systems in Austin, Texas, *ASHRAE Transactions* 118 (1) (2012) 143–150.

Charles R. Upshaw

Charles Roberts Upshaw is a Mechanical Engineering PhD student at the University of Texas at Austin, studying the interaction of electricity, thermal energy, and water in residential houses. He received both his BS (May '10) and MS (May '12) in Mechanical Engineering, also from the University of Texas, where he was honored with the Engineering Outstanding Scholar-Leader Award when he graduated in May 2010 (that recognition is awarded to the top student out of the entire Cockrell School of Engineering). During his undergraduate career, he was active in the student chapter of ASME at UT, including service as its President. Charlie worked closely with the project team on data characterization, analysis and research.

Charlie produced four academic publications that utilized data Pecan Street collected through this project:

- Upshaw, Charles R., Joshua D. Rhodes, and Michael E. Webber "Optimizing Rainwater, Gray Water, and AC Condensate Collection System Designs to Maximize Water and on-Peak Energy Efficiency in Residential Buildings," 2015 *ASHRAE Winter Conference*, Chicago, IL, January 24–28, 2015.
- Upshaw, Charles R., Joshua D. Rhodes, and Michael E. Webber, "Modeling a Combined Energy-Water Storage System for Residential Homes and Analyzing Water Storage Tank Size." *ASME IMECE 2013* (conference paper)
- Upshaw, Charles R. "Modeling Peak Load Reduction and Energy Consumption Enabled by an Integrated Thermal Energy and Water Storage System for Residential Air Conditioning Systems in Austin, Texas." Energy and Buildings (journal paper, in Review)
- Upshaw, Charles R. "Estimating Water Savings from an Auxiliary Water Collection System, as Part of an Integrated Thermal Energy and Water Storage System for Residential Buildings." *ASHRAE Winter Conference 2015* (conference paper)

Robert L. Fares

Robert is a PhD student in the Department of Mechanical Engineering at The University of Texas at Austin. As part of Pecan Street Inc.'s ongoing smart grid demonstration project, Robert's research looks at how energy storage models can be used with large-scale data and optimization for economic operational management of batter energy storage. Robert's PhdD research seeks to analyze the cost-benefit tradeoffs of grid-connected battery energy storage. Because the present grid has essentially no capacity to store electricity, grid-based energy storage has numerous opportunities to reduce the cost of electricity, improve the grid's reliability and integrate intermittent forms of renewable energy. At the same time, many energy storage technologies are cost prohibitive at this time and have uncertain emissions and energy footprints.

To understand the cost-benefit tradeoffs of using battery energy storage, Robert connects control-oriented battery models with optimization and economic analysis to show how battery storage could participate in Texas' wholesale electricity market. He also uses Pecan Street's high-resolution electricity data to quantify the benefits of adding electricity storage at the grid's distribution level.

Publications and conference papers produced by Robert Fares using Pecan Street data include:

- R.L. Fares and M.E. Webber, "Life Cycle Greenhouse Gas Emissions From Lithium-Ion Grid Energy Storage," Environmental Science and Technology (In Review).
- R.L. Fares and M.E. Webber, "Combining a dynamic battery model with high-resolution smart grid data to assess microgrid islanding lifetime," Applied Energy 138 p. 482{489 (2015).
- R.L. Fares and M.E. Webber, "A flexible model for economic operational management of grid battery energy storage," Energy (2014).
- R.L. Fares, J.P. Meyers, and M.E.Webber, "A Dynamic Model-Based Estimate of the Value of a Vanadium Redox Flow Battery for Frequency Regulation in Texas," Applied Energy 113, Pages 189{198 (10pp) (2014).
- R.L. Fares and M.E. Webber, "Dynamic Modeling of Community Energy Storage for Life-time Estimation during Islanding," 223rd ECS Meeting in Toronto, Ontario, Canada (May 12-16, 2013).

National Renewable Energy Laboratory

National Renewable Energy Laboratory (NREL) is a Federally Funded Research and Development Center (FFRDC) that provided consultation services to Pecan Street on the design and instrumentation of Pecan Street's lab. NREL's project team visited Pecan Street's research testbed in Austin and conducted face-to-face meetings with the project team to understand the goals and objectives for the lab. NREL's team, led by Bill Kramer, worked closely with Pecan Street's technical team to review and refine building and technical specifications for the lab, helping to ensure the building would serve its purpose as a state-of-the-art testing facility. Through an iterative review process, the NREL team reviewed the design, specifications and equipment lists for the lab and provided input that was taken into account in the lab's construction.

Cost Share Partners

Austin Energy, Environmental Defense Fund, Austin Technology Incubator, and The City of Austin.

Austin Energy

Austin Energy is the nation's 8th largest publicly-owned electric utility, serving more than 420,00 customers with more than 1 million residents in a service area of over 437 million square miles. Austin Energy is a political subdivision of the City of Austin (the City Manager appoints the General Manager, and the City Council serves as the utility's board of directors). Therefore, while Austin Energy is an enterprise organization regulated by the Texas Public Utility Commission, its cost share is technically provided through the City of Austin as well.

Austin Energy's cost share is provided to perform these project functions:

- Build the electrical distribution system at Mueller required to carry out the demonstration project
- Deploy the customer information software system needed to integrate billing into electrical distribution management, and specially configure that software system for this project to enable the testing of consumer behavior interventions, pricing models and demand response
- Provide professional utility and legal services for carrying out the project's research and development work

In addition to the electric distribution infrastructure that Catellus is deploying to connect to distribution trunk lines, Austin Energy will construct new distribution feeder infrastructure at Mueller. Austin Energy is modifying the design and functionality of this infrastructure to incorporate the systems being deployed through this demonstration project.

Austin Energy, in partnership with IBM and Oracle, is designing and deploying an enterprise scale Customer Information System. Austin Energy and the project team are modifying this system at Mueller make it possible to deploy multiple pricing systems and collect data from participating customers in up to 15-minute increments. An additional component of Austin Energy's cost share is implementation of the CIS that enabled the utility to share 15-minute interval meter data for participants who signed a release authorizing AE to share their meter data with Pecan Street. Austin Energy staff provided batch files to Pecan Street containing this data.

Austin Energy employees also dedicated considerable employee time to this project. For example, Austin Energy employees served as co-leads of the Utility Side of the Meter, Data and Pricing and Commercialization Teams, attended quarterly workshops with the Industry Advisory Council members and university researchers, attended technical meetings as needed, and provided guidance on connection of distributed energy, energy storage and smart home technologies.

Austin Technology Incubator

As cost share, ATI commercialization officers provided additional commercialization services to the project team and provided foregone indirect costs as part of their relationship with The University of Texas at Austin.

ATI's Director Isaac Barchas and Clean Energy Incubator Co-Directors Mitch Jacobson and Michael Webber worked closely with the project team to identify relevant emerging technologies, provide guidance on technology review and testing, and guidance on commercialization activities.

City of Austin

The City of Austin and its municipally owned utility, Austin Energy, are performing three core project functions:

- Building the electrical distribution system at Mueller that is required to carry out the demonstration project
- Deploying the customer information software system needed to integrate billing into electrical distribution management, and specially configuring that software system for this project to enable the testing of multiple pricing models – none of which are currently deployed by Austin Energy
- Providing project management services for the development of Mueller and altering the project plan to integrate this demonstration project into the project management plan
- Providing professional utility and legal services for carrying out the project's research and development work

The City of Austin provided project management services for the development of Mueller, which enabled integration of this demonstration project into the community build-out. City of Austin employees also coordinated with the project team to provide updates on build-out timeline, guidance on interconnection of community energy storage and community distributed generation systems, and technical information on community infrastructure required for technology impact modeling.

Environmental Defense Fund

Environmental Defense Fund (EDF) provided third party environmental verification of environmental benefit of demonstrated systems. It also provided guidance on development of smart grid clean energy systems to optimize economic and environmental outcomes. EDF employees served as co-leads on two project teams: the Customer Side of the Meter team and the Data team.

Additionally, EDF completed an emissions analysis of greenhouse gas emissions avoided through the deployment of distributed generation systems and electric vehicles within this project.

The University of Texas

The Principal Investigator and each of the faculty receiving funding from the project will contribute 11% of their academic appointment, which equates to one month of effort for each year of the project. Contributed salary and fringe benefit amounts are indicated in the detailed budget. UT also contributed the indirect rate value of its total cost share.

Industry & Academic Partners

Industry Advisory Council

In 2011 Pecan Street establish an Industry Advisory Council (IAC) to provide critical industry insight into emerging technologies, demonstration design requirements, and research questions. IAC members serve for a period of one-year, with the option to annually renew membership. Throughout the course of the project performance period, the IAC has included Intel, Shell, Landis+Gyr, LG Electronics, Sony, 3M, GM/OnStar, Whirlpool, Texas Gas Services, Xerox PARC, Alliander, Austin Energy, Best Buy, Oncor Energy, Schneider Electric, Siemens and San Diego Gas & Electric.

Research Consortium

The anonymized data from our volunteer participants' home electricity use, solar panel performance, electric vehicle charging, and response to utility programs has become the world's largest research database of customer water and disaggregated electricity insight. This unique research network data is at the core of Dataport, an online portal accessible to registered users via Pecan Street's website, which makes the terabytes of customer data accessible, manageable, visible and usable for university researchers around the world. Currently researchers from more than 50 universities in 12 countries have joined.

The Research Consortium is led by the five members of our Data Advisory Board:

- Dr. Zico Kolter, Assistant Professor, School of Computer Science, Carnegie Mellon University
- Dr. Inês Azevedo, Associate Professor, Department of Engineering and Public Policy, Carnegie Mellon University
- Dr. Michael Baldea, Assistant Professor, Department of Chemical Engineering, The University of Texas at Austin
- Dr. Duncan Callaway, Assistant Professor, Energy and Resources Group, The University of California, Berkeley
- Dr. Marta C. González, Assistant Professor, Civil and Environmental Engineering, MIT

Project Overview

The Pecan Street Smart Grid Demonstration Program at Austin's Mueller community is a collaborative effort of Pecan Street, private sector firms and the Project team. Pecan Street leads the demonstration project.

The Project team has chosen to base system designs and implementation on open platform principles. With the breadth of technologies and functions involved in integrating customer-premise technologies and systems with the traditional utility-side of the meter systems, maintaining interoperability not only within the demonstration project itself but with evolving standards and specifications in the broader smart grid community is paramount.

As with the internet and the subsequent convergence of the telecom and information technology sectors, creating a distributed, networked electricity system with open protocols has the potential to catalyze significant economic opportunities. Such a system also faces significant security and privacy challenges. Cyber security for such a system must ensure confidentiality, availability and integrity of information and systems for newly developed technologies and innovative methods for managing smart grid functions. The cyber security approach must also address the challenges of customer-premise hardware integration with the distribution management system. Demonstrating that systems operating on an open platform can be effective, interoperable and secure is a major criterion for project success.

Working with volunteer participants, the Project team will demonstrate and optimize integration of customer-side of the meter systems along with deployment of utility-side of the meter energy monitoring systems. The project has also deployed and is comparing different consumer behavior interventions, including Time-of-Use (TOU) pricing.

Project Objectives

1. Create an interoperable, standards-based technical approach that can be integrated into other systems with minimal additional engineering and design.
2. Establish a cyber security protocol that allows for interoperability of systems without risking the security and privacy of participants.
3. Demonstrate and optimize integration of customer-side smart grid systems along with deployment of utility-side of the meter energy monitoring technologies on the distribution feeders serving Mueller.
4. Deploy and compare different consumer behavior interventions, including pricing models and features, to identify a menu of options that incentivize investments in smart grid systems without jeopardizing utilities' revenue stream.
5. Construct and operate a lab located in the Mueller community that will serve as a testing laboratory, public education and research facility. The lab will enable the Project team to test key technologies and systems in a carefully controlled setting on the distribution feeder serving Mueller prior to deploying in customer premises.

Timeline

Pecan Street created and updated its Project Management Plan, included as Appendix A, to ensure all milestones were completed on schedule and within budget.

Key Project Milestones

Table 1 shows the project milestones and timeline identified in this program's Project Management Plan, including a generalized schedule for when the milestones are expected to be met and the actual completion date, as applicable.

Table 1. Project Milestones

Title	Planned Completion	Actual Completion
Complete Updated Project Management Plan	12/04/2010	12/07/2010
Complete Metrics & Benefits Plan	02/04/2010	06/22/2011
Sign up 1,000 homes and 25 commercial properties to participate in demonstration	12/01/2011	08/31/2012
Acquire leases/access rights to commercial space for PV installation	03/01/2011	11/9/2012
Select solutions and technologies for deployment in demonstration project	05/01/2011	09/30/2011
Design behavioral trials	08/31/2011	08/31/2011
Acquire plug-in electric vehicles for deployment in participant homes	09/01/2011	09/30/2012
Open Lab to the public	01/01/2012	06/11/2013
Complete baseline data collection	02/01/2012	02/1/2012
Deploy selected solutions	02/01/2012	11/30/14
Complete data collection from demonstration	11/02/2014	11/30/14
Dismantle demonstration systems	02/05/2015	02/05/2015

Key Decision Points

Decision points were used by the project team and DOE to assess the technical status, results, funding requirements, programmatic needs, and relevant risk factors of the project. The success criteria at these decision points was used to assess achievement of specific goals which were typically at the end of each phase or at appropriate points in the project execution.

The project scope was initially divided into the following three phases with decision points between phases:

- Phase I – Project Definition and NEPA Compliance
- Phase II – Design and Construction

- Phase III – Operation

Decision Point 1 – Planning and NEPA Compliance

- Updated PMP completed and approved by DOE
- NEPA Environmental Questionnaires completed and approved by DOE
- Interoperability & Cyber Security Plan completed and approved by DOE
- Metrics & Benefits Plan completed and approved by DOE

Go/No-Go Decision Point 1 – End of Phase I

- Required documents submitted to, and approved, by DOE
- Project efforts on schedule and within budget

Decision point 2 – Design and Installation

- Establish field trial
- Perform baseline study
- Construct lab
- Integrate pricing and behavioral trials
- Quarterly build metrics provided to DOE

Go/No-Go Decision Point 2 – End of Phase II

- Field trial established with residential and commercial participants
- Technologies for deployment procured
- Project efforts on schedule and within budget

Decision Point 3 – Operation and Analysis

- Data collected for 24 months
- Quarterly build metrics and other information, as requested, provided to DOE
- Interim TPRs provided to DOE
- Final report provided to DOE

Go/No-Go Decision Point 3 – Mid-Phase 3

- Data reporting from systems as expected
- Submitted reports approved by DOE

Technologies and Systems Demonstrated

To create the Energy Internet, Pecan Street deployed packages of established and emerging consumer technologies in the homes and businesses of participants. The technologies collectively simulate the neighborhood of the near future in which utilities are balancing a significantly changing residential energy consumption profile, driven by new technologies like electric vehicles and energy efficiency technologies, with often-unpredictable and unreliable customer-owned distributed generation resources. Deployed systems utilize the participant's broadband Internet for communication between devices and with Pecan Street's data servers, sometimes aided by a Power Line Communications (PLC) device.

Through this demonstration, Pecan Street deployed and collected data from the following suite of customer-oriented smart grid technologies.

Home Energy Management Systems

HEMS, with in-home displays, online portals, and/or smart phone/tablet apps, provide real-time feedback to customers regarding their energy use, the cost equivalent of kilowatt-hours used and estimated bills, enabling users to more readily manage their energy consumption. The project team theorized that providing this data in near real-time to participants may result in significant and measurable peak energy use reductions.

The HEMS also provide a critical research function by providing the project team with granular, near real-time data on energy consumption and generation, when PV is present, from the homes and businesses of participations. The HEMS deployed by Pecan Street provide data on the whole home, 8-24 individual circuits within the property, and PV generation when relevant. This data became the foundation of Pecan Street's research.

Smart Meters

Smart meters, an important component of a smart grid system, record electricity consumption and communicate that information to the utility for monitoring and billing purposes. AMI smart meters enable two-way communication between the meter and the central utility, and between the meter and smart devices within the home. In addition to enabling the utility to provide better customer service through notification of outages and problems, smart meters have the potential to evolve the utility's relationship with its customer by allowing homes to participate in grid balancing services through programs such as demand response and dynamic pricing.

Austin Energy, which operates the grid at the demonstration site, completed one of the nation's first and largest smart grid deployments in 2009. It is a first generation smart grid encompassing over a million customers, 440 square miles, 500,000 devices and 100 terabytes of data. AE is a member of the GridWise Architecture Council, has played an active role with the NIST and the Electric Power Research Institute (EPRI) in the definition of the Interim Smart Grid Standards.

Most smart meters involve real-time or near real-time sensors, power outage notification and power quality monitoring. Pecan Street elected to include Advanced Metering Infrastructure (AMI) smart meters as a critical component of its study because the project team theorized they would play an important role in the relationship between utilities and their customers, and that many of the expected benefits of AMI meters, such as sending demand response signals to smart devices within the home and enabling Non-Intrusive Load Monitoring that provides a low-cost service to help customers better manage their energy load, would need to be evaluated and the process to achieve those benefits refined.

Smart Grid Water Systems

Smart grid water systems enable the development of a water monitoring and management network. The installation of these meters can result in time-of-use billing, convey end-use information to consumers and the utility, and provide the possibility of remotely operated controls for water-intensive activities, such as automatic shut-off when a leak is detected between the home and the meter.

Providing real time use information to consumers may lead to water conservation of 5-15 percent, resulting in related energy savings for water distribution and in-home hot water uses. Reducing peak water demand may lead to improved electrical system reliability and peak electric demand reduction by reducing associated energy use.

To investigate the ability for smart water systems to reduce peak electricity demand, Pecan Street conducted a market evaluation of smart water meters and undertook research on the energy savings potential of gas versus electric-powered hot water heaters and instant versus tank electric-powered hot water heaters.

Distributed Solar Photovoltaic Energy

Solar Photovoltaic (PV) energy is the fastest growing form of distributed energy in the country. With adoption of PV distributed generation (DG) on the rise, Pecan Street theorized that customer-sited DG would play a critical role in the smart grid with a suite of potential benefits and challenges for the utility.

Pecan Street's research focused on two aspects of residential PV systems. First, the project team investigated the optimal installation configuration that would maximize utility and customer benefits. Second, the project team analyzed the grid impacts of dense deployments of PV generation within neighborhoods. The project team theorized that dense deployments of PV generation would result in minimal impact on utility grid infrastructure, and that west-facing solar power generation would best align with peak energy demand, which occurs in Texas in the summertime between the hours of 4-7pm.

Plug-In Electric Vehicles

Plug-in electric vehicles are gaining popularity in the marketplace and, depending on when electric vehicles are charged, could have a significant impact on the electric grid. Electric vehicle adoption is following a standard technology adoption curve and it is anticipated that electric vehicles will become a more common household purchase. Plug-in electric vehicles therefore have the potential to significantly alter the residential demand profile.

Through study of electric vehicle adoption in major markets, it is apparent that the adoption trend will result in dense networks of electric vehicles focused within specific neighborhoods. The project team theorized that the impacts of electric vehicle charging is therefore anticipated to be most pronounced on transformers and distributions feeders. The behavioral economics and consumer preferences driving purchase of EVs and vehicle charging patterns were studied to analyze the effects on the grid of greater electric vehicle adoption and effective mechanisms to reduce electric vehicle charging during peak demand times. Two electric vehicles were purchased by the project for use at the Lab to create and evaluate hardware and software systems that provide remote and/or intelligent control of the charging.

Distributed Energy Storage

Battery storage could serve as the link allowing the use of renewable energy during any time of day, not just when the sun is shining or the wind is blowing, and stabilizing grid demand throughout the day. The project team theorized that integration of battery storage will play a critical role in balancing the power demands and power quality of homes with distributed generation. To accelerate the adoption of energy storage, the project team studied optimization of sizing of battery storage system sizing, integration of storage within the home, and connection of storage to the grid. Pecan Street worked in partnership with Sony to test installation guidelines and interconnection procedures at residential premises, and installed a 30 kWh battery system at its Pike Powers Lab to explore and test integration and control solutions.

Table 2. Energy Storage Applications and DOE Smart Grid Functions by Project

Application	Applicability to Project
Energy Storage Applications	
Electric Energy Time Shift	No
Electric Supply Capacity	No
Load Following	No
Area Regulation	No
Electric Supply Reserve Capacity	No
Voltage Support	No
Transmission Support	No
T&D Upgrade Deferral	No
Substation Onsite Power	No
Time-of-Use Energy Cost Management	Yes
Demand Charge Management	Yes
Electric Service Reliability	No
Electric Service Power Quality	No
Renewables Energy Time Shift	No
Renewables Capacity Firming	No
Wind Generation Grid Integration, Short Duration	No
Wind Generation Grid Integration, Long Duration	No
DOE smart grid function	
Fault Current Limiting	No
Wide Area Monitoring, Visualization, and Control	No
Dynamic Capability Rating	No
Power Flow Control	No

Adaptive Protection	No
Automated Feeder Switching	No
Automated Islanding & Reconnection	No
Automated Voltage and VAR Control	No
Diagnosis & Notification of Equipment Condition	No
Enhanced Fault Protection	No
Real-time Load Measurement & Management	No
Real-time Load Transfer	No
Customer Electricity Use Optimization	No

Behavioral Research Trial

Pecan Street's behavioral research trial was designed to improve understanding of the impacts that non-pricing intervention tools have on consumer behavior, as well as the relative effectiveness of these behavior-based tools at managing and shifting customer energy consumption. The project team was made up of Pecan Street staff and researchers from the University of Texas at Austin. Through a field intervention trial experiment conducted over a period of 20 months, the project has produced findings that document the relative efficacy of three different intervention measures on consumer electricity consumption behavior. More so, the project results provide some additional insights into vital utility-provider questions about the viability of behavior-modification tools such as: a) predictability of the change in customer electricity usage; b) relative costs of the tools both to customers and to utilities; c) complexity of implementing the tools both for customers and utilities; and d) impact on customer satisfaction.

Technology developed or procured and deployed for these experiments included:

- Online portal
- Mobile application
- SMS text messaging service

The online portal was selected by evaluating websites that offered customers value-added information on their electricity consumption data. The PlotWatt website was found to be superior because of its ease of use and visualizations used to display information. PlotWatt was willing to serve as a contractor to Pecan Street and develop a customized portal for participants that would integrate eGauge data as well as provide a platform of Pecan Street's design to conduct pricing and behavioral trials.

Pecan Street could not find a mobile application within the marketplace that met its needs, so the project team created one. The application is called Pumpkin Pie and is available for free on both Apple and Android devices.

Pecan Street used a SMS text messaging service to send demand response requests to participants in its behavioral research trials. The project team evaluated 5 online-based services and selected EZtexting.com for its competitive price, service level guarantee and superior features.

Technical Approach for Interoperability & Cyber Security

The Pecan Street Smart Grid Demonstration Program is largely a "Customer-Side" research project in which the existing Home Area Network (HAN), residential Internet gateway, and the Internet provide the foundation for the deployed systems. The Pecan Street Project Energy Internet Demonstration at Austin's Mueller community is a collaborative effort of Pecan Street Project Inc., The University of Texas, Austin Energy (AE), the National Renewable Energy Laboratory, Austin Technology Incubator, the City of Austin and private sector firms.

The project team has chosen to base system designs and implementations on open platform principles. This design decision brings multiple benefits, and also causes challenges in creating a secure, interoperable system. One of the project goals in creating an interoperable, standards-based technical approach is that it can be integrated with other systems with a minimum of additional engineering and design. With the breadth of technologies and functions involved in integrating customer-premise technologies and systems with the traditional utility-side of the meter systems, maintaining interoperability not only within the demonstration project itself but with evolving standards and specifications in the broader smart grid community is of paramount importance.

As with the Internet and the subsequent convergence of the telecom and Information Technology sectors, creating a distributed networked electricity system with open protocols has the potential to catalyze significant economic opportunities. Such a system also faces significant security and privacy challenges. Cyber security for such a system must ensure confidentiality, availability, and integrity of information and systems for newly developed technologies and innovative methods for managing smart grid functions. The cyber security approach must also address the challenges of customer-premise hardware integration with the distribution management system.

Interoperability and security will be tightly coupled activities for this project, and these joint activities must satisfy multiple requirements in both domains: interoperability requirements for transparency and clarity in system interfaces and relationships, and security requirements for resistance to attack, self-checking and self-protection, and system access control.

Demonstrating that systems operating on an open platform can be effective, interoperable, and secure is a major criterion for project success. The system architecture and interfaces for this demonstration project will be complex, and the challenge for both interoperability and security will be to manage this complexity and reduce the likelihood of failures in either area of concern.

Pecan Street's Chief Technology Officer Bert Haskell led the project team's Interoperability and Cyber Security Groups. Mr. Haskell's previous experience includes serving as Director of Product Development for Heliovolt (a thin film solar manufacturer), as Product Technology Strategist for Advanced Micro Devices and seven years as Vice President, Consumer Electronics Research, for the Microelectronics and Computer Consortium (MCC, the nation's first major technology consortium).

Interoperability

Pecan Street's Energy Internet Demonstration brought together a wide variety of devices and systems. A system that can handle a diversity of devices and sub-systems is fundamental to promoting a scalable, commercially dynamic Energy Internet. Because of this diversity, maintaining consistent operation requires interoperability of different platforms and applications.

To ensure that all deployed systems were interoperable, Pecan Street selected, tested, deployed, re-tested, operated and collected data from multiple applications.

The project team created an interoperability structure that applies to every application deployed. The interoperability requirements focus on two aspects of project management - standardized time-stamped data collection from multiple devices deployed in the home and communication of devices across the HAN.

Device interoperability was a frequent challenge faced by the project team. The team often employed open platform gateways to overcome the difficulty of incompatible implementations of existing communications standards. Most often the various incarnations of ZigBee Smart Energy Protocol caused issues. Inclusion of an open platform gateway, such as a Raspberry Pi, in the HAN emerged as an enabling interoperability structure that allows communication of multiple devices across various HAN protocols and across proprietary device implementations. The gateway serves as a highly distributed communications and computing resource that converts sensory and actuator data, very close to the source of the data, to encrypted standard

TCP/IP data traffic, reducing cost and complexity of system interoperability, enabling devices to communicate across the HAN and to report standardized data back to the database.

To meet the demonstration project's obligations to develop systems that are replicable and scalable and to promote the commercialization of emerging technologies, Pecan Street's database architecture, described in the Data Management section, serves as an open platform standards that is readily transferrable across commonly used database formats, enables integration of multiple information sources, and supports the National Institute of Technology and Standards (NIST) emerging smart grid framework.

Pecan Street's interoperability structure ensures that every deployed application is configured so that the project team can carry out the following critical project functions:

- Integrate multiple applications into a single functioning system
- Inventory monitoring of deployed applications
- Measure and evaluate the performance of deployed applications
- Provide remote software upgrades
- Detect and correct faults
- Document user interface and ease-of-use issues

Since Wi-Fi is firmly entrenched in the market as the HAN technology of choice, we believe it makes sense that these devices be able to connect to the HAN directly as Wi-Fi devices or by means of an adapter connected to the gateway either by wireless (Wi-Fi) or wired (Ethernet) means. This adapter may communicate with the utility device by any number of means including ZigBee, HomePlug, or a proprietary wireless/wired link. As long as the adapter can connect the utility device to the existing residential gateway, then a reasonable level of interoperability is maintained. We recognize that some vendors have residential gateways that have both Wi-Fi and ZigBee radios. We view this as a gateway with an integrated ZigBee adapter, and we have a preference for such dual radios HEMS.

The creation or adoption standard set of Application Programming Interfaces (API) along with a common data format standard will play an important role in allowing middleware and service providers to rapidly develop portal services for managing the utility appliances.

Information Exchange Interfaces for Communicating Devices

Figure 2 depicts the conceptual system architecture designed to ensure information exchange among deployed devices. For these applications, key information exchange interfaces were:

- The meter

- In-home display
- In-home appliances
- Gateway – both in the meter and in the premises
- Inter-gateway – between the meter and the premises gateway(s)
- The distribution system communication network

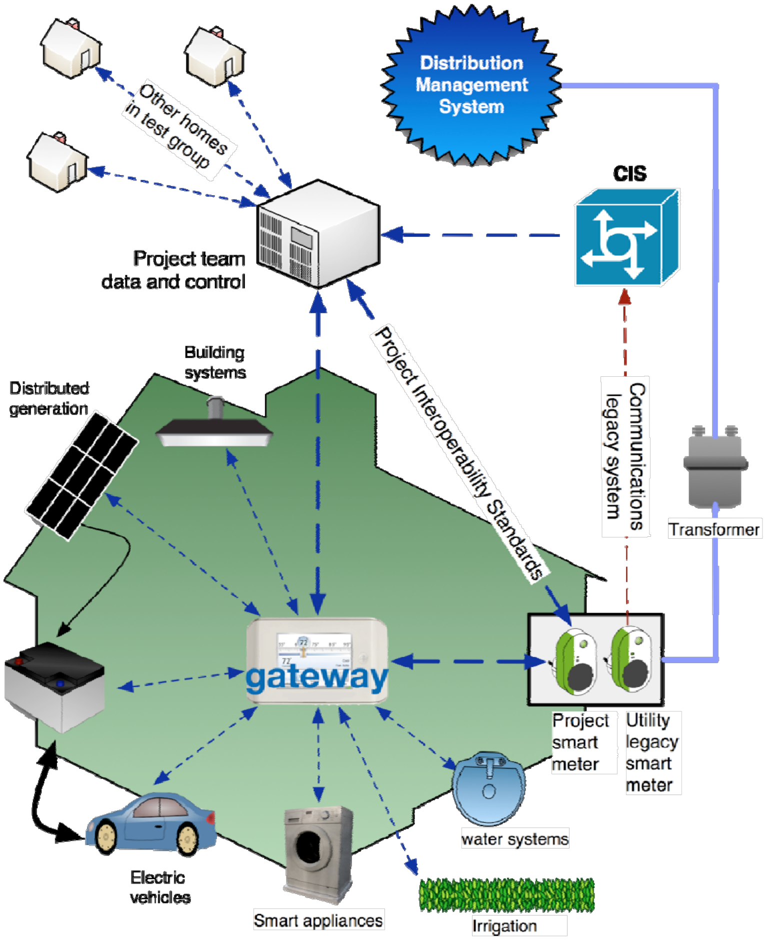


Figure 2. Overall network architecture

The customer-premises equipment communications medium could be either wired (one of the power line carrier standards such as HomePlug or IEEE 1901) or wireless (one of the wireless standards such as Wi-Fi or 802.15.4g).

The project's preferred approach was for the gateway to reside in the customer premises as a separate device from the meter. For deployments in this configuration, the meter required only two interfaces — one to the distribution system and one to the gateway. In that architecture, the gateway needed to support multiple home networking connectivity approaches. This led the project to favor modular designs not only for the gateways but also the appliances and in-home displays. Modular designs also make hardware upgrades more efficient.

If the gateway were to be integrated with the meter, the meter would have interfaces into the appliances in the home and the in-home display, and possibly a different interface to the distribution system. In this case there may need to be multiple interfaces in the customer-premises equipment to support multiple home networking standards. This approach increases complexity and system vulnerability, both for the customer as well as the grid operator.

Pecan Street employed standardized and openly available interface specifications for systems deployed as part of the demonstration project. Much as wireless Internet home systems integrate openly available communications standards (e.g., Wi-Fi, Bluetooth or cellular networks) into proprietary technologies through hardware or firmware (e.g., computers, video game systems, smart phones) or software, Pecan Street's project interoperability standard used open platform standards by which technologies from multiple suppliers can communicate and interact. Pecan Street's Cyber Security Plan ensures the data is protected from unwanted intrusions. Mueller is a relatively new development that is approximately half built. Austin Energy's legacy system in place at the demonstration site already has smart grid functionality with Automated Meter Reading (AMR). This legacy smart grid system was used as a baseline in parallel with other systems deployed for the demonstration, as depicted in Figure 2.

To enable communication between the meter and the in-home devices without disrupting the utility's ability to manage its meter network and bill customers, Austin Energy and Pecan Street installed a dual meter research network. In this configuration, a second utility-grade Advanced Metering Infrastructure (AMI) meter was installed on the participant's property on a dual socket. Landis+Gyr provided Pecan Street with an instance of its utility backhaul control system, Command Center, through which Pecan Street could collect data from these meters and send messages over them.

Austin Energy used the Pecan Street backhaul to test their over the air upgrade from AMR to AMI meters. Since a real-world test was needed for process verification, the Pecan Street backhaul provided the testbed for this rollout without risk to the utility. The meter firmware is being upgraded over the air and the billing meters aren't affected.

Because interfaces were based on certified industry standards as noted above, the potential existed to integrate legacy devices into the system by virtue of the backward compatibility nature of the certification programs.

Cyber Security

Pecan Street's Energy Internet Demonstration is largely a "customer-side" research project in which program did not install systems that interface with the utility's private network. The existing Home Area Network (HAN), the residential Internet gateway and the Internet provided the foundation for the systems deployed. This project did not install systems that interface with the utility's private network, so the scope of the cyber security plan was to provide an appropriate level of security for systems that interface with the HAN. The following cyber security plan was developed by Pecan Street in partnership with the Department of Energy's NETL and has been updated annually through an auditing process. The cyber security Plan provides an appropriate level of security for systems that interface with the HAN.

The cyber security protocols have been tested through the past four years of Pecan Street's operations. Compliance with this plan ensures that project participants' privacy and identity is protected. The organization has never been the subject of a successful cyber attack and its data has never been compromised. More importantly, the procedures outlined in this plan ensure that even if a hacker accessed and stole participant data, the security and privacy of our participants would not be compromised because it is impossible to link energy consumption data with personally identifiable information without physical access to the code key. All personnel with access to energy data and/or participant data are subject to a background check prior to beginning employment with the organization.

The system architecture and controls designed by the Pecan Street Project will create a system implementation that has a low risk from a cyber security perspective, provided the architecture and controls are adhered to.

Our plan is to a conduct a semi-annual project cyber security audit to make sure that the systems deployed maintain a "low risk" assessment. These audits will be conducted under the supervision of the Pecan Street Project Industry Advisory Council. The projects Technology Director, Bert Haskell, will be accountable to the Industry Advisory Council for the cyber security of the project.

The audit will include, but is not limited to, the following actions:

1. A review of all Home Energy Management System architectures deployed in the project to establish;
    a. that the systems are not passing control signals to utility assets nor providing a logical path to utility databases
    b. that the systems are adhering to the encryption requirements for all residential data streams moving over the HAN or Internet
        i. Binary obfuscation (or better) encryption for resource usage data telemetry
        ii. AES-128 (or better) encryption for energy management control signals
2. A review and verification that the policy of de-coupling residential identity information from the individual data streams and the aggregated database by the following means:

c. All data packets are identified by a unique MAC address and/or unique project ID number but contain no personal information that reveals the source of the data such as an address, phone number, name, credit card number, social security number, or identifier that is associated with an online account.

d. The file that links personal identification to the unique project ID number or MAC address is maintained on a secured drive that is not stored on database servers accessible to the internet, and that access to the drive is limited using a secure hardware password. Access to this drive is limited to a small set of Pecan Street staff on a need to know basis.

The sections below include some background regarding the security status of our utility partner, Austin Energy, and a discussion of the Risk Assessment (modeled after the process outlined in NIST 800-30) that was conducted in developing the Cyber Security plan for this project.

System Characterization

A generalized architecture for our deployment approach is shown in Figure 3. While a variety of systems were deployed, they all fit this architecture and were governed by the same set of cyber security measures.

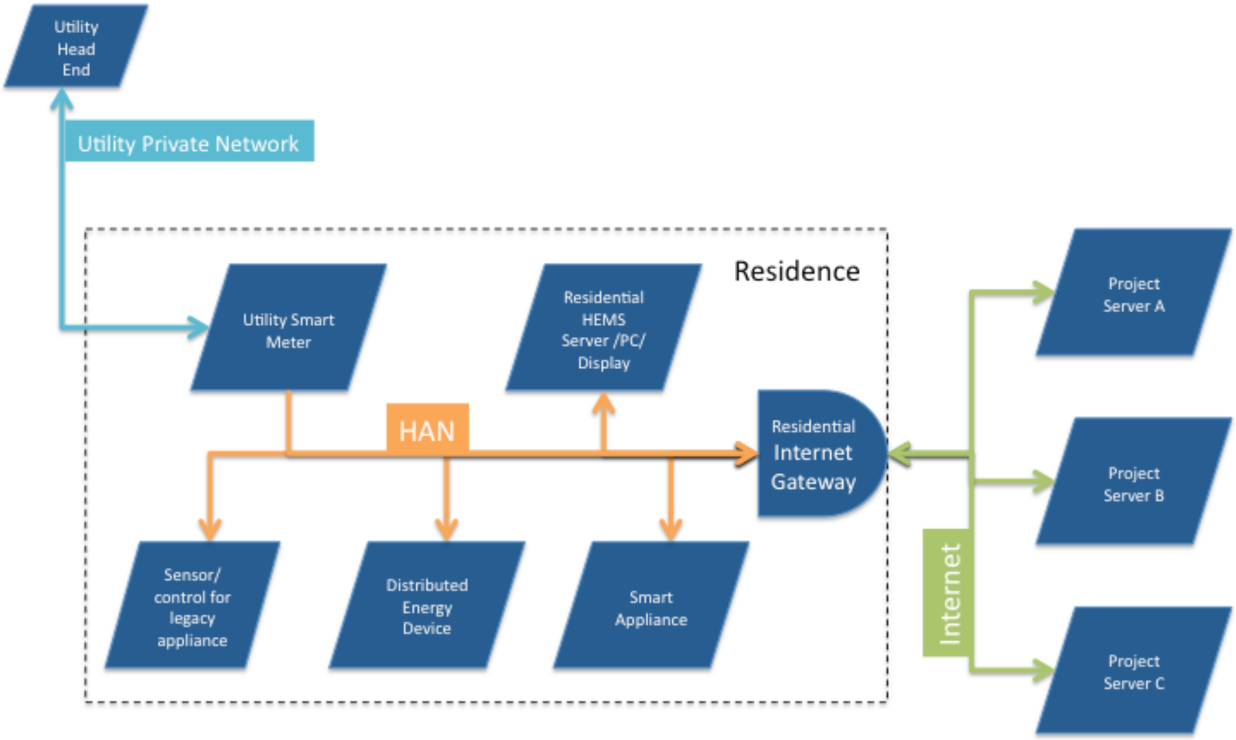


Figure 3: Elements of the Customer Domain and associated logical interfaces to the customer premises elements of our architecture

Key elements of the system architecture are described below.

Sensors/Control for legacy appliances

Sensors and control for legacy devices monitor and control the a utility resource (electricity, gas, water) being provided to a legacy (non-intelligent) load (appliance). Current transducers can be used to monitor loads of individual circuits. Plug monitors can be used to monitor and/or disable specific appliances. Other technologies (such as signal processing of noise signatures) are also available for achieving various levels of load data disaggregation. Sensors and controls will be connected to the Home Area Network (HAN) through wireless and wired means.

Utility Smart Meters

Utility smart meters measure the aggregated consumption of a utility resource (electricity, gas, water) by the customer. In our architecture, we do *not* provide a logical path for any data or control signals from the residential hardware back to the utility network. Any capture of data from the utility smart meter data will be done wirelessly through the residential HAN, but no connection to the utility network by Pecan Street Project systems will be deployed.

Smart Appliances

Smart appliances perform some type of work for the residential occupants. These devices are also able to provide resource usage data and are able to receive some level of instruction to intelligently perform the task at hand. Examples include smart refrigerators, AC units controlled by a smart thermostat, and smart water heaters. Smart appliances are connected to the HAN.

Distributed Energy Devices

Distributed energy devices facilitate the production, conversion or management of energy within a residence. Examples include PV arrays, Fuel cells, batteries, EV charging stations. They will usually contain embedded intelligence for remote control and monitoring of resource usage and are connected to the Home Area Network.

Residential Internet Gateway

These devices are the consumer's gateway to the Internet. Smart Appliances, Sensors/Controls, Utility Smart Meters, and Distributed Energy Devices will communicate to these gateways directly over the Home Area Network or by means of intermediate "Gateway Adapters". Gateway Adapters, when used, will be only for the purposes of short-range wireless data links to the residential broadband gateway. Our project will rely primarily on the residential broadband gateway (typically cable modem) but some information may be communicated as TCP/IP traffic over cellular data networks.

Residential HEMS Server/PC/Display

These are devices (such as PCs, Tablet PCs, Smart Phones, In Home Displays [IHD] or purpose built processors) that process information from other HEMS elements in the residence to provide data visualization and device control. The Residential HEMS server may also communicate over the Internet through the Residential Broadband Gateway to augment its functionality.

System and Data Criticality

This section discusses the criticality of the installed NILM and HEMS devices as well as that of the data generated by the devices relative to each of the major HEMS functions mentioned above. The criticality is summarized in Table 3.

Table 3: System and Data Criticality of HEMS Installed by Pecan Street

Function	System criticality	Data criticality
Resource Usage Monitoring	***Not*** **critical to Utility** ***Not*** **critical to Residential Customer** ***Critical*** **to Project**	***Not*** **critical to Utility** ***Not*** **critical to Residential Customer** ***Critical*** **to Project**
Resource Price Plan Selection	***Not*** **critical to Utility** ***Not*** **critical to Residential Customer** ***Critical*** **to Project**	***Not*** **critical to Utility** ***Not*** **critical to Residential Customer** ***Critical*** **to Project**
Management of Smart Appliances and Distributed Energy Devices	***Not*** **critical to Utility** ***Not*** **Critical Residential Customer** ***Critical*** **to Project**	***Not*** **critical to Utility** ***Not*** **critical to Residential Customer** ***Critical*** **to Project**

A major feature of Pecan Street's project is that the HEMS architecture selected creates criticality, which is largely confined to the interests of the project, but does not have a critical impact on the normal operations of the Utility or the individual residence if the system or data is compromised. In the event of Resource Usage Monitoring/Price Plan Selection system failures at an individual residence or across a large number of residences, the utility may legally revert to their existing billing system. Failure of these systems from a residential consumer perspective may be disappointing, but not critical to the physical or economic well being of the residence. Similarly, failure of the system or data related to the Management of Smart Appliances and Distributed Energy Devices will have no impact on the Utility assets or networks (particularly on the limited scale of the project deployment). All appliances and devices under control of the HEMS are required to have autonomous default modes of operation in the event of a HEMS system failure, so the impact on the residence will be minimal.

Thus, the criticality of the installed HEMS impacts the project success, but not the safety or security of the Utility or the residence. The systems implemented and data collected are, however, very critical to the success of the Pecan Street Project.

System and Data Sensitivity

While the architecture of our project avoids introducing a critical point of failure for other stakeholders (utility and residential customers), it does create data that is sensitive to all parties. Data regarding resource usage, the comparative accuracy of utility meters and sub-meters, and consumer preferences/dissatisfaction with various products are all points of sensitivity. The residential customer may consider information about personal energy usage, pricing preferences, and smart appliance inventory to be very sensitive as well. The Pecan Street Project also considers the body of data to be an intellectual property resource on which it can generate significant value provided the integrity and quality of the data can be maintained. Thus, the data collected in this project should be viewed as highly sensitive.

Threat Identification

The following potential threats were identified at the beginning of the project, and a mitigation plan was developed to prevent them from comprising the security of the project.

Natural Threats

Natural threats possible in the Mueller community where the HEMS systems are being employed include fire, flooding, tornadoes, and electrical storms.

Environmental Threats

Environmental threats include long-term power failure, extended Internet outages, and environmental degradation of system electronics.

Human Threats

Human threats are more likely and dangerous since they are conducted with intelligence and motivation. The table of human threats in Table 4 was extracted from NIST 800-30.

Table 4: Human Threats -Threat-Source, Motivation, and Threat Actions (from NIST 800-30)

Threat Source	Motivation	Threat Actions
Hacker	Challenge Ego Rebellion	• Hacking • Social engineering • System intrusion, break-ins • Unauthorized system access

Computer criminal	Destruction of information Illegal information disclosure Monetary gain Unauthorized data alteration	• Computer crime (e.g., cyber stalking) • Fraudulent act (e.g., replay, impersonation, interception) • Information bribery • Spoofing • System intrusion
Terrorist	Blackmail Destruction Exploitation Revenge	• Economic exploitation • Information theft • Intrusion on personal privacy • Social engineering • System penetration • Unauthorized system access (access to classified, proprietary, and/or technology-related information)
Industrial espionage (companies, foreign governments, other government interests)	Competitive advantage Economic espionage	• Economic exploitation • Information theft • Intrusion on personal privacy • Social engineering • System penetration • Unauthorized system access (access to classified, proprietary, and/or technology-related information)
Insiders (poorly trained, disgruntled, malicious, negligent, dishonest, or terminated employees)	Curiosity Ego Intelligence Monetary gain Revenge Unintentional errors and omissions (e.g., data entry error, programming error)	• Assault on an employee • Blackmail • Browsing of proprietary information • Computer abuse • Fraud and theft • Information bribery • Input of falsified, corrupted data • Interception • Malicious code (e.g., virus, logic bomb, Trojan horse) • Sale of personal information • System bugs • System intrusion • System sabotage • Unauthorized system access

Vulnerability Identification

The vulnerability of the deployed devices to human threats is summarized in Table 5. The table was used as a checklist for identifying system vulnerabilities.

Table 5: Vulnerability of HEMS Systems to Human Threats

Vulnerability	Threat Source	Threat Action
Customer HAN is "Open"	Proximate hacker, thief, or malcontent	Connecting to the HAN with a Wi-Fi enabled client and accessing residential HEMS systems (and other systems)
Residential internet gateway firewall is not activated	Remote hacker, thief or malcontent	Accessing the HAN and *all* connected devices over the internet through the broadband gateway (usually a cable modem in our project)
Internet traffic is monitored	Remote hacker, thief or malcontent	Accessing the stream of project data on the internet as it moves between the residence and the project servers
Insufficient security policy implemented on Project Servers.	Remote hacker, thief or malcontent. Disgruntled project staff or researchers	Project data is destroyed or compromised. Sensitive data is accessed and misused.

Control Analysis

For each of the system vulnerabilities identified above, a control procedure was developed to reduce or eliminate the risk associated with that vulnerability.

Customer HAN is "Open"

While it is ill-advised to operate a residential HAN in an "Open" mode (SSID is visible, and no password is required) the reality is that many residences will be in this situation, and our project will not have the ability to implement or enforce a closed network configuration. In this situation it is extremely easy for anyone with a wireless client to access other systems that are connected to the HAN. Thus, the Pecan Street Project requires that all data streams passing over the HAN will be encrypted. Data streams from sensors that include raw resource usage numbers are of little value in an un-normalized form and are neither critical nor sensitive to the stakeholders and of little value to a hacker. Since encryption requires overhead in the transmission bandwidth, placing a rigorous encryption burden on these data streams is not cost effective. Thus, for raw data feeds from resource usage sensors, we will require simple low overhead encryption such as a binary obfuscation scheme. For more sensitive and critical data flow such as control signals passed over the HAN to Smart Appliances and Distributed Energy Devices we will require AES-128 encryption.

Residential Internet gateway firewall is not activated

While it is ill-advised to operate a residential Internet gateway without firewall protection, the reality is that a small percentage of residences will be in this situation, and our project will not have the ability to implement or enforce a closed network configuration. Without a firewall, (or if a firewall is penetrated) it is possible for a hacker to access other systems that are connected to the gateway and HAN. Thus, the Pecan Street Project requires that all data streams passing over the HAN will be encrypted. Data streams from sensors that include raw resource usage numbers are of little value in an un-normalized form and are neither critical nor sensitive to the stakeholders and of little value to a hacker. Since encryption requires overhead in the transmission bandwidth, placing a rigorous encryption burden on these data streams is not cost effective. Thus, for raw data feeds from resource usage sensors, we will require simple low overhead encryption such as a binary obfuscation scheme. For more sensitive and critical data flow such as control signals passed over the HAN to Smart Appliances and Distributed Energy Devices we will require AES-128 encryption.

Internet traffic is monitored

Once the data from an individual customer's premises has been collected it is sent to Pecan Street Project Servers over the Internet. It is difficult to predict how this flow of data might be monitored but there are two controls that can reduce the risk of adverse effects. First, all project data is de-coupled from identification with the premises at which the data was collected. No personal identification information is transmitted with any of the systems that are being deployed by the Pecan Street Project. Secondly, all data transmitted over the Internet will be encrypted. Data streams from sensors that include raw resource usage numbers are of little value in an un-normalized form and are neither critical nor sensitive to the stakeholders and of little value to a hacker. Since encryption requires overhead in the transmission bandwidth, placing a rigorous encryption burden on these data streams is not cost effective. Thus, for raw data feeds from resource usage sensors, we will require simple low overhead encryption such as a binary obfuscation scheme. For more sensitive and critical data flow such as control signals passed over the HAN to Smart Appliances and Distributed Energy Devices we will require AES-128 encryption.

Insufficient security policy implemented on project servers

The most critical security concern from a project perspective is the integrity, availability and confidentiality of the aggregated project data once it has been assembled on the project servers.

The data on the project servers is not critical to stakeholders other than the Pecan Street Project itself, which must rely on this data to produce our research results. The data could be sensitive to all stakeholders, however, if it were to be stolen. A primary control in ensuring that this does not happen is to de-couple the data from identification with individual residential sources.

The Pecan Street Project maintains a single copy of a database which links the identity of the residences with specific data sets through a unique project ID number and/or a unique hardware MAC address. Access to this database is limited to Pecan Street Project Staff for customer service, communications, and research. It is not made available to the broader group of researchers at UT, Austin Energy, and EDF. Researchers that do have access to the aggregate data through the servers can only access that data through a secure username and password protected site. Even if this data is stolen and made public, however, its sensitivity is greatly reduced without the personal ID information of the individual residences.

Likelihood Determination

The likelihood of each human threat vulnerability being exercised was analyzed to determine the appropriate level of prevention measures that should be taken. Table 6 is a vulnerability matrix showing the likelihood of each identified vulnerability per the process described in NIST 800-30.

Table 6: Vulnerability Likelihood Assessment

Vulnerability	Comments	Likelihood determination
Customer HAN is not encrypted	Though the ZigBee HAN is not encrypted, it is proprietary, which makes connection extremely difficult without access to the utility backhaul network.	Low
Residential internet gateway firewall is not activated	Residential energy data intercepted by a hacker over the resident's LAN does not contain PII and is therefore low risk.	Low
Internet traffic is monitored	Residential energy data intercepted by a hacker over the resident's LAN does not contain PII and is therefore low risk.	Low
Insufficient security policy implemented on Project Servers.	Pecan Street has implemented multiple methods to ensure sufficient security policies are in place to deter hackers. The organization has an enterprise-class firewall in place to protect the servers. Additionally, Pecan Street has implement an Intrusion Prevention System (IPS) that is a Cisco stand-alone device, which detects intrusion attempts into the network. These measures coupled with the privacy protection policies helps to ensure protection of sensitive data.	Low

Impact Analysis

To further determine appropriate resource allocation for prevention of human threats, an impact analysis was undertaken to understand the consequences of a vulnerability being leveraged to compromise the security of the project. Table 7 is a vulnerability matrix showing the impact of each identified vulnerability per the process described in NIST 800-30.

Table 7: Vulnerability Impact Assessment

Vulnerability	Comments	Impact Analysis
Customer HAN is “Open”	Residential energy data intercepted by a hacker over the resident’s HAN does not contain PII and is therefore the impact is negligible.	Low
Residential internet gateway firewall is not activated	Residential energy data intercepted by a hacker over the resident’s LAN does not contain PII and is therefore the impact is negligible.	Low
Internet traffic is monitored	If project data were monitored and decrypted on the internet, it would still be impossible to assemble the data into a threatening form because the data being transmitted over the internet does not contain PII. There would be minimal impact to the project and its stakeholders.	Low
Insufficient security policy implemented on Project Servers.	If the project servers were breached, PII data would still remain confidential and decoupled from energy use data. The impact to the project is minimal because the energy use data is available for free online through www.wiki-energy.com	Low

Risk Determination

The risk level matrix below (Table 8) is taken from NIST 800-30.

Table 8: Risk Level Matrix

Threat Likelihood	Impact		
	Low (10)	***Medium*** (50)	***High*** (100)
High (1.0)	**Low** 10 X 1.0 = 10	**Medium** 50 X 1.0 = 50	**High** 100 X 1.0 = 100
Medium (0.5)	**Low** 10 X 0.5 = 5	**Medium** 50 X 0.5 = 25	**Medium** 100 X 0.5 = 50
Low (0.1)	**Low** 10 X 0.1 = 1	**Low** 50 X 0.1 = 5	**Low** 100 X 0.1 = 10

Risk Scale: High (>50 to 100); Medium (>10 to 50); Low (1 to 10)[8]

This risk matrix is suitable for our situation so we will apply this mapping to our Vulnerability scenarios to determine the risk as shown in Table 9.

Table 9: Risk Determination of Identified Vulnerabilities

Vulnerability	Likelihood Determination	Impact	Risk Determination
Customer HAN is "Open"	Medium	Low	Low
Residential internet gateway firewall is not activated	Low	Low	Low
Internet traffic is monitored	Low	Low	Low
Insufficient security policy implemented on Project Servers.	Low	Medium	Low

Based on this analysis, the risk for the systems that we will be implementing in the Pecan Street Project will be low. This is primarily due to the fact that none of our systems will impact the utilities network or control systems and also because we have taken precautions to de-couple the personal identification information from the residential data that is being collected.

Lifecycle Control Plan

The lifecycle control plan was developed to provide guidance on how the project team would implement the cyber security plan in every phase of the engineering lifecycle of the project, including design, procurement, construction, installation, commissioning and operation.

Pecan Street's Energy Internet Demonstration brought together a wide variety of devices and systems. A system that can handle a diversity of devices and sub-systems is fundamental to promoting a scalable, commercially dynamic Energy Internet. These systems deployed on the customer side of the meter must maintain the privacy of customer data and ensure that utility systems cannot be compromised.

To ensure that all deployed systems were secure, Pecan Street selected, tested, deployed, re-tested, operated and collected data from multiple applications using the following process:

1. Set cybersecurity requirements, based on available standards and technologies, that apply to all devices, systems and technologies deployed on the customer side of the meter. No systems was deployed that enabled a logical connection to the utility-side network.
    A. The requirements for all customer side systems and devices are as follows:
        I. Systems deployed will not pass control signals to utility assets nor provide a logical path to utility databases
        II. Systems will encrypt all residential data streams moving over the HAN or Internet by the following methods:
            a. Binary obfuscation (or better) encryption for resource usage data telemetry
            b. AES-128 (or better) encryption for energy management control signals
2. Determine technologies to be deployed, through an RFI process in which vendor solutions are reviewed based on their ability to meet the cost, research, interoperability and cyber security objectives of the program. In our architecture, a typical deployment will involve an energy device such as a Power Monitor (CT module) or a smart appliance that communicates with a HEMS gateway. The link between the device and the gateway may be achieved by a number of standards including Zigbee, Wi-Fi, Homeplug, PLC, or even a proprietary wired or wireless link. We have not, and likely will not settle on a single standard for this type of link, but we will require that the data stream that occurs across this link be encrypted as specified above and that the data stream remain encrypted as it travels across the Internet. Furthermore, this data stream must not include any recognizable personal identification information other than a unique technical system identifier such as a MAC address or serial number.
3. Baseline System Selection and Implementation: For phase one of our program (100 home baseline), a home energy monitoring system from Incenergy was selected and deployed based on its price/performance characteristics, and on the ability of this system to provide the necessary level of encryption (binary obfuscation) of data flows across the HAN and Internet. This system consists of CT collar array modules that

monitor the energy usage in multiple residential circuits. Each module digitizes the power usage data, and transmits it in encrypted form over a 433MHz wireless link to the system gateway. The system gateway encrypts a time stamp and MAC address for the system and attaches it to the received data. The gateway is connected to the customers' broadband connection through an Ethernet port. The encrypted data packets were sent to the Incenergy NOC where the data is normalized, re-formatted and forwarded to the University of Texas TACC. TACC removed the MAC address and replaces it with a unique project ID and accumulates the data into a research database stored on a secure server. All data at rest in this location was de-coupled from the identity of the original residence except for a unique project ID and geographic area tag in the form of a census block location. TACC received the master list of MAC Addresses and corresponding project IDs and census block locations from Pecan Street staff. Pecan Street maintains the file which links individual Identification with MAC Addresses and project IDs on two separate encrypted hard drives that each require two factor authentication for access.

4. The RFI for Phase 2 systems (1,000 home HEMS deployment) requires that all selected vendors meet our cybersecurity requirements. While most vendors of these systems claim to have extensive cybersecurity controls, we will require all finalists to provide a detailed review of their cyber security measures. We will verify that the systems encrypt the residential data streams at all points through the system. Data that is passed through to University of Texas servers for research purposes and is at rest on UT servers will be de-coupled from the personal identification of the residence from which the data is being collected. Separate from the research database is the database maintained by the Pecan Street Project that makes personal data accessible to the residential volunteers. Pecan Street maintains the file which links individual Identification with MAC Addresses and project IDs on two separate encrypted hard drives that each require two factor authentication for access. Any use of this data to provide commercial services or research will be governed with the full consent and signature of the residential customer. The data will not be used for any purposes that are not fully disclosed to the residential customer.

5. Deploy systems in the architecture of an Energy Internet.

    A. Systems selected for deployment will be first installed in a small number (approximately 5) of homes for full testing of performance and cyber security. Pecan Street will verify that the systems function as specified and that all requirements for encryption of data flows and for ID de-coupling and/or two-factor authentication are adhered to at the UT Research Network Operations Center (NOC) and the HEMS service provider NOC. We will also verify that no systems are deployed in such a way as to be able to access the utility side network. Since our architecture relies on the residential Internet connection, and since most such connections are accesses through Wi-Fi router, it is highly preferable that these networks be operated in a secure and hidden mode. Pecan Street Project will provide information to all residential participants on how to set-up a hidden and password secured Wi-Fi network and will encourage them to implement these security measures prior to installation of our systems.

B. Once the initial systems are installed and verified to meet the cybersecurity requirements of the program, the broader phase two deployments to 1,000 homes will begin. System vendors will be required to demonstrate that their installation procedures include enabling of encryption features on all relevant hardware and that a post installation verification of those features is conducted before the system is commissioned.

6. Operate the deployed systems.

Pecan Street conducted annual project cyber security audits. These audits were conducted under the supervision of Pecan Street's Chief Operating Officer and Chief Technology Officer.

The audits included, but were not limited to, the following actions:

A. A review of all Home Energy Management System architectures deployed in the project to establish:
    I. That the systems are not passing control signals to utility assets nor providing a logical path to utility databases
    II. That the systems are adhering to the encryption requirements for all residential data streams moving over the HAN or Internet
        a. Binary obfuscation (or better) encryption for resource usage data telemetry
        b. AES-128 (or better) encryption for energy management control signals

B. A review and verification that the policy of de-coupling residential identity information from the individual data streams and the aggregated database by the following means:
    I. All data packets are identified by a unique MAC address and/or unique project ID number but contain no personal information that reveals the source of the data such as an address, phone number, name, credit card number, social security number, or identifier that is associated with an online account.

II. The file that links personal identification to the unique project ID number or MAC address is maintained on a secured drive, and that access to that file is limited by secure pin and to a limited set of Pecan Street staff on a need to know basis.

III. Methodology

Pecan Street's Smart Grid Demonstration deployed an integrated two-way Energy Internet system that incorporated customer-side-of-the-meter smart grid devices, distributed generation, energy storage, smart meters, and grid-connected EVs linked to solar and energy storage.

The project sought to demonstrate:

- The integration of advanced smart grid technologies in a unique Energy Internet configuration to demonstrate how the sum of the parts creates greater value than the parts can do separately.
- The viability of different business models in deploying distributed generation and demand response solutions.
- How the combination of demand response, distributed generation, energy efficient building design, and efficient management of the distribution system can materially reduce demand for power from the grid during peak consumption hours.
- How designing an open platform that is open to new technologies and new energy service offerings can increase the commercialization opportunities for new energy technologies and systems.
- The role that distributed energy resources can play in improving distribution system reliability.
- The key role that environmental metrics play. They can help demonstrate how an integrated smart grid reduces air pollution, water consumption, and greenhouse gas pollution. By focusing on environmental outcomes in system design and collecting environmental data, the project can give businesses and homeowners information that encourages them to reduce their environmental impact to help clean the air during ozone episodes or conserve water during a drought.

Technical Approach

Pecan Street carried out this demonstration in three integrated programs:

- Program 1: Demonstrate Energy Internet capabilities on customer side of the meter
- Program 2: Demonstrate integration of distributed energy resources onto the Energy Internet

- Program 3: Demonstrate impacts of a customer-driven smart grid on utility infrastructure

Program 1: Demonstrate Energy Internet capabilities on customer side of meter

The capabilities demonstrated in this program element are:

- Demand response
- Customer control capabilities, including control from remote locations

The overall project tasks and project budget items dedicated to this program are:

- Acquire and install energy monitoring systems
- Test business models
- Seed field trial with customer-owned rooftop PV and energy storage
- Acquire and install smart water meters
- Construction of lab
- Creation of program legal documents

The project benefits tested in this program are:

- Impact on customer electricity usage
- Impact on customer water usage and energy usage attributable to water usage
- Impact on customer utility bills
- Influence on customer's environmental impact
- Customer's electric system impact

Program 2: Demonstrate impacts of the Energy Internet on utility infrastructure

The capabilities demonstrated in this program element are:

- Demand response and load leveling
- Impact of distributed energy resources on utility infrastructure
- "Plug and play" open deployment platform for new technologies and electricity services

The overall project tasks and project budget items dedicated to this program are:

- Create a model of the utility's distribution system serving Mueller
- Acquire and install monitoring devices on utility infrastructure
- Create open platform for testing of new products and services on the utility's grid

The project benefits tested in this program are:

- Impact on utility load profile
- Influence on utility net environmental impact
- Ability of private sector to have opportunity to provide new products and services

Program 3: Demonstrate electric vehicle integration onto the Energy Internet

The capabilities demonstrated in this program element are:

- Integrating distributed generation into EV charging
- Load impacts and load leveling potential from grid connected PEVs

The overall project tasks and project budget items dedicated to this program are:

- Seed field trial with a dense network of plug-in electric vehicles with Level 2 EVSEs in homes with distributed energy resources
- Purchase 2 Electric Vehicles to be owned by Pecan Street Inc. for testing and demonstration

The project benefits tested in this program are:

- Consumer charging behavior
- Alignment of EV charging with PV power production
- Impact on utility load profile
- Influence on utility net environmental impact

Pecan Street worked in partnership with Austin Energy and The University of Texas at Austin on the design, implementation, and analysis of each project.

Research Design

To assess how the technologies tested through this project impact customers' energy use and impact the utility's grid infrastructure, Pecan Street established a field trials methodology modeled on pharmaceutical research trials. The following stack depicts Pecan Street's field trials approach. Each layer builds upon the previous ones to create a comprehensive field trials environment that yields replicable and scalable results. The bottom layer is the first one to be implemented, building to the top. The blue layers serve as the critical components of a field trial that enable implementation of interventions and product testing, followed by analysis of results.

Analysis layer	With the first seven layers providing high quality research data and product performance data, companies and university researchers are able to use this data to analyze specific issues such as the impacts of different variables on customer water use and the performance of tested products when used by actual customers in real world settings.
Intervention & testing layer	With the first six layers in place, researchers and companies can begin testing behavioral response and product performance in actual homes. Behavioral response trials will typically require that the research team have a method for communicating information and messages to participants. This usually requires the manager to develop and operate a web portal and a mobile app.
O&M layer	Pecan Street operates and maintains all measurement equipment and provides on-going customer service to participants.
Data acquisition, management, validation & storage layer	Pecan Street acquires behavioral and use data from participants' measurement equipment. This is done by connecting the data center to each participant's installed measurement equipment over the Internet. The data is uploaded into a custom architected database that enables storage in a manner that anonymizes the data and protects the database from remote intrusion while providing secure online access to authorized users. After the data has gone through an initial round of error checking (typically done through database correction scripts), the research team analyzes the data to validate it and denote gaps or errors.
Communications layer	For behavioral trials and large scale research trials, energy use data is transmitted over the Internet, often with the device connected via PLC. As such, research participants must have broadband Internet service. When a participant has home Internet service, researchers typically can port the measurement equipment to the premises' Internet gateway. When a participant does not have Internet service, effective substitutes include installing a 3G or LTE router.
Measurement & verification equipment layer	Pecan Street selects and procures equipment, schedules installation, performs installation and verifies equipment performance. Pecan Street also carries out home/business audits to record water using devices in the home and other relevant research data pertaining to the premises and its grounds.
Product testing layer	For research trials that include installing and operating third-party equipment in participating properties, Pecan Street tests the product in a controlled setting, such as its commercialization lab before installing large numbers in the field. This helps identify configuration, interoperability and operational issues and plan and/or correct for them in the lab.
Participant recruiting layer	Research trial manager recruits participants in target communities, provides participant legal agreements and obtains executed agreements.

The foundation of the field trials is collection of granular information on how participating properties use energy. This information reveals the systems and behaviors that drive consumption throughout the day and throughout the seasons. The data also reveals the specific impacts of introduced technologies or behavioral programs, such as pricing trials and conservation messaging, on energy consumption.

To provide insight into the effect of consumer smart grid technologies on residential load profile, the challenges preventing broad adoption of consumer smart grid technologies, and the impact of these technologies on the utility's infrastructure, Pecan Street undertook a five-phased approach to establishing its field trials:

1. Engage participants
2. Establish a baseline
3. Construct a research and development lab to test and demonstrate smart grid technologies
4. Seed the field trial with technologies to create the neighborhood of the near future
5. Implement pricing and behavioral trials
6. Analyze the resulting data

Participant Engagement

Pecan Street focused its initial efforts on recruitment of project participants within the targeted geographic area of Mueller. Recruitment was conducted through a combination of articles in community newsletters, local media, attendance at neighborhood events, and word of mouth. Pecan Street established an Executive Committee to help design the research trials and provide guidance on analysis. Two members of the Mueller community were selected through a competitive application process to serve on the Executive Committee. Their participation helped ensure direct feedback from participants was taken into account and that the participants' perspectives were considered in all research questions.

The project team initially recruited only single-family participants because of the legal and technology challenges of expanding the study to include multi-family tenants. With additional support from the Verizon Foundation, in 2013 Pecan Street was able to include 140 income-restricted apartments in the project. Inclusion of low-income, multi-family participants was valuable in understanding how renters on a fixed income were able to utilize Internet-enabled technologies to reduce their utility bills.

All participants in the study were volunteers, and therefore self-selecting. The volunteers represent a diverse demographic group; however, the majority of volunteers represent an "early adopter" profile. Early adopters of technology tend to have higher education and income than the average family, an interest in new products and service, and spread the word about the pros and cons of their latest purchase. Inclusion of early adopters in the study was critical. The majority of technologies studied in this project were pre-market or new to market, and therefore aimed at early adopters. The established technologies included in the study, specifically electric vehicles and photovoltaic systems, are experiencing a high degree of innovation in the components, integration, and in the business models surrounding them, therefore making them targets for early adopters as well. Feedback from participants on selection of technologies and brands to be included in the study as well as feedback on technologies tested in their homes and businesses was invaluable as a real-world sanity check.

Baseline Study

From February 2011 - February 2012, Pecan Street conducted a 12-month baseline study on 200 homes - 100 new, green-build homes and 100 older homes - gathering granular power use data for all major appliances and for the whole home. Data gathered during the baseline study included the results of advanced energy audits, sub-circuit monitoring and whole-home circuit monitoring. Approximately 20 different types of devices were monitored on sub-circuits, including sixteen homes with photovoltaic systems. After completion of the baseline period, 94% of participants elected to remain in the study and they received a HEMS along with a portal to view their energy consumption data.

During the baseline study, HEMS were installed in the participants homes for the purpose of gathering information on how energy was used in the home, but participants were blind to this data. The baseline data was compared to the data for the same and additional homes that received a portal to view their HEMS data after the “blind period” to gauge the impact of technologies and consumer behavior interventions on peak demand, customer satisfaction and the environmental impact metrics.

Lab Construction

During the project performance period, Pecan Street acquired a site within Mueller and built a the Pike Powers Lab & Center for Commercialization to serve as an educational and testing site for the technologies and systems being deployed, in addition to technologies and systems of interest to researchers, utilities, and companies that are affiliated with Pecan Street. Located just three miles from the Texas Capitol, it also serves as an educational resource for the Texas Public Utility Commission.

The lab was designed in partnership with NREL. The NREL team lead by Bill Kramer provided guidance on building design, specifications, lab equipment procurement, and lab testing programs. The lab design and layout were created by The University of Texas’s Dr. Matt Fajkus and Dr. Ulrich Dangel. The final lab design was created by the Michael Hsu Office of

Architecture in Austin, Texas. The lab was constructed by The Muskin Company, an Austin-based home building company that specializes in 'urban infill' construction. The lab's energy management system was donated by Schneider Electric.

The lab's capabilities are specially configured for testing hardware or software that generates or manages power at the building or device level, communicates wirelessly or integrates energy use data into its operations. Pecan Street's lab has specialized capabilities for developing, testing and validating consumer electronics and applications that incorporate metrology, building controls, solar PV, natural gas fuel cell, machine-to-machine, vehicle charging and disaggregation technologies.

The 3-story, 3,800 square-foot facility is equipped with multiple workstations and testing configurations. It has a split phase 800A electrical service, south- and west-facing solar arrays, multiple conduit raceways, AC and DC distribution buses, all LED lighting, a full building automation system and zonal refrigerant air conditioning.

With a full set of appliance stub-outs on every floor, the lab can simulate three residential structures for demand response, fuel cell and building management scenario testing. Every outlet on every floor is measurable. The lab can also test natural gas fuel cell or combined heat and power micro-turbines up to 10-15kWp output.

These capabilities enable Pecan Street's researchers and partners to simulate thousands of real world use cases and to test, develop and verify the performance of customer products and services including:

- Smart meters and meter components
- Natural gas fuel cells
- Energy management
- Energy monitoring
- Building control and appliance control systems
- Disaggregation algorithms
- Solar panels and solar inverters
- Customer HAN devices
- Software applications using Green Button and customer HAN device data
- Demand response
- Electric vehicle charging
- HVAC

- Ancillary services
- Lighting
- Installed Equipment

The lab contains:

- 14 Dell Workstations and 4 Dell Servers with Network and Direct Attached Storage
- NI PXI Chassis Equipment:
    - 7.5 Digit DMM
    - Vector Signal Transceiver
    - 6 GHz Vector Network Analyzer
    - 8 GHz Programmable Amplifier
    - Modulation Toolkit
    - Wireless Test Software Suite
    - 64 Channels 50MHz Digital I/O
    - Qty. 2 6.5 Digit DMM
    - 2Gs/S 500MHz Digitizer
    - 1 TB Signal Storage
- NI cRIO Chassis Equipment:
    - 128 Channels 250kS/S Analog I/O
    - 128 Channels Thermocouple Measurement
    - 16 Channels 100 Ohm RTD 24bit 100S/s
    - 24 Channels 300V High Voltage Measurement
    - 32 Channels High Isolation 100S/S Analog Input
    - 24 Channels 5A Current Input 24 bit
    - 16 Channels +/- 10V 25kS/s 16 bit Analog Output
    - 16 Channels 20mA 100kS/S Analog Output
    - 16 Channels Relay Isolation Modules
    - 32 Channels Digital I/O
    - CAN Interface, Low and High Speed
    - RS-232/RS-485 Interface

  - Single Axis Brushed DC Servo Drive
  - Ethernet Communication
- Multiple LabView and MultiSim Development Seats with most plug-in options
- Oscilloscopes
- Spectrum Analyzer
- Power Quality Analyzers
- Programmable AC and DC Loads and Supplies
- Hot Air Solder Rework Stations

Prior to construction of the Pike Powers Lab, Pecan Street rented a single-family home in Mueller in which it tested and demonstrated customer systems prior to deployment in the field. Upon completion of the lab, Pecan Street purchased two Chevrolet Volt electric vehicles for testing EVSE system performance, EV monitoring technologies, communications and controls software, and EV charging integration with other residential uses as well as with distributed energy resources.

Pecan Street uses the lab to educate the public, policymakers, educators, and the private sector on the benefits of smart grid and the new opportunities for consumers and businesses that are created by the systems the project is testing. Pecan Street is carrying out its education efforts through lab operations and exhibits, technical conferences with industry and academic publications, social media, media outreach, presentations at community events and technical conferences, presentations to policymakers and other means. Pecan Street hosts teachers participating in its Smart Grid for Schools program at the lab for a two-day workshop during the summer. Pecan Street will continue to use the lab beyond the Period of Performance, without obligation, to achieve the objectives for which Pecan Street was awarded FOA36 funds.

Technology Selection & Deployment Approach

To determine which technologies to deploy, an open request for proposals/request for information invited the private sector to participate in the program, either by deploying, operating, or collecting and evaluating the data. The project received and considered proposals for home energy management technologies and systems from multiple vendors. Systems deployed were either acquired through procurement by Pecan Street or through a research collaboration with the supplier (in which the supplier provides the systems to be tested as part of the collaboration).

The project's interoperability requirements were defined to ensure that every deployed application was configured so that the project team could integrate multiple applications into a single functioning system, inventory the monitoring, measure and evaluate the performance, provide remote software upgrades, detect and correct faults, and document user interface and ease-of-use issues.

Participants in Pecan Street's distributed energy and electric vehicle research trials were allowed to select their own systems based on guidelines provided by Pecan Street. These guidelines are discussed in more detail in the "Technology Selection" section. This method is thought to have created the densest network of retrofitted residential rooftop PV and non-fleet electric vehicles in the nation.

Home Energy Monitoring Systems

The process for selecting HEMS technologies to be deployed in a way that ensured the project's research goals would be achieved followed these steps:

- Release draft interoperability requirements for comment. *September 2010*
- Initiate 12-month baseline study on hourly load profile, down to the major appliance level, of at least 100 homes at Mueller. *February 2011*
- Release project Request for Proposals and Request for Interest for systems and technologies to be deployed. The RFP/RFI will incorporate project interoperability requirements that have been modified based on comments. February *2011*
- Close RFP/RFI period. *May 2011*
- Complete review of proposals and begin deployment planning with selected technology partners. *September 2011*
- Begin deployment of systems in volunteer participants' premises. *January 2012*

Pecan Street received 25 proposals from the following companies:

- Intel
- Sony
- Incenergy
- Powerhouse
- TimberRock-CES
- CheckIt
- Best Buy
- Landis+Gyr
- Ecotality

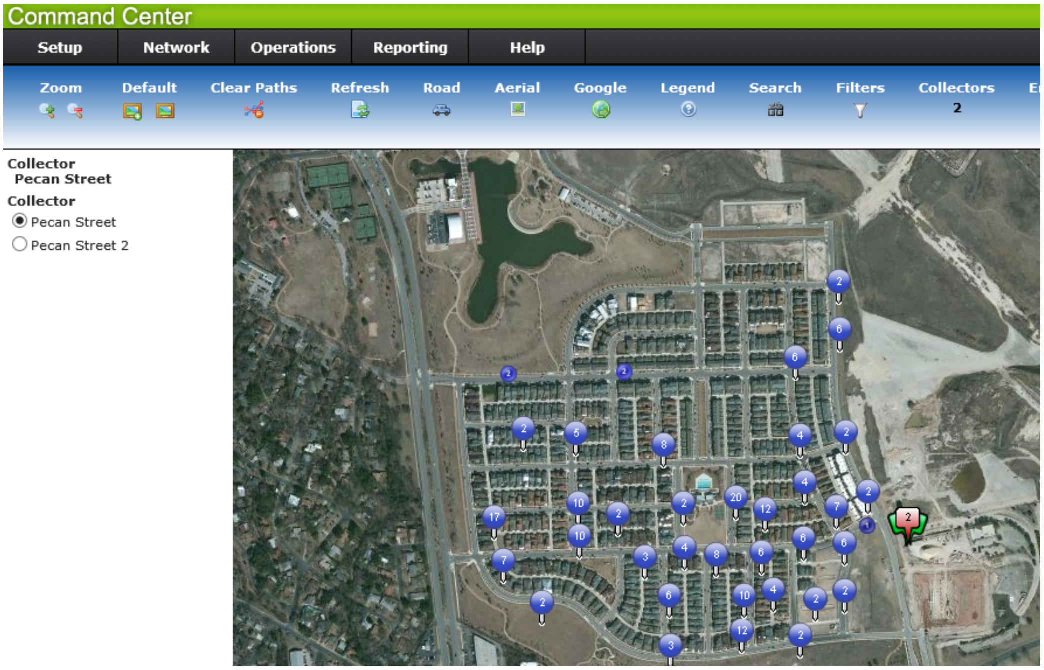
- Firefly
- Freescale
- Gridco
- Ignite Solar
- Linestar
- PowerCEO
- SolarBridge Technologies
- E3 Greentech
- DynamoLabs
- Greenwave
- NRG & Cisco
- Consert
- Energate
- Prudent Energy
- TriTrack
- Verdigris

For a system to be eligible to be deployed in a project participant's premises, the system was required to have UL or comparable safety certification, meet the project's interoperability requirements, performance requirements, and data requirements. This ensured that the project was able to measure and manage every system deployed and to aid in inventory management.

After considering proposals, the project team selected systems from Intel, Sony, Incenergy, Powerhouse, TimeberRock-CES, CheckIt (combined with Best Buy installation services), and Landis+Gyr for hardware and installation testing in Pecan Street's lab. Systems that passed these tests were deployed to a limited number of participating homes to verify performance within an assortment of building types. Systems from Intel, Sony, Incenergy, CheckIt/Best Buy and Landis+Gyr were found to meet the performance requirements through field testing and were deployed to a broader pool of participants within the study. Through the course of the team's data monitoring on solar PV systems at participating premises, the energy monitoring system from eGauge was found to provide high-quality data, on-site data caching, and a user-friendly portal interface. After conversations with eGauge, Pecan Street also procured these devices for energy monitoring within the study.

Smart Meters

To mimic the utility-side smart meters, Pecan Street provisioned 259 Landis+Gyr AMI smart meters and deployed a majority of the units within Mueller. These meters are industry standard and act as a HAN gateway. Data is collected in 15-minute whole-home readings. A map of the deployed meters is shown in Figure 4.

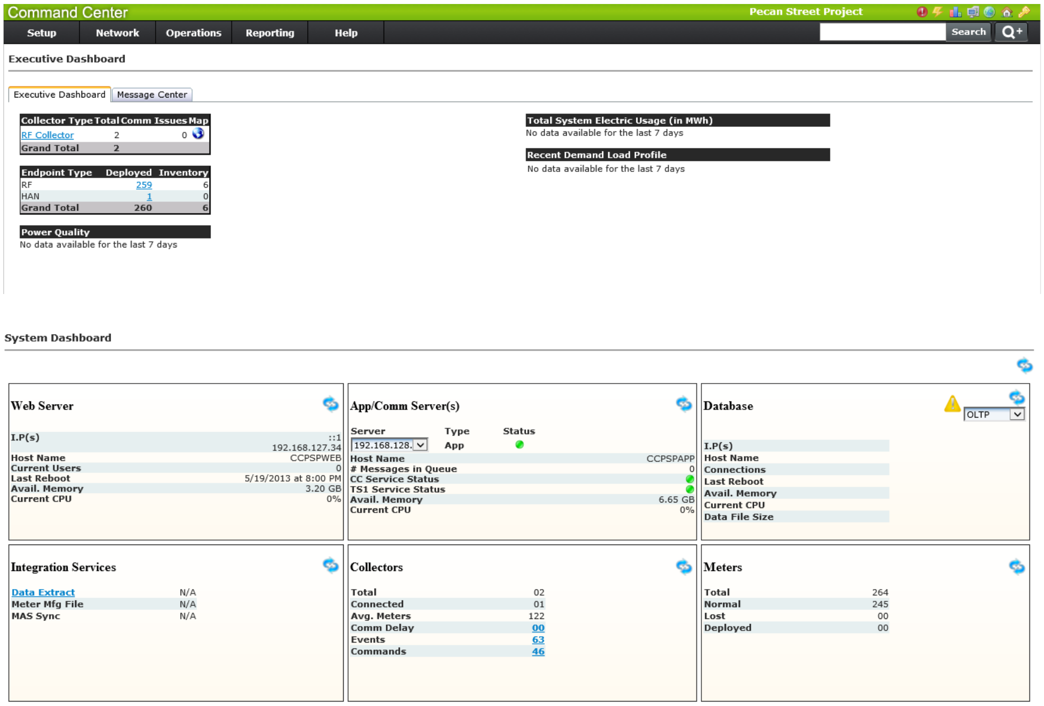


Collector
Pecan Street
Collector
● Pecan Street
○ Pecan Street 2

Figure 4. Distribution of Landis+Gyr meters in Mueller

The deployment of these meters was a success. The meter network was used to collect baseline meter data on the homes, send communication signals into the home via the meter for demand response and pricing trial programs, and test the roll-out and management of a large-scale AMI meter deployment for Austin Energy.

Landis+Gyr provided a license of Command Center to the project team for management of the meters. Command Center is a user-friendly tool that links the meters to the end user, and works as an interface to control all of the meters. Figure 5 is a screenshot from the Command Center System Dashboard.



Executive Dashboard

Collector Type	Total	Comm Issues	Map
RF Collector	2	0	
Grand Total	2		

Endpoint Type	Deployed	Inventory
RF	259	6
HAN	1	0
Grand Total	260	6

Power Quality
No data available for the last 7 days

Total System Electric Usage (in MWh)
No data available for the last 7 days

Recent Demand Load Profile
No data available for the last 7 days

System Dashboard

Web Server

I.P(s)	::1 192.168.127.34
Host Name	CCPSPWEB
Current Users	0
Last Reboot	5/19/2013 at 8:00 PM
Avail. Memory	3.20 GB
Current CPU	0%

App/Comm Server(s)

Server	Type	Status
192.168.128.	App	●

Host Name	CCPSPAPP
# Messages in Queue	0
CC Service Status	●
TS1 Service Status	●
Avail. Memory	6.65 GB
Current CPU	0%

Database
OLTP

I.P(s)	
Host Name	
Connections	
Last Reboot	
Avail. Memory	
Current CPU	
Data File Size	

Integration Services

Data Extract	N/A
Meter Mfg File	N/A
MAS Sync	N/A

Collectors

Total	02
Connected	01
Avg. Meters	122
Comm Delay	00
Events	63
Commands	46

Meters

Total	264
Normal	245
Lost	00
Deployed	00

Figure 5. Command center dashboard for research meter network management

Smart Water Systems

Smart water systems were installed in the homes of 57 participants to collect data on how water is used the house and opportunities to reduce energy and water consumption where the two resources overlap. Smart water systems were selected for deployment based upon ease of installation, quality of data transmission, and replicability.

Residential Photovoltaic Systems

To optimize the project's resources, Pecan Street offered financial incentives to participants to encourage the installation of PV systems and the purchase or lease of an electric vehicle, rather than purchasing these systems outright. All participants in a technology field trial were required to also participate in Pecan Street's broader smart grid demonstration project to provide Pecan Street with the ability to monitor the participant's circuit-level energy use and gain access to the premises if the HEMS stopped properly functioning.

Participants in the PV field trial were required to also participate in Austin Energy's Residential PV Rebate Program. Austin Energy offers a robust residential PV rebate. Participants in this program are required to comply with Austin Energy's thorough inspection and installation verification process. By requiring participating in Austin Energy's program, Pecan Street was able to piggyback on the inspection and verification process rather than undertaking a duplicate process.

To create a dense network of PV systems on one sub-station, Pecan Street's PV rebate program was limited to residents of the Mueller neighborhood. Participants in this field trial were required to select an inverter for their PV system that was capable of reporting detailed power production information over an Internet connection. Additionally, participants were required to grant Pecan Street periodic access to the resident's roof to test the performance of the PV system.

To encourage installation of west-facing systems, Pecan Street offered the following incentive structure:

- $0.50 per watt for south-facing PV installations
- $0.75 per watt for west-facing PV installations
- $0.80 per watt for combined south- and west-facing installations with an inverter for each orientation and at least 2 kilowatts in west-facing panels.

Similarly to Austin Energy's Residential PV Rebate program, the incentive was capped at 6 kilowatts to ensure funding assisted the maximum number of participants. The rebates were provided on a first-come, first-served basis, and were awarded to 163 households. The rebate program was closed after the budgeted amount of funds were allocated. An additional 48 households in the study have PV systems that were not rebated by Pecan Street, bringing the total number of homes in the study with PV to 211.

Participants were able to select their own installer and equipment, and they could elect to receive the rebate directly or have it paid to their solar installer. Five solar installers were selected by the participants, with the majority of participants electing to work with one installer — Lighthouse Solar — that provided them with a bulk purchasing discount. Pecan Street worked closely with local solar installers to ensure that installed systems met the program requirements, and to complete the 163 installations within a 6-month timeframe.

Electric Vehicles

Pecan Street initiated an electric vehicle behavioral research trial within, and surrounding, Mueller. The goal of this research trial was to understand residential charging patterns, how EV charging impacts utility infrastructure, and the elasticity of temporal charging preferences. To create a testbed that would enable the project team to answer these questions, the team decided that it would be critical to understand how PV generation aligns with EV charging, and the impact of the two technologies installed in the same homes on the utility's distribution infrastructure.

To facilitate the creation of a dense network of electric vehicles that represents the neighborhood of the near future, Pecan Street offered incentives that matched the federal EVSE rebate to participants in its PV rebate program. To be eligible for the rebate, participants had to purchase an electric vehicle or lease one for a two-year period. Participants in the study were provided with a Level-2 EVSE installed at their home to enable analysis of Level 1 and Level 2 charging. The incentive program were highly successful and resulted in 69 homes acquiring electric vehicles.

The project team also sought to understand differences in power quality and charge time that may occur between Level 2 Electric Vehicle Supply Equipment (EVSE) that charges the car. Six EVSEs were donated by companies to the study and evaluated at Pecan Street's lab. The testing consisted of evaluating four brands of EVSE's to evaluate power quality and the differentiation between actual charge time required versus stated charge time. The project team found that all the EVSE devices had no impact on the power quality presented by the vehicle, and the charge time required aligned with the manufacturers specifications. The vehicles themselves determine the power quality presented to the grid, and in the case of the vehicles from Chevy and Nissan measured well, similar to resistive heating elements.

Distributed Energy Storage

Energy storage is the critical link that converts distributed generation from an intermittent resource that may not overlap with consumption needs to an on-demand resource that can be leveraged to meet critical needs. The project's energy storage research focused on four critical challenges currently inhibiting broader adoption of residential energy storage systems:

1. interconnection and permitting requirements
2. control strategies
3. optimal sizing of energy storage systems
4. integration of energy storage systems within the home to maximize value to the customer, and integration with the utility to maximize value to the utility

Pecan Street's energy storage research followed two tracks: (1) efforts undertaken at Pecan Street's lab to analyze system integration and optimal sizing guidelines and (2) interconnection and permitting requirements development with Austin Energy and Sony.

Pecan Street procured 7 residential battery systems (battery module plus battery server and gateway) from Sony, and Sony donated an additional 60 1.05 kWh lithium ion storage systems to the project. Five Sony batteries were installed at the home's of participants and two were installed at Pecan Street's lab in parallel with Austin Energy's grid to first understand the installation requirements. The project team worked with Austin Energy to establish model interconnection guidelines for connection of residential energy storage to the grid. At the time of system procurement, Austin Energy (AE) did not have interconnection guidelines for customer-owned energy storage systems, considered a distributed resource by AE. Pecan Street and Sony worked closely with Austin Energy to establish installation guidelines, interconnection requirements, and a permitting process. Pecan Street, Sony and Austin Energy teams met frequently over the course of a year; however, AE was not able to develop interconnection requirements and the Sony battery systems were not able to be deployed.

Behavioral Research Trial

To evaluate the effectiveness of behavior-based intervention tools on consumers, the field intervention experiment measured the comparative behavioral change and predictive quality of the following intervention methods:

- Web portal access only (38 homes)
- Generic text message appeal to reduce energy consumption (44 homes)
- Actionable text message appeal to reduce energy consumption (44 homes)

While a number of pilots have tested each of these methods individually, this experiment tested all of the aforementioned intervention measures concurrently in a single experiment to compare the relative efficacy of each method.

The behavioral research trial was carried out on a total of 126 project participant homes, largely located in the Mueller Community. Unique and particularly valuable features of this neighborhood to the experiment include: its dense concentration of electric vehicles and rooftop solar PVs per capita, and its newer homes outfitted with latest technology energy efficient appliances.

To observe the impact of the intervention methods, the project team analyzed data collected from a total of 27 critical peak period (CPP) events over a period of 20 months. The relevant months were June to September in 2013 and 2014 and there were twelve and fifteen CPP events in each of these years respectively. CPP events were triggered by determination through the regional electric system operator, ERCOT's day-ahead system-wide load forecast system that the electric grid would be most strained. Participants in the intervention experiments were notified via a text message, except for participants in the 'Web-Portal Only Group," a day before each CPP event to enable them to take appropriate measures to shift energy use to outside the peak time frame the following day.

Methodology

Before the field experiment commenced, the intervention groups received e-mail communications outlining the experiment design and suggestions for shifting or reducing their energy consumption (e.g. reducing air conditioner use during CPP hours). Each intervention tool operated as follows:

1. Web Portal Access Only – participants in the web portal access only group did not receive any CPP event notifications throughout the experiment period. Each participant in this group was given secure access to a personal online web portal which provided real-time detail on their energy usage. The web portal also provided participants with the following information:

- Monthly whole home energy use in kWh
- Monthly energy cost in U.S. dollars per appliance
- Energy generation value in U.S. dollars, based upon Austin Energy's value of solar rates, if the participant has solar panels
- Real-time energy consumption in kWh
- Monthly energy cost comparison to other participants within the same zip code
- Monthly energy usage trends

The goal was to estimate consumers' response, in terms of changes in their energy consumption patterns, as result of having access to their real-time energy usage.

2. **Generic Text Message** – participants in the generic text message appeal group had all of the features of web portal access only access group. In addition, participants in this group received a generic cell-phone Short Message Service (SMS or "text") message and an e-mail communication by 6:00 p.m. the day before a CPP event day. Below is an example of a generic text message:

"Tomorrow is a Critical Peak Pricing event from 4:00 pm - 7:00 pm"

This was essentially a reminder about the upcoming CPP day and the goal was to estimate consumers' response, in terms of changes in their energy consumption behavior, as result of having access to their real-time energy usage and advance notice of a CPP event.

3. **Actionable text message** – participants in the actionable text message appeal group had all of the features of web portal access only access group. In addition, participants in this group received an actionable cell-phone Short Message Service (SMS or "text") message and a similar e-mail communication by 6:00 p.m. the day before a CPP event day. Below, is an example of such an actionable text message:

"Critical Peak Pricing event. Please do not use your range/oven between the hours of 4 p.m. and 7 p.m. tomorrow. Pecan Street Inc."

This served as a reminder about the upcoming CPP day and also provided specific directions on actions that participants could take to shift loads during the CPP hours. As compared to the other two groups above, the actionable text message appeal was not only for information purposes, but also a call to action with defined behavior modifications that consumers could make during the CPP hours. The goal here was to estimate consumers' response, in terms of changes in their energy consumption behavior, as result of having access to their real-time energy usage, advance notice of a CPP event, and specific directions of energy savings actions to take.

Analysis

Pecan Street collected 24 months of operational data from the deployed customer systems. Energy audit data documenting building attributes was collected for 250 homes, and sociodemographic information was collected through an annual omnibus online survey provided to all participants. Average response rate to the survey was 53%. The omnibus survey collected important information, including:

- Demographic attributes of research trials participants
- Home attributes, including age, HVAC system(s), ventilation and weatherization
- Appliances and electrical devices
- Behaviors of residents that impact energy use, such as whether occupants work from home, how often they run appliances/entertainment systems and temperature set points
- Retrofits and improvements made to the home, including appliance upgrades and home remodels
- Water use patterns
- Landscape and yard elements
- Transportation patterns, including make and model of vehicles, number of vehicles in each household and transportation behaviors

Additional data collected included meter data from the project's dual research meter network, water and gas consumption data from smart meters deployed by Texas Gas Service and Austin Water Service, and customer satisfaction information, environmental impacts, and performance of the systems tested.

The data is stored in Pecan Street's custom-architected database, where it is managed in accordance with the Department of Energy-approved Cyber Security Plan. The project team dedicated over $3 million in resources to developing a robust data management framework and to building a talented data management team. As the Internet of Things, smart devices that interact with the utility meter, and distributed energy resources become more prevalent, the ability to manage and draw useful information from big data is becoming increasingly important to utility business operations. Pecan Street's database architecture along with its Interoperability and Cyber Security Plan provide a useful foundation for other entities to develop effective big data management systems. Database architecture and management practices are discussed in more detail in the "Data Management" section.

For the systems tested inside of volunteer customer premises, electric use data was collected at the device level for major building systems, such as HVAC, electric vehicle charging, major appliances, solar panel generation, heating, water heating, and irrigation systems. The baseline data was compared with the demonstration period data to analyze the impact of deployed systems on household consumption. Pecan Street's Data Team evaluated the data collected to test against hypotheses and to determine how various systems and pricing models performed and interacted with each other.

Data is collected through a variety of sensors, meters and intelligent appliances. This data is stored on the device itself and reported over the residential Internet gateway and the utility networks, where practical. A key feature of the data communication and management strategy is that it does not rely on the utility network for data collection. All project data is transmitted, with minimal but variable latency, to secure servers at the Pike Power's Laboratory and Center for Commercialization. Pecan Street personnel concatenate and synchronize data flows from various sources and link all data from individual residences to a unique project identifier. Pecan Street personnel, through use of database processing techniques, create custom data sets in various formats for research teams, available on wiki-energy.org. In general, resource consumption data is gathered at 15-minute intervals and, where possible, 1-minute.

Project data is available for free to university researchers via direct access to Pecan Street's database and, beginning in 2014, through an online portal. Pecan Street's university researchers developed a robust body of academic analysis using Pecan Street's data that addresses critical public interest research questions on electric grid reliability and resiliency, climate change mitigation and adaptation, and behavioral economics.

The Pecan Street team evaluated the data collected to test against hypotheses and to determine how various systems and consumer behavior trials performed and interacted with each other.

Interaction with Project Stakeholders

Pecan Street – The board of directors and staff met monthly to communicate all project issues, review designs, approve budgets, disseminate project documents, review press releases and make sure staff is aligned with DOE and external stakeholder expectations.

Department of Energy – Pecan Street staff interacted regularly with DOE and their project management team in order to communicate changes in scope and project management issues associated with project milestones. Monthly progress reports also communicated changes in scope, budget, and schedule. Additional governmental communication was augmented as needed to ensure that the project met American Recovery and Reinvestment Act (ARRA) and DOE goals and requirements.

Executive Committee – Pecan Street staff and DOE Project team met regularly with the Executive Committee, which included two residents from the community, in order to disseminate information about the project and gather information about key community issues during the project planning and deployment phases.

Utility Side Team – DOE Project team Council and Pecan Street staff met regularly with the Utility Side Team in order to communicate project management issues related to the utility-side deployment and the data it will generate.

Customer-Premises Team – DOE Project team Council and Pecan Street staff met regularly with the Customer-Premises Team in order to communicate project management issues related to the customer-side deployment and the data it will generate.

Data Team – DOE Project team Council and Pecan Street staff met regularly with the Data Team in order to communicate project management issues associated with data collection, survey gathering and modeling of such data.

Pricing and Commercialization Team – Pecan Street staff and researchers met regularly to communicate issues associated with the development and testing of pricing models.

Lab – The Lab Design Team and Pecan Street staff met regularly with the Lab sub-team to communicate expectations, review designs, and develop scientific and educational programming for the lab during building design and construction.

Participant Communication – The executive board for the Smart Grid Demonstration Program has two residents from Mueller to ensure two-way communication between the volunteers and Pecan Street. A Resident's Council that includes 12 members of the community was also formed by Pecan Street in 2011 to broaden resident engagement in the project planning. The Council met regularly during planning and design of the study and the members served as a distribution network for information about the program.

Industry Community – In 2010, Pecan Street established an Industry Advisory Council composed of technology companies and utilities leading the smart grid industry. Through access to Pecan Street's research assets, these companies collaborate on pre-competitive research in the areas of smart grid, clean energy, consumer preferences and electric grid reliability.

Member companies also support Pecan Street's Research Consortium through mentorship and by curating research topics answerable using Pecan Street data that address questions of interest to industry.

Data Collection & Management

Selection of Data Collection Equipment

Pecan Street's Customer-Side Team released a Request for Information (RFI) in 2010 to private industry to test and deploy energy data collection technology for the baseline study. While 25 companies submitted proposals, only six met the criteria listed in the RFI and were considered for the Smart Grid Demonstration Program. It was important that the device had a built-in web server, on-board storage and remotely reconfigurable software.

In the initial project phase of baseline data collection, an energy monitoring device was used that provided 15-second interval sub-circuit level data. A total of eight circuits were monitored in each home during the baseline, including two circuits that captured whole-home measurements. Circuits were prioritized for monitoring based on a list of circuit types that typically have high power draws, and then narrowed down for each home depending on which circuits have a dedicated power draw and could therefore be disaggregated from other uses.

Due to the amount of data that was lost during transmission during the baseline period, the project team undertook a second round of evaluations for home energy monitoring devices that had on-site data storage. Three systems were considered and evaluated in the field. The first system proved to provide reliable data quality and a user-friendly online portal, but the device was susceptible to outages and required a monthly service charge. The project team ultimately decided not to pursue deployment of this product.

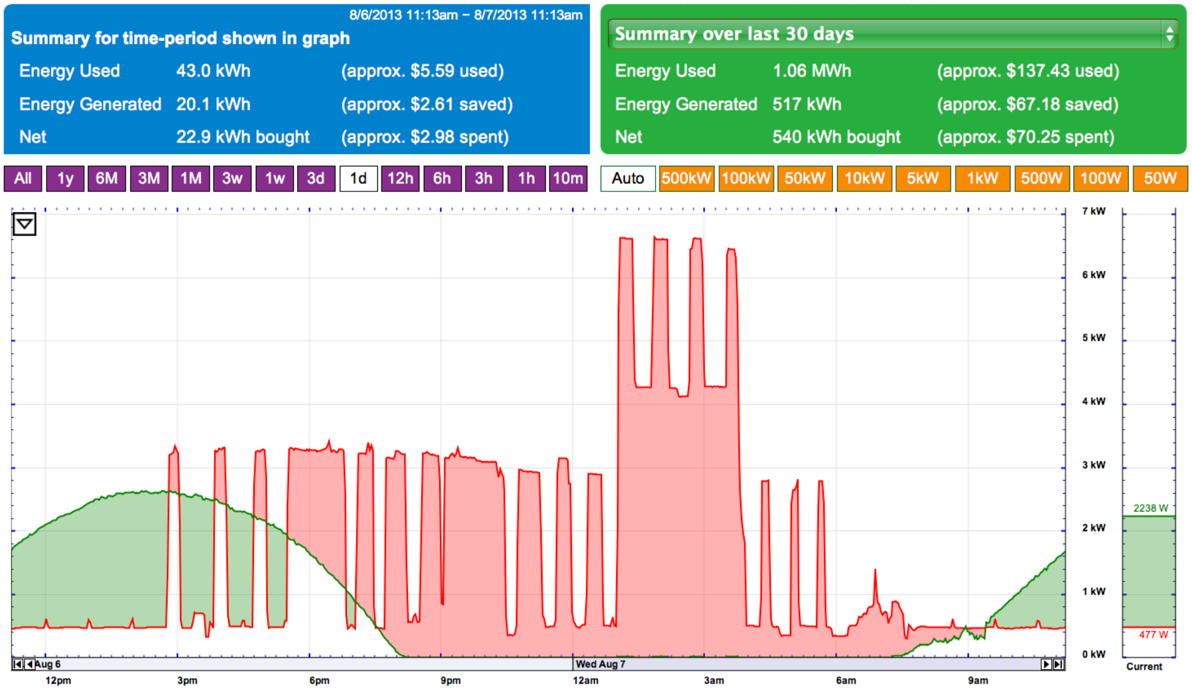
The second system, a test product manufactured by Sony, provided reliable data, on-site storage and a user-friendly portal that would not require a monthly service fee. This product was deployed in 200 homes.

A third system that was common in PV systems installed in participants' homes, eGauge, was selected for wide-scale deployment. This system most closely met the team's criteria, which included:

- a built-in web server that provided immediate customer and researcher access to data
- local data caching for up to a year's worth of data
- ability to retrieve all data even if the team's backhaul is down for an extended period

- remote reconfigurability through firmware downloads
- no cloud service fees

The selected system also provides a user-friendly web portal interface that delivers real-time data to the participant. Figure 6 is an example screenshot from the web portal.



8/6/2013 11:13am – 8/7/2013 11:13am

Summary for time-period shown in graph

Energy Used	43.0 kWh	(approx. $5.59 used)
Energy Generated	20.1 kWh	(approx. $2.61 saved)
Net	22.9 kWh bought	(approx. $2.98 spent)

Summary over last 30 days

Energy Used	1.06 MWh	(approx. $137.43 used)
Energy Generated	517 kWh	(approx. $67.18 saved)
Net	540 kWh bought	(approx. $70.25 spent)

Figure 6. eGauge web portal screenshot

Data Collection

Acquisition of ground-truth data has been a keystone part of Pecan Street's ability to generate cutting edge research and attract international investment for the regions in which it offers field testing services. One-hour interval smart meter data can only identify broad trends in daily electricity use. Such low resolution data can be problematic in efforts to evaluate the level of behavioral response to interventions, such as pricing information. A number of electricity-using devices are always on, others operate using scheduling components (such as smart thermostats), a third category can have a very different level of electricity use based on whether the appliance uses electricity or gas to generate heat (such as water heaters and clothes dryers) while a fourth category reflects intentional behavior (such as turning on televisions and light switches). Without knowing which devices were turned on, off or left as is in response to an intervention, it can be difficult to extract how much of a given change can be attributed to conscious behavioral versus non-intentional use changes.

Additionally, at resolutions of one hour, instantaneous changes in electricity use are averaged out over the course of the hour. This can obscure when a change in use happened (or even if a change happened at all).

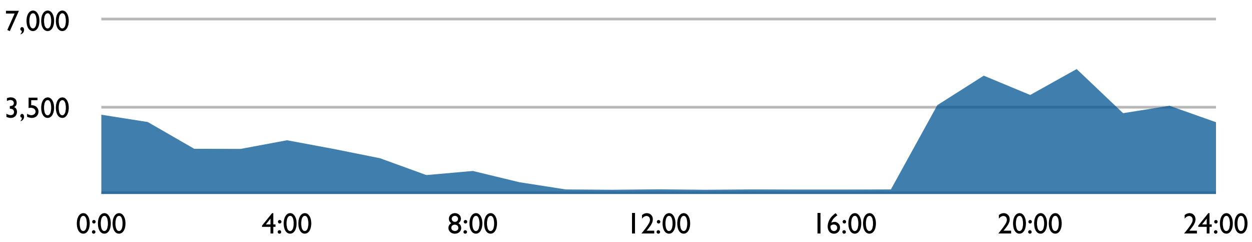


Figure 7. One-hour whole home electricity use (in watts/hr) for a single-family home

Disaggregated data providing appliance-level use information at 1-minute intervals, by contrast, can detect instantaneous changes in use of individual appliances. This can provide a high level of insight not just on how and on what individual residents use electricity but also on how their behavior changes in responses to external conditions and interventions. Figure 8 shows disaggregated electricity use (in watts/hour) at one-minute intervals for the same home on the same day using Pecan Street's research instrumentation and data systems.

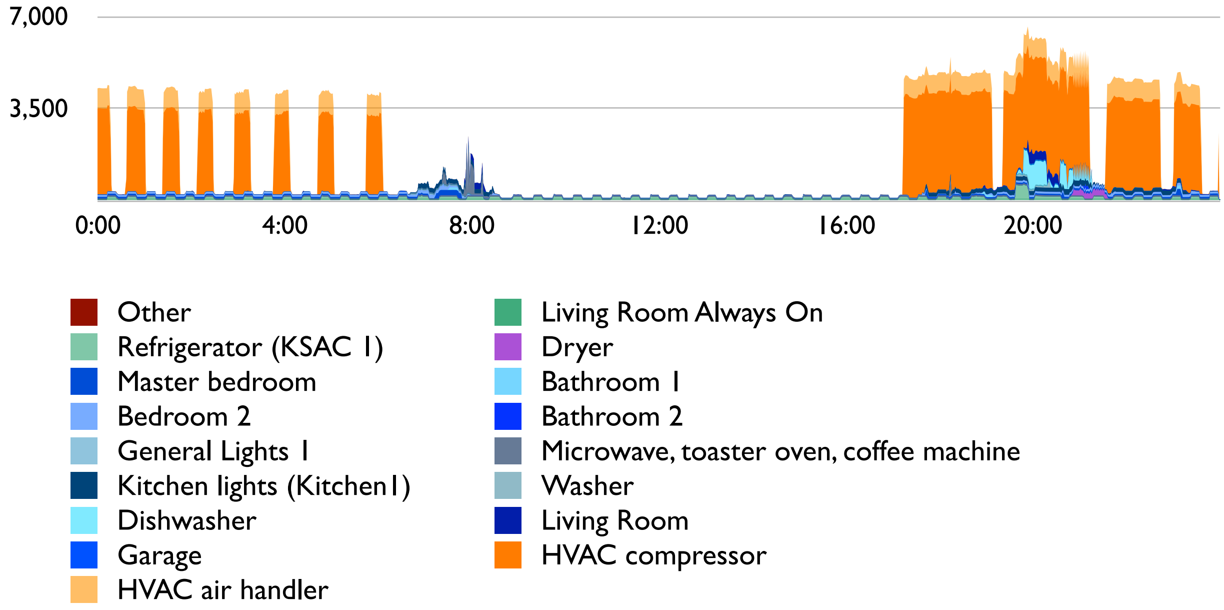


Figure 8. Disaggregated electricity use (in watts/hour) at one-minute intervals

For example, when viewed at the whole home level, an electric dryer, electric oven and air conditioner can exhibit comparable use profiles when on. If a price signal were sent to a resident of a home for which the researcher only had one hour interval whole home data, would a resulting change in use result from a clothes dryer ending a normal use cycle, from an air conditioner being turned off, or from the resident turning off lights and televisions at the moment the signal was received? One hour data would in most instances provide little insight to this question.

By comparing disaggregated electricity use of residents living in different housing types, for example multi-family versus single-family homes, and normalizing for square footage and other applicable variables, Pecan Street was able to isolate specific correlations and differences.

Data Management

Pecan Street created a custom database architecture to house the data collected through this study. The Pecan Street team includes a data team comprising three staff members: Data Group Director, Database Administrator, and Programmer. The data team configures real-time data transmission and local data caching to ensure no data is lost in the event of network failure.

With data obtained over the course of the study, the Project team was able to perform advanced analyses to complete the Benefits Analysis, such as average power draw and energy consumption across different time periods, load profiles showing the relative loads of different devices in the home, regression analysis to determine the impact of various home energy retrofits, and Savings to Investment Ratio (SIR) calculations looking at the cost and benefit of carrying out these retrofits. Home energy consumption data were collected for all participants and energy generation data were collected for participants with a PV system. In addition, time-stamped weather data were collected for the study period in order to correlate home energy use with external temperature and cloud conditions.

The project team undertook annual audits of its data management practices to ensure compliance with its Department of Energy-approved Cyber Security Plan and to verify that the plan was adequately addressing all potential threats.

Database Architecture

All project data flows to Pecan Street's secure data center where it is stored in accordance with Pecan Street's Department of Energy-approved Cyber Security Plan. The data is processed in near real-time and resides in the organization's custom-architected database, which is indexed to maximize data querying speed.

Project data was initially housed at The University of Texas's Advanced Computing Center (TACC). After the year-long baseline data collection period from February 2011 to February 2012, the data collection team moved the data from TACC to Pecan Street's custom-designed and wholly-owned data center to enable more rapid evaluation, troubleshooting and data analysis.

All data that is collected by Pecan Street is archived in native format on a data storage server. This server is backed up to a remote server using a commercial backup service. Furthermore, all data that is downloaded is extracted and placed into the Pecan Street database for use by Pecan Street staff and researchers. This database currently houses over 100 billion records of data, and has the ability to scale to larger amounts. The database is based off of PostgreSQL, and runs on Linux servers housed at the Pike Powers Lab, located in Austin, Texas.

The database has a redundant hot-swappable instance running adjacent in the event of a hardware failure. In the event of a power failure, the Pike Powers Lab has multiple uninterruptible power supplies (UPS), as well as an automatic transfer switch for a natural gas generator on-site. The natural gas generator can power the data resources of the lab indefinitely, until power is restored by the utility.

Energy consumption data collected from the field includes, but is not limited to, text and binary data that is collected from sensors installed in participants' homes. Examples of field data include comma-separated value (CSV) exports, extensible markup language (XML), and data derived from public and private APIs and data streams. Example of sources of data include sub-metered electric data collected by eGauge. eGauge data is extracted from in-premise sensors, and archived in a long-term datastore in native format. Upon extraction from the sensor, the data is transformed, extracted, and loaded into the Pecan Street database for easy and intuitive access from researchers and Pecan Street staff. This data is typically gathered on a 1-minute or 1-second basis for 12 to 24 circuits in each home, depending upon the specific layout and construction of the home.

Sometimes inaccurate data readings are present due to internet connection loss. These readings could be either too high or too low to be considered reasonable, or could be a series of numerous duplicate readings. The inaccurate data points are filtered out by using standard deviation and tests for numerous consecutive duplicate readings.

Produced Data

Additional support provided to Pecan Street by its industry partners enabled the organization to produce value-added data using the raw data collected from the field and sources of third-party data that are time-stamped or time series, such as weather, irradiance and utility generation emissions. Produced data includes curated data that is manually processed by data team members to ensure it is configured correctly and cleaned through an automated process to remove errors, analyzed data such as digital images, published tables, and tables of the numbers used for making published graphs. Furthermore, metadata — such as descriptions of suitable citations of experiments, apparatuses, raw materials, computational codes and computer calculation input conditions — were created and maintained for the project timeline to enable ease of data analysis.

Data Dissemination

Dissemination of project data to authorized third parties was conducted via two methods — website access and direct database access. No access to the raw underlying data was permitted due to the size and nature of the raw data. Only the processed and screened data was made available.

Pecan Street developed a custom web portal called Dataport (https://dataport.pecantreeet.org) that is used to disseminate data to project partners. The portal was created to meet the high demand for researcher access to the database. Before creation of Dataport the only means of extracting data from the database was through SQL queries. Pecan Street published standard SQL queries and instructions for how to construct SQL queries to aid researchers in accessing the data; however, it soon became apparent that an online user-friendly interface would expedite this process.

The first cut at creation of such a portal was named WikiEnergy and was hosted on its own website. A second iteration of the portal that included more features requested by project partners, such as real-time visualizations, was developed and launched in 2014 through Pecan Street's website. The new portal is hosted on Pecan Street's website to facilitate researchers who were aware of Pecan Street's smart grid demonstration in finding the data access resources.

Users can apply for access to the data on the Dataport site via an initial log-in screen. Once they are provided access to the Dataport site, additional instructions are provided for accessing the interactive data tools to download and visualize data directly within the site. Some users might want to access larger volumes of data directly from a database. When a user creates a Dataport login, an additional Dataport database account is created by Pecan Street as well. The user can access the underlying data in the native database format. There are no restrictions placed on the depth or breadth of information that can be requested from the database. Project data is typically made available for dissemination after a curation effort that takes approximately one to two weeks from the date of collection.

Some datasets deemed private or confidential are not be eligible for dissemination, even at the conclusion of the project. This data contains personally identifiable information (PII) or data used to link PII with research data. As such, this data is protected from distribution. Data used to link PII with result data is deemed highly confidential, and is kept on secured drives protected by two-factor authentication — a knowledge factor and possession factor. Only approved Pecan Street staff on a need-to-know basis have access to the highly confidential data.

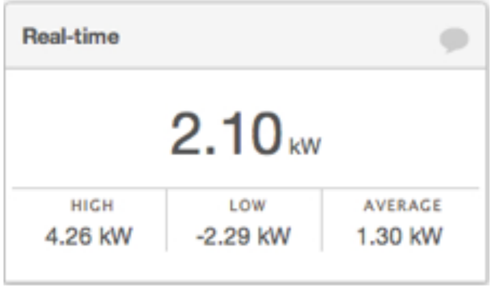
Participant Access to Data

At the conclusion of the baseline research period, Pecan Street provided all its field trial participants that received a HEMS with access to their home's or business's consumption and generation data (for homes with distributed generation).

In the first two years of the project, participants were provided with a secure, user-friendly portal to view their data. All deployed HEMS included a custom portal. Pecan Street commissioned a third party with an extremely user-friendly portal that provides advanced features such as bill tracking and goal setting called PlotWatt to create a custom portal that integrates project eGauge data. PlotWatt's standard portal uses utility meter data and is available for free to anyone in the USA. PlotWatt's portal provided significant additional value to participants and the project team received excellent feedback from this service. The PlotWatt portal was additionally used as the interface for the pricing and behavioral trial participants.

Pecan Street received funding under a separate Cooperative Agreement with the Department of Energy to create a custom mobile app, which was made available to all participants with an eGauge system in 2013. The mobile app, named Pumpkin Pie, is available for download on the Apple App Store and Google Play Store. Pumpkin Pie provides participants with enhanced value from their energy consumption data, including real-time budgeting, costs to run each monitored appliance in the home, comparison of energy consumption over time and between comparable homes, and custom recommendations for how to reduce energy use.

In addition to the eGauge monitoring system, Pecan Street commissioned PlotWatt to create and host a customized online portal for research participants that provides a user-friendly interface to view real-time whole home and monthly circuit-level energy use data. The energy information is shown on the portal in a series of easily understandable graphics that summarizes energy use as well as estimated usage costs for either whole home or by appliance. Figure 9 represents an example home's real-time, whole-home energy use in kilowatts (kW).



Real-time

2.10 kW

HIGH	LOW	AVERAGE
4.26 kW	-2.29 kW	1.30 kW

Figure 9. PlotWatt's real-time whole energy use data statistics

Figure 10 shows the daily energy usage and costs and a usage comparison to the previous day.

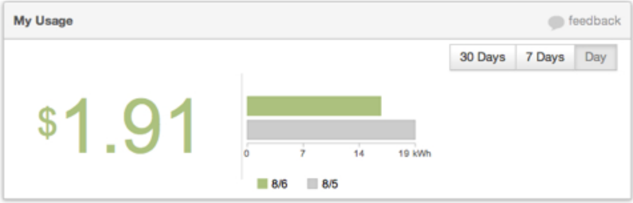


Figure 10. PlotWatt's real-time whole energy use data statistics

Figure 11 shows an example of monthly cost per appliance, which gives participants a view into what appliance is costing the most money to operate.

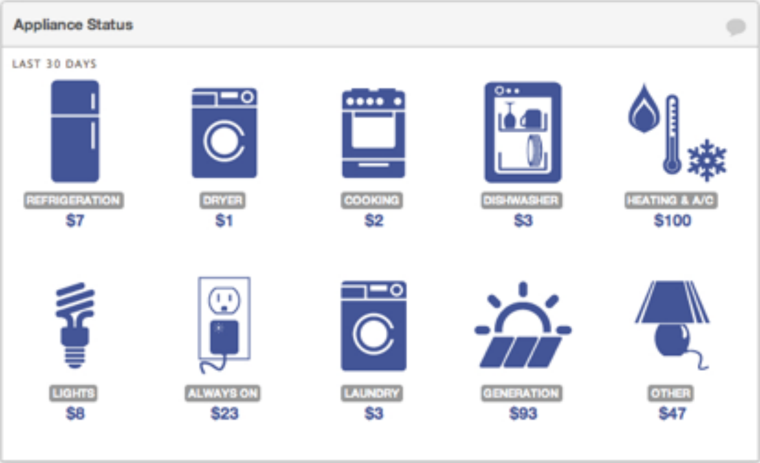
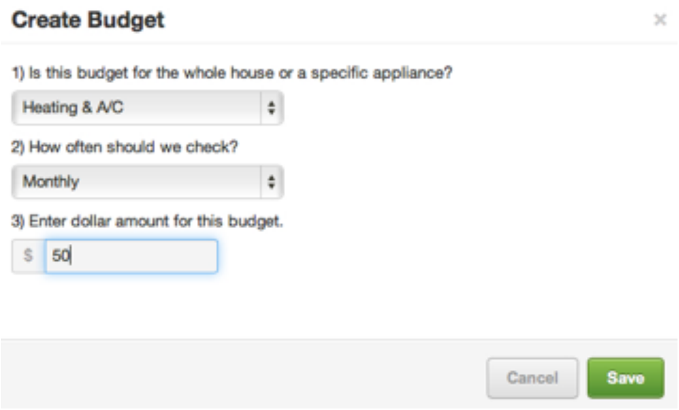


Figure 11. PlotWatt's appliance status by cost

PlotWatt also provides tools to help participants track their energy costs. Energy budgets are one such tool that allows participants to set a monthly, weekly, or daily goals based on a user-specified monetary amount for either whole home or by appliance. The participant receives email alerts when budgets are exceeded. Figure 12 shows the interface to which participants can create their own personalized energy budgets.


Create Budget

1) Is this budget for the whole house or a specific appliance?

Heating & A/C

2) How often should we check?

Monthly

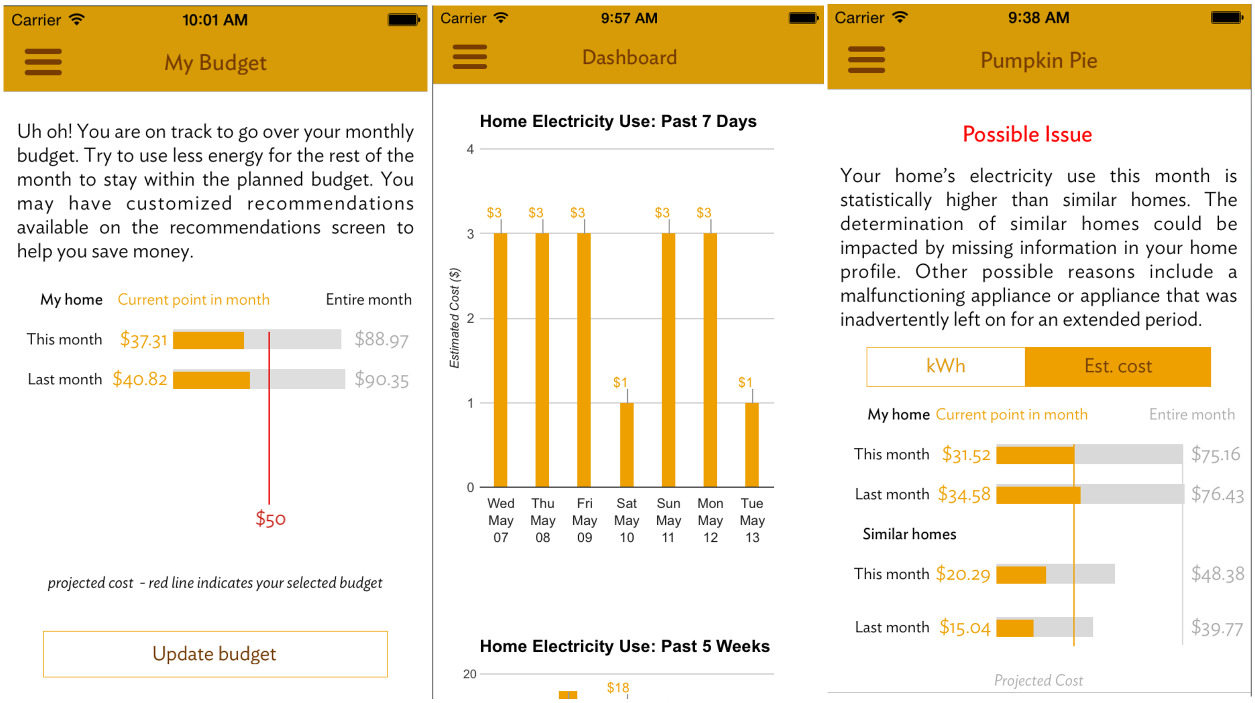
3) Enter dollar amount for this budget.

$ 50

Figure 12. Personalized energy budget tool

Pecan Street also created a mobile application, available for Apple and Android devices, that participants were able to access for free.

The app, called Pumpkin Pie, provides value-added information on participants' energy consumption and, where applicable, generation data. The app features comparisons of the user's home against comparable homes in the study, a budgeting tool, the ability to see the cost of each monitored device over a customized period of time, and custom recommendations for how to reduce energy use. The app was one of the communication tools used to conduct the behavioral trials.



Uh oh! You are on track to go over your monthly budget. Try to use less energy for the rest of the month to stay within the planned budget. You may have customized recommendations available on the recommendations screen to help you save money.

Possible Issue

Your home's electricity use this month is statistically higher than similar homes. The determination of similar homes could be impacted by missing information in your home profile. Other possible reasons include a malfunctioning appliance or appliance that was inadvertently left on for an extended period.

Figure 13. Screenshots of the Pumpkin Pie mobile application

Benefits Analysis & Metrics

The project metrics include analysis of how the deployed smart grid technologies influence the customer's environmental impact, affect the customer's electric bill, promote private sector interest offering new products and services, impact the load curve of the customer, and impact utility infrastructure. In addition to the Build and Impact Metrics created by the Department of Energy to track project achievements and progress, Pecan Street posed research questions for each system demonstrated and sought to answer those questions through a benefits analysis. The results of these analysis are discussed in the Results section.

Build Metrics & Benefits Analysis

This section contains each of the Build and Impact Metrics that Pecan Street reported to the Department of Energy. Build metrics typically focus on equipment costs associated with and reported for a project. The metrics apply to the total project supported by the DOE and to Pecan Street cost shared funds. Included in the Build Metrics are explanations of the data collection methods, frequency, and aggregation and analytical methods used to determine the metrics.

Monetary Investments

Pecan Street reported on funds expended for the deployment of the Smart Grid Demonstration Program. The report includes the DOE grants award and the cost share of all recipients. Pecan Street reported investments related to the 'installed cost of equipment' once the assets are deployed and considered utility assets.

Financial analysts will utilize the Pecan Street Financials System to determine or estimate the monetary investments related to the installation of equipment. Pecan Street expects to develop some estimates, based on vendor contracts and internal labor rates for equipment installation, testing and commissioning and apply those costs as assets are installed.

Equipment Asset Build Metrics

Pecan Street reported on the equipment asset build metrics as either project or system metrics throughout the reporting period. Project metrics were reported for the assets and programs funded by DOE and through cost share. System metrics determined to be applicable to the were reported project Smart Grid assets and programs that were already in place or were deployed using only Pecan Street funding during the reporting period. The system metrics were reported as a cumulative amount representing the total assets deployed on the Transmission and Distribution Systems.

Pecan Street assessed its impact primarily in the area of customer systems deployed and pricing models tested. Customer systems and AMI meters were reported based upon the number of research trial participants that received one or a combination of the following technologies:

- In-Home Display
- Programmable Communicating Thermostats
- Smart Appliances
- Energy Management Devices/Systems

Any modifications made by Austin Energy to the local distribution system in response to the systems deployed on the customer-side were planned to be documented and analyzed for applicable lessons learned in other residential distribution systems throughout the nation; however, because of Austin Energy's infrastructure planning and system sizing processes, the utility did not need to make any infrastructure modifications as a result of technologies deployed on customer premises. The one exception is the utility's deployment of dual sockets and secondary utility-grade meter on 247 homes selected to take part in the research meter network.

Impact Metrics & Benefits Analysis

Impact metrics typically define reductions in energy use and in environmental emissions as a result of technology implementations. Total generation, use, and electric vehicle charging consumption were calculated using data collected by Pecan Street. Environmental impacts were calculated by developing a per kWh emissions estimate using system-wide Austin Energy emissions data, and applying that emissions estimate to consumption and generation data collected by Pecan Street, and then calculating energy and associated emissions savings. Utility system data reported was provided by Austin Energy and represents information for the entire Austin Energy territory.

Electric Distribution Systems

Pecan Street developed Electric Distribution System Impacts by installing GridSense Transformer IQ monitors on four transformers serving homes in Mueller participating in the study. The transformer monitors revealed the impact on the utility's infrastructure from dense deployments of distributed PV generation and electric vehicles.

Using data provided by Austin Energy and data collected by the project on energy use and generation in participating homes, the project team compared baseline system performance with the system performance after the installation of tested technologies and behavioral programs.

Consumer Systems

The Project and System Metrics look at impacts observed from the systems deployed, including HEMS, distributed energy resources, electric vehicles, and electric vehicle charging.

Pecan Street combined detailed appliance-level and distributed energy system-level data gathered from the installed HEMS with data collected by the research meter network, smart meters, and annual sociodemographic survey to calculate the impacts of the project on customers and the utility.

Home Energy Management Systems

Pecan Street theorized the by providing real-time feedback to customers on their energy use, HEMS would enable users to more readily manage their energy consumption and result in a peak demand reduction. The project team also theorized that installation of HEMS that collect granular, near real time data on energy consumption would be critical to evaluating the impacts of smart grid technologies and behavioral interventions on energy use, and that only with this level of data could the project develop meaningful insights about consumer behavior, preferences, and the impacts of smart grid technologies.

To demonstrate the benefits of HEMS for energy management within the residential and small commercial customer classes, Pecan Street established a baseline of energy use within 200 homes spanning a variety of building types and collected data on their energy consumption for one year. After the baseline period of 12 months, the research team provided these participants with a user-friendly online portal to view their information. The project team analyzed difference in energy consumption during the baseline period and for the 24 months that participants had access to their data consumption.

The benefits that data from HEMS provide to the research and development sectors is made clear by the research findings the project team was able to develop on the customer systems and behavioral trials tested through this project. Throughout the project period, Pecan Street collected over 200 billion data records and collects as much information daily from its field trials as a utility that collects hourly smart meter data from three million customers. Currently, 150 academic researchers from 89 universities in 27 countries are accessing Pecan Street's data through its free online portal. The overwhelming interest from leading researchers and the volume of academic publications produced using Pecan Street's data is further testament to the on-going value of the dataset produced by this project.

Smart Meters

To demonstrate the benefits of smart meters, Pecan Street installed 247 dual-socketed Landis+Gyr Focus AX meters in a research meter network configuration. These meters were used to test the benefits of AMI smart meters, including:

- Two-way communication with the customer that enables utilities to send demand response event and pricing signal information to specific customers, and for customers to respond either through behavior modification or automatic changes in appliance behavior by smart appliances
- Non-Intrusive Load Monitoring (NILM) that enables utilities or approved third parties to ascertain the appliance-level energy use within a property to develop customized recommendations for how the property can reduce or shift its energy consumption
- HAN testing and configuration development

Additional benefits from AMI smart meters are derived by utilities; however, this project only focused on benefits accrued to the customer.

To analyze these benefits, Pecan Street established individual research trials to investigate two-way communication optimization and impacts, and the effectiveness of NILM technologies. For the former, Pecan Street first undertook a project at its lab and within its field trial to analyze and test connection of smart appliances to the Home Area Network (HAN). The project team then connected LG Electronics smart appliances to the HAN in the homes of 13 participants in addition to the lab.

LG Electronics smart refrigerators were deployed in 3 homes and its lab, and LG Electronics smart clothes washers and dryers were deployed in 10 homes plus one set at the lab. All LG smart appliance were donated to the project by LG Electronics. Pecan Street paired these appliances to the research meters installed on each home. Once the devices were paired, Pecan Street sent pricing signals and demand response events to the appliances. Using data provided by LG Electronics, Pecan Street was able to calculate the frequency of which the appliances were able to receive and respond to the signal. Pecan Street additionally gathered information from participants in the field trial on their experience with the appliances, how often they over-rode the 'efficiency setting' that went into effect when prices were raised or a demand response event was in place, and whether they would elect to participate in a utility program that required their appliances to use the 'efficiency setting' when called upon via the meter.

To analyze the benefits of current NILM technologies, Pecan Street held a conference in partnership with Carnegie Mellon University in June 2014 on the current state of NILM technologies, challenges to the field, and recent advancements. Presenters at the conference included:

- Brewster McCracken, Pecan Street Inc.
- Zico Kolter, Carnegie Mellon University
- Mario Berges, Carnegie Mellon University
- Karim Said Barsim, University of Stuttgart
- Kyle Anderson, Carnegie Mellon University
- Rahul Mohan, Bidgely
- Hal Alles, Verlitics
- Shankar Sastry, University of California at Berkeley
- Oliver Parson, University of Southampton
- Sean Barker, University of Massachusetts Amherst
- Jack Kelly, Imperial College of London

Pecan Street additionally worked with the Data Science for Social Good program in the summer of 2014 and with EEME company spun out of Carnegie Mellon University to evaluate the accuracy and usefulness of current NILM technologies. Pecan Street additionally integrated its data into NILMTK (http://nilmtk.github.io/), an open source NILM toolkit. The evaluated NILM algorithms were applied to meter data collected by Pecan Street. The results were compared to the circuit-level data also gathered for those homes to evaluate accuracy. A NILM system that was at least 85% accurate in its disaggregation of uses based upon 15-minute smart meter data was deemed useful to the customer. To gain further insight in the accuracy and usefulness of the NILM technologies, the project team calculated the percent of use accurately identified over home's the total use. By looking at the percent of the load accurately identified in addition to the number of devices accurately identified, the project team was able to more thoroughly understand the usefulness of the algorithm in helping customer's reduce total consumption.

Smart Grid Water Systems

To evaluate the impacts of smart grid water systems, Pecan Street collected water consumption data from 57 homes that also had an installed HEMS, and evaluated smart water monitoring systems in its lab to investigate their accuracy and usefulness in water management. The data on water consumption was collected at 1-minute to 30-minute intervals by ERT readers connected to a gateway installed in the home of participants in this field trial. ERT reading devices sent the data to Pecan Street's data center over the participant's broadband Internet. When Internet connection was unavailable, the gateway cached the data locally until an Internet connection could be re-established. Pecan Street also installed an ERT reader on the roof of its lab that pinged water meters from participating homes within a half-mile radius of the lab and collected their water meter data on a 15-minute interval.

The water meter data was collected for a period of 12 months. The data was paired with the circuit-level energy consumption data also collected by the project team and analyzed to determine the energy-intensity of water consumption and the potential for residential water conservation to reduce energy consumption. Hot water heating is the most energy-intensive water use in homes; therefore, the project team analyzed the relative energy savings associated with a tankless hot water heater versus a tanked hot water heater. Since most of the project participants have natural gas-powered heat and hot water, the results of this study are anecdotal rather than statistically significant.

To understand the potential impact of smart water meters that collect data at a frequency high enough to enable near real-time leak detection and meaningful disaggregation of water consumption that would enable users to make reductions in water consumption, Pecan Street undertook an analysis of the state of smart water meter technology and field tested promising systems. The results of this analysis are discussed in the Results section.

Distributed Solar Photovoltaic Energy

With adoption of PV distributed generation (DG) on the rise, Pecan Street theorized that customer-sited DG would play a critical role in the smart grid with a suite of potential benefits and challenges for the utility.

Pecan Street's research focused on two aspects of residential PV systems. First, the project team investigated the optimal installation configuration that would maximize utility and customer benefits. South-facing solar is the standard configuration for most installations because south-facing captures the most sunlight throughout the day over the course of a year. However, Pecan Street theorized that west-facing solar systems may better align with in-home consumption, particularly during peak consumption periods.

To evaluate optimal installation configuration, Pecan Street created a dense network of customer-sited solar PV generation with a mix of south- and west-facing systems totaling over 1MW of power generation capacity with an average per-home system size of 5.5 kWh. To ensure installation of sufficient west-facing PV for a meaningful analysis of the benefits of south- versus west-facing PV systems, the project team provided additional incentives to participants for installation of west-facing solar. Pecan Street's PV rebate program resulted in 375 kW of west-facing solar spread across 115 homes and 537 kW of south-facing solar spread across 145 homes. 91 homes installed both south- and west-facing systems, 49 homes installed only south-facing systems, and 23 homes installed only west-facing systems. 5 homes installed south-facing systems with a few east-facing panels.

Participants were required to install an inverter that was capable of reporting detailed, near real time power production information over an Internet connection, and for systems with multiple orientations either an inverter for each orientation must be installed or one inverter for the system capable of reporting separate information for each orientation.

The project team used the generation information to track power production by time of day across the seasons, and compared the power production information to consumption. The analysis demonstrated the differences in overlap of power production with on-site power consumption by PV system directional orientation. The project team also compared the detailed power production information with the transformer monitoring data to discern the impact on the grid's infrastructure from dense deployments of distributed generation. The results of this analysis are discussed in the Results section.

Plug-In Electric Vehicles

The project team theorized that purchase of plug-in electric vehicles will continue to grow at an exponential rate, electric vehicles will be purchased in geographic clusters, and therefore have the potential to significantly alter the residential demand profile.

The project team theorized that electric vehicles were likely to be charged during peak demand times of 4-7pm, when most people get home from work, and would therefore have pronounced on transformers and distributions feeders. The project team also theorized that the potential negative grid impacts of electric vehicle charging could be offset by concurrent installation of PV systems and through behavioral programs that incentivize EV charging during off-peak hours.

To undertake this analysis and demonstrate options for integration of electric vehicles onto the Energy Internet, in February 2012 Pecan Street offered incentives for the purchase or lease of an EV to participants in its PV research trial. By offering the incentive to participants in the PV trial, Pecan Street was able to create a dense network of EVs that mirrored the modeled adoption pattern that has been witnessed to date. The incentive program was successful and resulted in 69 participating homes acquiring electric vehicles within a 6-month timeframe. Pecan Street also purchased two electric vehicles for testing at its lab to evaluate hardware and software systems that provide remote and/or intelligent control of the charging.

Participants in the Electric Vehicle research trial received a Level 2 EVSE from Pecan Street. At the time of the EVSE installation, Pecan Street installed a CT collar on the dedicated circuit that would power the EVSE and connected that CT collar to the HEMS for the premises. This ensured Pecan Street could collect near real-time data on the home charging pattern for the EV.

The project team collected data on EV charging from the research trial for a period of 12 months, and then introduced a pricing trial and behavioral trial program to analyze the elasticity of charging behavior and the most effective method for encouraging EV owners to charge during off-peak hours. To analyze the opportunity for distributed PV generation to offset EV charging, the project team compared the EV charging times and duration with the PV generation data. To ascertain the grid impacts of dense networks of electric vehicles with home charging systems, the project team compared the EV charging data for homes on transformers monitored by Pecan Street with the transformer monitoring data. By overlaying the transformer data with the EV charging data, the project team was able to discern the unique impacts of EVs onto the transformers.

Distributed Energy Storage

The project team theorized that integration of battery storage will play a critical role in balancing the power demands and power quality of homes with distributed generation. To analyze the benefits of distributed energy storage and methods to accelerate adoption of energy storage, the project team worked closely with its Industry Advisory Council and academic research partners to model various distributed generation configuration, test and analyze intelligent control systems, test and evaluate methods for integration of storage within the home and interconnection of storage to the grid.

Pecan Street's energy storage research followed two tracks: (1) efforts undertaken at Pecan Street's lab to analyze system integration and optimal sizing guidelines and (2) interconnection and permitting requirements development with Austin Energy and Sony.

Pecan Street worked in partnership with Sony, the provider of batteries used in the field trials, to test installation guidelines and interconnection procedures at residential premises. Pecan Street procured seven residential battery systems (battery module plus battery server and gateway) from Sony, and Sony donated an additional 60 1.05 kWh lithium ion storage systems to the project. Five Sony batteries were installed at the home's of participants and at Pecan Street's lab, but not grid-connected, to first understand the installation requirements. The project team then worked with Austin Energy to establish model interconnection guidelines for connection of residential energy storage to the grid. At the time of system procurement, Austin Energy (AE) did not have interconnection guidelines for customer-owned energy storage systems, considered a distributed resource by AE. Pecan Street and Sony worked closely with Austin Energy to establish installation guidelines, interconnection requirements, and a permitting process. Pecan Street, Sony and Austin Energy teams met frequently over the course of a year; however, AE was not able to develop interconnection requirements and the Sony battery systems were not able to be connected to the grid. At the time of this report, Austin Energy had not developed detailed procedures for connection of energy storage systems to its grid, and procedures to handle energy storage systems in parallel with the Austin Energy distribution system have not been developed.

To undertake an analysis of optimal energy storage system integration within a residential premise and optimal battery sizing, Pecan Street installed 8 Valence Technology lithium iron magnesium phosphate batteries at its lab, resulting in 30 kWh of energy storage. The batteries were donated by the Center for Commercialization of Electric Technologies (CCET). The energy storage system is paired with a 3 kW crystalline silicon solar array that is south-facing and 2.8 kW of CIGS thin film solar that is west-facing, totaling 5.8 kW of solar production capacity, and is connected to a 18kW natural gas generator. The energy storage system has both AC and DC distribution capabilities and is connected to an intelligent breaker panel that enables powering some loads from the storage system while powering others from the grid. The energy storage system can operate in parallel with the grid or island from the grid to provide critical power in the event of a utility outage.

The lab's energy storage system was utilized to develop an open-source platform for energy storage integration, called the Energy Switch, that enables utilities to engage with homes, businesses and building campuses as a source of cost-effective load balancing, calling upon distributed generation and demand resources as needed.

Behavioral Interventions

The Project team demonstrated multiple consumer behavior interventions to determine the most effective strategies utilities can employ to reduce peak demand and promote energy conservation behavior.

Additionally, working in partnership with IAC members Landis+Gyr, LG Electronics, and Austin Energy, Pecan Street tested demand response programs in the lab and within the homes of a group of project participants. This research trial resulted in a framework for communication protocols between the meter and smart appliances that enables the appliances to respond to pricing events and/or demand response events in a manner that participants found satisfactory.

IV. Results

Operation of Smart Grid Technologies and System

A summary of the operating performance and associated costs of Smart Grid technologies and systems demonstrated to date is included in Table 10, below.

Tables 10. Operating and Performance Costs

Task	Cost Share	Federal Share	Total
Establish Guidelines			
Develop Operating Guidelines	0	$169,452	$169,452
Design and Construction			
Energy Internet Demonstration planning and preparation	$1,975,205	$945,559	$2,920,764
Collect Baseline Data	$0	$206,728	$206,728
Construct Lab	$0	$1,291,564	$1,291,564
Operate Lab	$0	$448,672	$448,672
Create and Deploy Behavioral Trials	$4,718,693	$610,382	$5,329,075
Select and Deploy Utility Side Systems	$0	$2,400	$2,400
Select and Deploy Customer Side Smart Grid Systems	$6,024,176	$1,935,716	$7,959,892
Deploy Electric Vehicles	$7,699	$566,098	$573,797
Promote Commercialization of Smart Grid Technologies	$267,267	$385,080	$652,347
Operation			
Issue Project Reports, Share Findings and Conduct Education	$0	$633,513	$633,513
Collect and Evaluate Data	$1,260,468	$3,207,296	$4,467,764
Dismantle Project	$0	$1,109	$1,109
Total Costs for Energy Internet Demonstration Program	**$14,253,508**	**$10,403,569**	**$24,657,077**

Program 1: Demonstrate Energy Internet capabilities on customer side of the meter

Smart Meters

To mimic the utility-side smart meters, Pecan Street procured 471 AMI smart meters that Austin Energy deployed on a dual socket configuration in Mueller and the surrounding neighborhoods. These meters are industry standard and act as a HAN gateway. Data is collected in 15-minute whole-home readings.

The deployment of these meters was a success. Command Center software provided by Industry Advisory Council member Landis+Gyr provides a user-friendly interface that enables Pecan Street to control all of the meters. Because the meters were deployed on a dual socket, Pecan Street's research activities over this meter network does not interfere with Austin Energy's billing meters.

This meter network constitutes the nation's only research meter network where companies can develop, and verify the performance of hardware and software using actual customer data provided by representative smart meters. It's also the only group of smart meters with advanced home energy monitoring systems to compare the value of utility smart meter data to ground truth circuit monitoring systems.

NILM Evaluation

Smart meter data paired with the data collected from Pecan Street's installed home energy monitoring systems (HEMS), enabled the organization to evaluate the reliability and accuracy of Non-Intrusive Load Monitoring (NILM) load disaggregation algorithms. To Pecan Street's knowledge this research is unique and represents the first time that a commercial disaggregation algorithm has been validated by a third party so extensively and on such a large scale. It appears to also represent the first time that a commercial vendor has released public information on the accuracy metrics for its disaggregation algorithms.

The idea of using data collected from single point sensing at mains to infer appliance-level electricity consumption is not new. Technology to facilitate the collection of data required for such analytics has only recently started to become cost effective and pervasive owing largely to the adoption of Advanced Metering Infrastructure (AMI), also known as smart meters, by utilities. The Edison Institute reported in its September 2014 study that approximately 43% of US homes have a smart meter installed[1]. Accessing the smart meter data, which is typically collected at 15-minute or hourly intervals, is further streamlined through the Green Button data standard that was originally launched by The White House Technology Office and adopted by

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[1] The Edison Foundation. September 2014. *Utility-Scale Smart Meter Deployments*. Accessed at: http://www.edisonfoundation.net/iei/Documents/IEI_SmartMeterUpdate_0914.pdf

dozens of electric utilities and technology vendors[2]. Currently, more than 60 million US households and businesses are reported to have access to their utility usage information in XML or CSV format through Green Button. Given the increasing availability and ease of access to smart meter data, AMI-based demand-side analytics is emerging as a scalable value proposition.

The academic community has been exploring the problem of energy disaggregation, also known as Non-Intrusive Load Monitoring, or NILM, for more than two decades. A clear consensus on the correct features, methods, and algorithms for solving NILM is yet to be reached. What complicates the issue further is the lack of standard datasets with extensive ground truth in which the algorithms can be validated. Efforts like *NILMTK (NILM Toolkit)* are currently underway from within the academic community in part to resolve this issue[3]. Reviews of the field have currently placed the accuracy of disaggregation algorithms on low frequency data — the kind provided by smart meters - to be around 0.55[4]. The reader is advised to see the *Green Tech Media* article that summarizes such studies[5]. These validation-oriented reviews were subject to two limitations, namely, small sample sizes of a handful of homes and short time spans only covering a couple of months at most. Unfortunately, the utility smart grid ecosystem has not tapped AMI's full value as extensive validations are required before implementing new technology solutions – these reviews have failed to build a reliable business case for many stakeholders given their narrow scale and scope. For this reason, EEme, LLC (an energy analytics spin out from Carnegie Mellon University) decided to conduct a comprehensive third party validation study based on a large sample size of year-round ground truth residential load data to build the foundation for business cases that can leverage AMI analytics and load disaggregation.

The input data for a NILM device is usually a time-stamped, whole-home energy data stream. The interval for this data stream varies depending on the resolution of the energy device. Utility smart meters typically provide data intervals of one-hour or 15-minutes, with some smart meters having the capacity to provide a more granular interval of around 5 minutes. Commercially available, user installed energy monitors can provide smaller intervals of 1 minute or a few secondsSome such commercially available NILM devices can also provide high-

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[2] Greenbutton Homepage. Accessed at: http://greenbuttondata.org/

[3] Kelly, Jack, and Nipun Batra, Oliver Parson, Haimonti Dutta, William Knottenbelt, Alex Rogers, Amarjeet Singh, Mani Srivastava. *NILMTK v0.2: A Non-intrusive Load Monitoring Toolkit for Large Scale Data Sets* (Best demo award). In: 1st ACM International Conference on Embedded Systems For Energy-Efficient Buildings (BuildSys), Memphis, TN, USA. 2014.

[4] Armel, Carrie K and A. Gupta, A, G. Shrimali, A. Albert. *Is disaggregation the holy grail of energy efficiency?* The case of electricity. Energ. Policy 2013, 52, 213–234.

[5] GreenTechMedia. November 2013. *Putting Energy Disaggregation Tech to the Test.* Accessed at: http://www.greentechmedia.com/articles/read/putting-energy-disaggregation-tech-to-the-test

frequency voltage/current electric waveform sampling, potentially allowing energy loads to be identified by a characteristic waveform signature during start-up, operation, and/or shutdown.

Regardless of the NILM source data device, Pecan Street's data can be used to verify the accuracy of the NILM disaggregation algorithm by comparing the NILM load estimate for a particular appliance with the actual load data as measured by Pecan Street. A customary way to assess the accuracy of the NILM estimate is described by this equation:

$$Error\ (\%) = 100\% * (Inferred\ Appliance\ Usage - Actual\ Appliance\ Usage) / (Actual\ Appliance\ Usage)$$

Pecan Street has used its historic database to calculate the accuracy of various NILM device-algorithm combinations. The following table shows a monthly NILM appliance evaluation estimate based on a 15-minute whole-home data stream for each month being estimated.

Table 11. Monthly NILM Appliance Evaluation

dataid	datetime_start	datetime_end	hvac_percent_difference	dishwasher_percent_difference	refrigerator_percent_difference
22	9/30/13 0:00	10/29/13 23:45	-29.6	410.1	-30.7
22	10/30/13 0:00	11/28/13 23:45	-35.7	592.5	-15.2
22	11/29/13 0:00	12/28/13 23:45	-34.8	713.7	-15.6
22	12/29/13 0:00	1/27/14 23:45	-35.1	1930.5	-5.7
22	1/28/14 0:00	2/26/14 23:45	-37.6	947.9	-9.2
22	2/27/14 0:00	3/29/14 0:45	-41.9	306.7	-8.8
22	3/29/14 1:00	4/28/14 0:45	-47.6	3242.9	-4.9
22	4/28/14 1:00	5/28/14 0:45	-40.7	2791.6	-12.8
22	5/28/14 1:00	6/27/14 0:45	-32.8	8530.4	-23
22	6/27/14 1:00	7/27/14 0:45	-30.7	1327.1	-31.4
22	7/27/14 1:00	8/26/14 0:45	-31.2	1240.5	-38.1
22	8/26/14 1:00	9/28/14 23:45	-32.1	2399.3	-40.4
26	9/30/13 0:00	10/29/13 23:45	-66.7	89	-28.9
26	10/30/13 0:00	11/28/13 23:45	-35.9	50	-21.1
26	11/29/13 0:00	12/28/13 23:45	263.3	161	-2.3
26	12/29/13 0:00	1/27/14 23:45	180.3	22.2	14.2
26	1/28/14 0:00	2/26/14 23:45	125.4	67.3	5.8
26	2/27/14 0:00	3/29/14 0:45	-27.2	74.7	1.9
26	3/29/14 1:00	4/28/14 0:45	-39.7	188.3	-14.7
26	4/28/14 1:00	5/28/14 0:45	-57.1	117.9	-16.5
26	5/28/14 1:00	6/27/14 0:45	-45.8	163.1	-24.2
26	6/27/14 1:00	7/27/14 0:45	-34.6	72.5	-30.6
26	7/27/14 1:00	8/26/14 0:45	-38.2	110.4	-28.4
26	8/26/14 1:00	9/28/14 23:45	-54.5	93.6	-27.3

Other time intervals for source data and output data may be constructed and are usually determined by application. General home energy awareness and bill management may be accomplished by relatively large time intervals and reasonable accuracy. Real-time appliance management applications require much shorter time intervals. Residential micro-grid management might require much greater accuracy of the actual power measurement.

Dividing the error calculation by the whole home usage, as shown below, can help normalize the contribution of any particular appliance to overall home consumption and may be helpful in home energy management applications.

$$\text{Total Usage Referenced Error (\%)} = 100\% * (\text{Inferred Appliance Usage} - \text{Actual Appliance Usage}) / \text{Total Home Use}$$

Analyzing disaggregated NILM values also requires examination of various statistical parameters. For instance, the MEAN value of the disaggregation errors for various time intervals may appear unusually large if the estimate for a single time interval is high and the actual is unusually low. In such cases it may be more useful to look at the median value of errors rather than the mean.

Pecan Street has worked with a number of industry partners to measure and assess the effectiveness of various NILM devices and algorithms. The project team will build upon its expertise in this area to research available NILM devices, test selected devices in the lab to determine accuracy and reliability of data transmission, and then deploy worthy devices in the Phase 1 pilot group of homes for field evaluation. The project team also has experience evaluating the accuracy and reliability of plug-load monitors for similar projects, and will test these devices according to the same protocols as the NILM devices. Combinations of NILM and plug-load monitors may also be evaluated to determine if a multi-device system may produce the best results.

Case Study: EEme

EEme processed 15-minute smart meter interval data, provided by Pecan Street Inc. using its proprietary algorithms constructed at Carnegie Mellon University, and disaggregated the data into four end-uses: heating/cooling, refrigerator, dishwasher and clothes dryer. Pecan Street evaluated the disaggregation results comparing them with the actual ground truth data collected from the installed HEMS. This comparison was performed covering yearly and monthly timespans.

Other time intervals for source data and output data may be constructed and are usually determined by application. General home energy awareness and bill management may be accomplished by relatively large time intervals, e.g., monthly or yearly, and reasonable accuracy. As suggested by DSM providers, a 0.60 accuracy would be desirable for consumer segmentation and engagement, whereas a higher degree of accuracy would be necessary for compliance-driven program evaluation efforts in the absence of other data.

Real-time appliance management applications could require much shorter time intervals, e.g., hourly. Residential micro-grid management might require much greater accuracy of the actual power measurement. The list of use cases and coupled with the necessary accuracy and time intervals can be extended.

Pecan Street removed seven homes from the evaluation because anomalous sensor readings were identified for these homes. This resulted in a final sample of 264 households. The following error metric was computed for each household, end-use, and timespan, to depict the spectrum of uncertainty load that disaggregation can engender; this formula was used to construct the absolute error values for the disaggregated end-uses:

$$Relative\ Error = (Inferred\ Appliance\ Usage - Actual\ Appliance\ Usage)/\ Total\ Home\ Use$$

From yearly data sampled at 15 minutes from 264 homes, EEme achieved median absolute monthly error of -0.31 for heating/cooling, -0.28 for refrigerator, -0.45 for clothes dryer, and 0.33 for dishwasher.

Dividing the error calculation by the whole home usage as shown below, can help normalize the contribution of any particular appliance to overall house consumption and may be helpful in home energy management applications.

Since this metric normalizes the error by total home usage it puts the uncertainty in perspective from an end-user standpoint. End-users, who ultimately utilize such disaggregation-based energy insights, have the tendency to evaluate these insights relative to their total bill, e.g., “How much can a new fridge reduce my total electricity bill?”.

The monthly results’ accuracy values can be seen in Table 12. Yearly results’ accuracy values for all of the end-uses were found to be almost identical to the monthly ones.

Table 12. Median Error Terms for Monthly Disaggregation

	Absolute Error	**Relative Error**
Heating/Cooling	-0.31	-0.11
Refrigerator	-0.28	-0.02
Clothes Dryer	-0.45	-0.02
Dishwasher	0.33	0.003

As implied by the negative error terms, EEme’s algorithms underestimated the usage for three end-uses: heating/cooling, refrigerator and clothes dryer. In a benchmarking exercise using underestimated disaggregation values may cause underestimated energy savings potential. These results can be leveraged to fine-tune the load disaggregation models for future applications.

With this validation study administered by Pecan Street, EEme has charted the boundaries of reliability and accuracy of load disaggregation. NILM solutions and vendors have historically suffered from lack of extensive third party validation that is perceived as the foundation of technology adoption in the utility industry. Testing the algorithm against a robust database of actual loads is the only viable method of converging on an accurate and reliable product.

The accuracy figures generated in this study can pave a reliable path for smart-meter-based analytics for customer segmentation and engagement in energy efficiency and demand response for utilities and demand-side management (DSM) program administrators. This in turn can help reduce capital and operational costs that pertain to the design, implementation and evaluation of DSM programs.

A follow-on study will evaluate four more end-uses: electric vehicle, pool pump, water heater, and solar photovoltaic panel; and two more timespans: daily and weekly; and will utilize hourly-interval smart meter data.

Home Energy Monitoring Systems

Through collection of granular, 1-minute to 1-second interval electricity consumption data from HEMS deployed in 661 homes, Pecan Street has created and owns the world's largest disaggregated residential energy database, with over 1,000 home years of appliance level energy consumption measurements.

A baseline study was undertaken to determine whether enabling homeowners to access to their detailed energy use data results in any significant behavioral changes with regard to energy use. The study consists of two groups: a sample of 100 homes in the new Mueller development in Austin, Texas, designated the New Home Group, and a sample of 100 older homes in Austin, Texas, designated the Older Home Group. The New Home Group consisted of homes that had been constructed within the previous three years according to Austin Energy's 3-star or better green building standards. The Older Home Group consisted of homes that had were 15 to 89 years old. In both groups, energy use was monitored over the course of two years. In the first year, study participants were unable to access the energy use data. Participants were then granted access to the data in the second year.

Two sub-metering technologies were used to collect the participant data over the course of the study: Incenergy Sequentric systems and eGauge systems. Both technologies allow the collection of energy data from the whole home as well as individual circuits at one-minute intervals. Pecan Street installed Incenergy systems to collect participants' data over the course of the first year of the study. While Pecan Street had access to this data, participants were unable to view it. For the second year of the study, Pecan Street installed eGauge systems, which were each equipped with an online user portal.

The dataset used in this report consists of 43 homes in the New Home Group portion of the study and 32 homes in the Older Home Group portion of the study. The reduction in total homes used for analysis was primarily due to lack of comprehensive data necessary for a detailed study.

As previously mentioned, Incenergy system data was used to determine energy usage in the first year, while eGauge data was used to determine energy usage in the second year. Although some participants received an eGauge before February 1, 2012, they were not allowed access to the eGauge portal until that date. For a detailed analysis, the study calculates the participant energy use in the year prior to the date that data access was provided and the year following during which participants were able to view their energy consumption data in near real-time.

Both the Incenergy and eGauge systems experienced issues with device connectivity. Incenergy systems do not cache data for a long enough time to provide data to Pecan Street after network failure; therefore, some data from these systems was lost while the devices were unable to communicate with the Pecan Street server. EGauge systems cache data locally on the device for one year after data collection for data collected at one-minute intervals; therefore, loss of connectivity between the eGauge and Pecan Street's servers rarely resulted in loss of data.

To account for gaps in both datasets, the measured annual electricity usage values were normalized by dividing by the number of available readings and then multiplied by the expected number of readings to get the estimated annual electricity usage for each home.

In the New Home Group, the data show that 28 of the 43 study participants (65.1%) had some degree of an energy use reduction in the year in which they were able to view their energy consumption data. The remaining 15 participants (34.9%) are shown to have some degree of an energy use increase. Participants in the middle of the range for the first year used between 12,000 and 15,000 kWh of electricity.

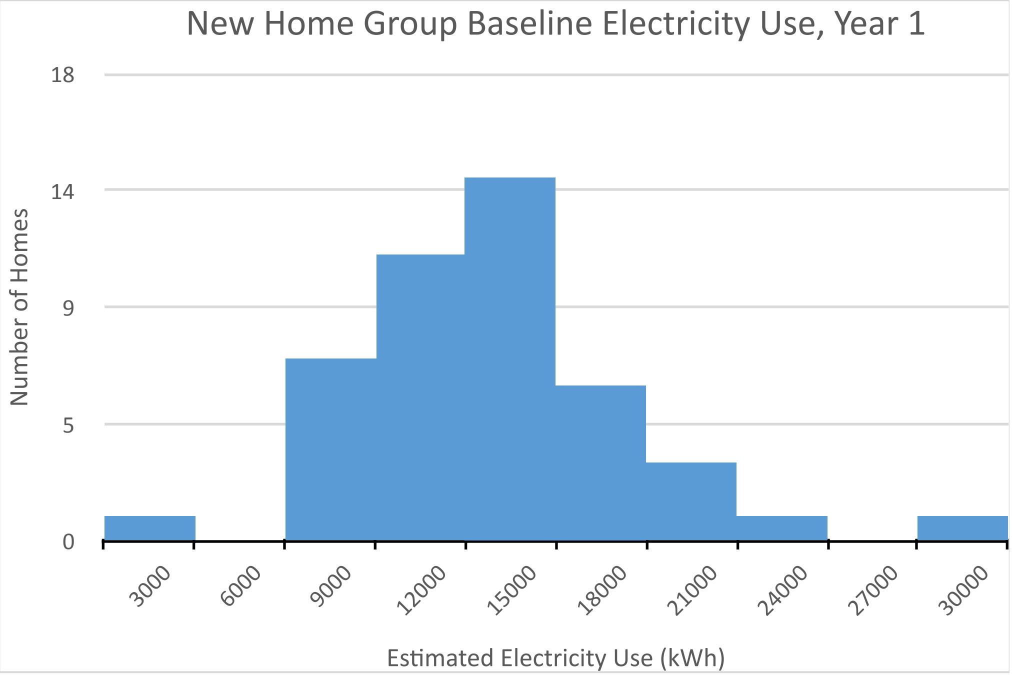


Figure 14: New home baseline electricity use, Year 1

In the second year, the distribution changed slightly, with more participants using between 9,000 and 12,000 kWh of electricity.

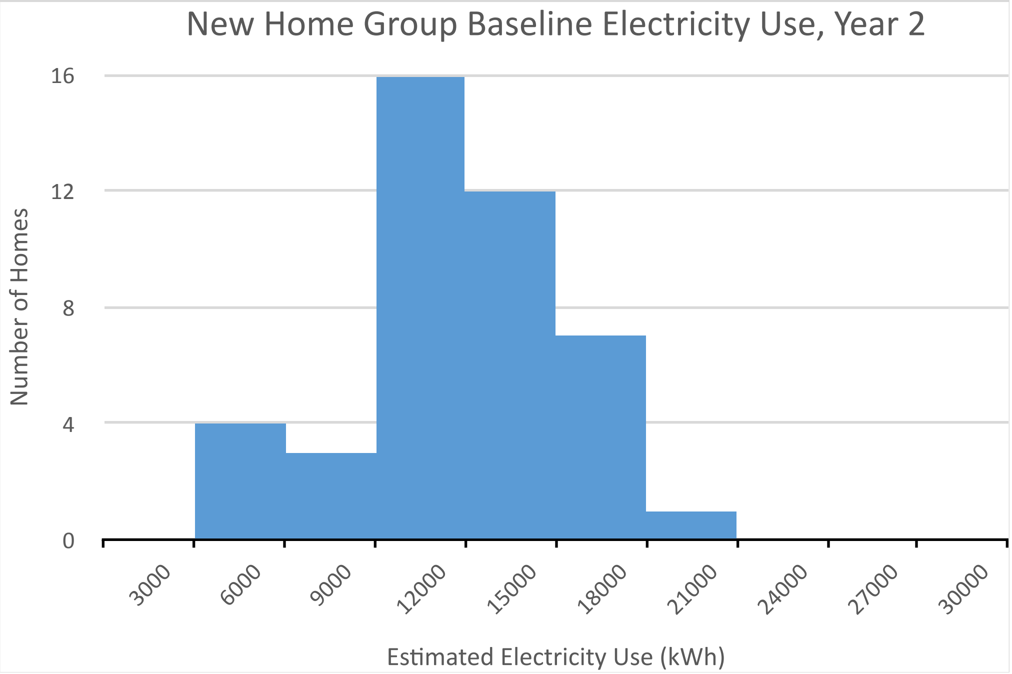


Figure 15: New home baseline electricity use, Year 2

In the Older Home Group, the data show that 20 of the 32 study participants (62.5%) had some degree of an energy use reduction in the year following their data release dates. The remaining 12 participants (37.5%) are shown to have some degree of an energy use increase in the second year. There are a number of factors that may have led to this outcome, which are considered below. In the first year, the most common whole home energy use range for the Older Home group was from 5,000 to 10,000 kWh annually.

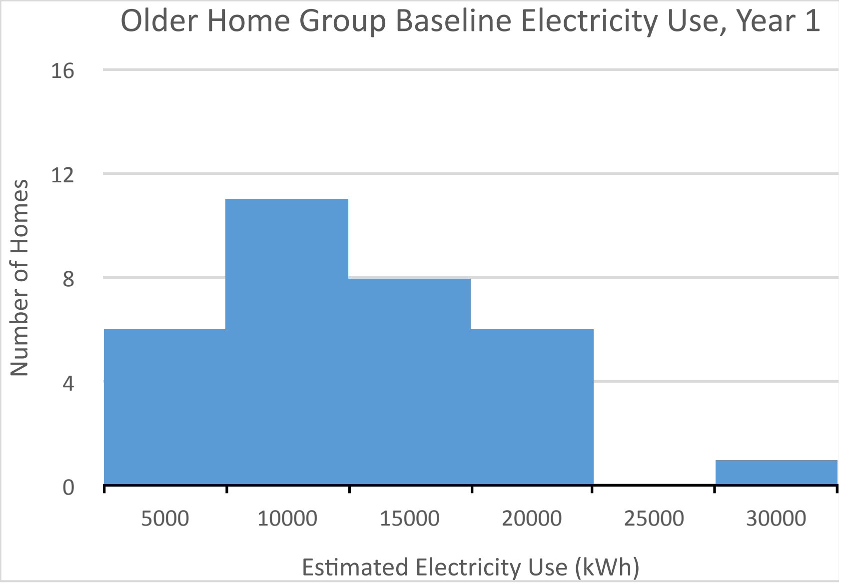


Figure 16: Older home baseline electricity use, Year 1

In the second year, the distribution shifted so that more homes in the Older Home Group used less than 10,000 kWh of electricity over the course of the year.

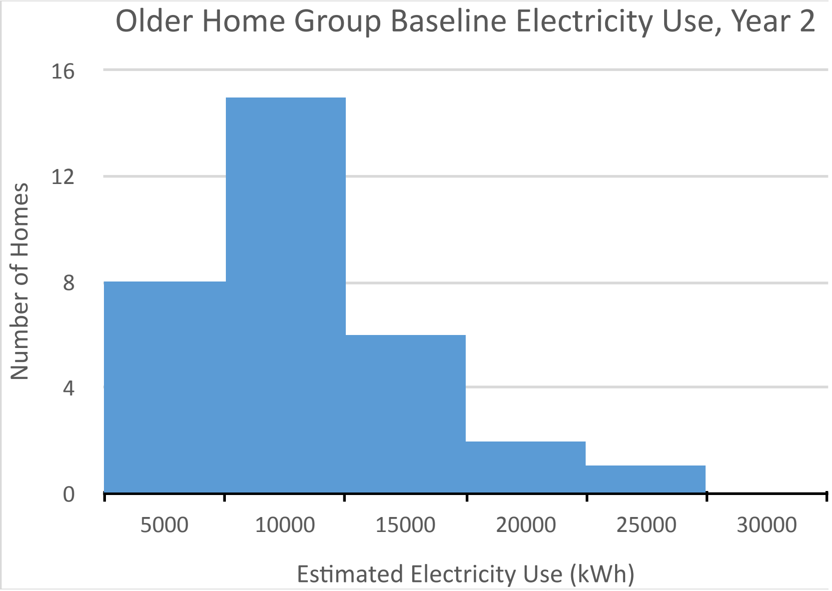


Figure 17: Older home baseline electricity use, Year 2

HVAC is the most significant component of electricity use in Texas (particularly air conditioning use during the summer); therefore, it is important to consider whether the weather in the first year differed significantly from the weather in the second year. According to the Pecan Street weather dataset summarized in Table 13, the summer in the second year for the New Home Group was over 4 degrees cooler on average than in the first year, with a slightly warmer winter in the second year. The data analyzed for the Older Home Group shows slightly different temperatures for each season, but with the same overall trend as in the years defined for the New Home Group. This indicates that both datasets may show a reduction in energy used for cooling in the summer, with a slight increase in heating in the winter, simply due to the effect of a change in the weather.

Table 13: Weather Variation over Year 1 and Year 2

Year	Average Winter Temperature (˚F)	Average Spring Temperature (˚F)	Average Summer Temperature (˚F)	Average Fall Temperature (˚F)
New Home Group, Year 1 (2011/02/01 – 2012/02/01)	53.43	72.95	88.81	72.19
New Home Group, Year 2 (2012/02/01 – 2013/02/01)	55.59	71.98	84.64	70.48
Older Home Group, Year 1 (2011/07/18 – 2012/07/18)	54.39	71.98	87.00	72.19
Older Home Group, Year 2 (2012/07/18 – 2013/07/18)	55.85	67.57	84.95	70.48

Paired two-sample t-tests for means were performed to determine whether the difference in annual energy consumption between the two years was statistically significant without accounting for weather variations. The test was performed separately for each group. For both groups, the null hypothesis was that there was no difference between the mean annual energy consumption from the first year and the mean annual energy consumption from the second year. A 95% level of confidence was chosen (p = 0.05). The tests' result tables are detailed in Tables 14 and 15 below.

Table 14: T-test for New Home Group

New Home Group	Year 1	Year 2
Mean	1,2636.33	1,1746.21
Variance	17,261,452	12,471,031
Observations	43	43
Pearson Correlation	0.5163	-
Hypothesized Mean Difference	0	-
df	42	-
t Stat	1.5286	-
P(T<=t) two-tail	0.1339	-
t Critical two-tail	2.0181	-

Table 15: T-test for Older Home Group

Older Home Group	Year 1	Year 2
Mean	1,0552.26	8,849.241
Variance	31,486,892	20,792,024
Observations	32	32
Pearson Correlation	0.5779	-
Hypothesized Mean Difference	0	-
df	31	-
t Stat	2.0216	-
P(T<=t) two-tail	0.0519	-
t Critical two-tail	2.0395	-

The results show that the null hypothesis cannot be refuted for either group at the 0.05 level. Therefore, the difference in annual energy use between the first year and the second year is not statistically significant for either group, with a p-value of 0.134 for the New Home Group and a p-value of 0.052 for the Older Home Group.

Multi-family Considerations

Pecan Street enrolled 140 low-income apartment residents in the Energy Internet demonstration study to the potential for home energy monitoring systems with a user-friendly interface to help participants reduce monthly utility bills.

Low-income households were defined in this study as households that earn between 30% - 80% of Area Median Income. These households devote a proportionately larger portion of their income towards energy bills than households at or above area median income. The project team theorized that home energy monitoring system that allows the resident to learn what systems and appliances use the most energy, set monthly utility bill goals, and receive real-time feedback on their progress in meeting those goals could provide significant benefit to these families.

For senior citizens living on a restricted income, home energy monitoring systems offer the same benefits of control and savings as they do to low-income families; however, they also offer the added benefit of health and activity monitoring. An energy monitoring system measuring circuit data at 1-minute intervals with real-time feedback through an online portal enables family members and care-givers to monitor the health of a loved one from afar. For example, a daughter living in Chicago could log into her mother's online energy portal during her lunch and break and see that her elderly mother, living in Austin, has woken up, made breakfast, watched a little TV and is currently doing laundry all by looking at the sub-circuit level energy consumption in her mother's home. An unusually quiet energy consumption pattern for the morning could signal that the mother has not been going through her daily routine and may need immediate assistance.

Three important variables were identified that impact home energy consumption for apartment renters:

- **Building stock type**: Diversity in building stock will be captured through inclusion of two new, green-built properties, one older property that has received energy retrofits and one older property that has not been retrofit.
- **Occupant demographics**: Diversity in demographics will be captured by enrolling 30 senior citizens from Wildflower Terrace and enrolling 60 primarily Spanish-speaking families from Sierra Ridge and Sierra Vista.
- **Information and training**: The research team will analyze the impact of varying levels of education intervention on the impacts of home energy monitoring. Foundation Communities, through support from Enterprise Green Communities, will design and implement three levels of education on home energy information and will track the success of households in using this information to meet their utility bill reduction goals.

To carry out the study, Pecan Street and the Verizon Foundation provided the following resources to the study:

- **HEMS**: An eGauge system was installed in the circuit panel at each participating apartment. The eGauge system includes an eGauge information device that will be installed by Pecan Street's electrician in the breaker box of each participating apartment, a HomePlug adapter that transmits collected data to Pecan Street's secure Energy Consumption Database, and 12 50A CTs for monitoring individual breakers within the apartment.
- **A secure, personalized online portal for energy monitoring and management:** Pecan Street commissioned PlotWatt to create and host a customized online portal for research participants that provides a user-friendly interface to view real-time whole home and circuit-level energy use data along with tools to help customers decrease consumption such as utility bill tracker that allows customers to see a projected bill based on actual, current assumption and tips for how to reduce energy use.
- **A secure, personalized mobile application for energy monitoring and management**: Pecan Street created a custom mobile application, called Pumpkin Pie, for use by its project participants. The app provides near real-time information on circuit-level energy use and the costs associated with use on each circuit, the ability to set a monthly electricity budget and receive notifications when the household is on track to surpass that budget, comparative information for how much energy the household is using compared to other comparable homes, and personalized recommendations for how to save energy.
- **A tablet computer and 4G wireless internet for each participating household**: Verizon Foundation provided each household with a tablet computer and a router that provides 4G wireless internet. Participants are each provided with 2GB of data per month that can be used to view their online portal and mobile application.
- **Specialized one-on-one training**: The training was intended to ensure participants understand their energy data and how behavioral changes can impact their utility bills. Pecan Street provided one-on-one training to participating residents on how to use the information provided through the PlotWatt portal and mobile app to help reduce energy bills and greenhouse gas emissions. The training was be followed by one-on-one outreach to ensure participants understood their home energy use information and were achieving energy bill reduction goals.

Of the 140 participants, 35 were placed into a control group. Pecan Street installed an eGauge monitoring system in the control group apartments; however, these households did not receive access to their energy data nor were they provided with any training on how to use energy data to reduce utility bills.

A portion of the study group, 70 households, also received a Nest thermostat. The Nests were installed by Pecan Street's electricians and participants were provided with an in-person training and printed materials describing how to program and operate the Nest. The smart thermostats were included to evaluate their impact on electricity consumption reductions.

The survey results yielded interesting insights into the demographic differences between the four properties. Sierra Ridge and Sierra Vista participants have a significantly lower average education and income levels than the other two properties, with over 30% of their population earning less than $15,000 annually. Wildflower Terrace has the smallest average household size at 1.07 people per apartments, and Sierra Ridge has the largest average household size at 3.2 people per apartment. The survey also revealed that approximately 80% of participants at Sierra Ridge and 63% of participants at Sierra Vista listed Spanish as their primary language while 5% of households at M Station and no households at Wildflower Terrace listed Spanish as their primary language.

As anticipated, energy use increased from the spring through summer months as temperatures rose. M Station has communal HVAC systems that each serve eight apartments. The property owner, Foundation Communities, pays for the energy used to power the air conditioning and heating for residents, who do not pay for their individual air conditioning use though they do pay for the energy used by their furnace, which serves as the air conditioning blower. Since the blower will be operating when the HVAC system is delivering cool or heated air to the apartment, it is possible to get a sense of how much air conditioning is being used by M Station participants.

Table 16. Average Monthly Temperatures, in Fahrenheit Degrees, for Austin, Texas: February - August 2014

Month (2014)	Austin Avg High	Austin Avg Low
February	66	43
March	71	47
April	80	59
May	85	64
June	91	73
July	95	74
August	99	75

Air conditioning (air compressor plus furnace use) accounted for 49% of total consumption in August at Sierra Ridge and Sierra Vista, and 45% of consumption at Wildflower Terrace. At M Station, the blower (furnace circuit) accounted for 25% of energy consumption in August. In comparison, furnace use at the other three properties accounted for 8%, 13% and 15% of total energy minus air compressor use consumed in August at Sierra Vista, Sierra Ridge and Wildflower Terrace, respectively. The difference indicates that residents at M Station may be consuming more energy for air conditioning than the other properties though they do not pay for that energy.

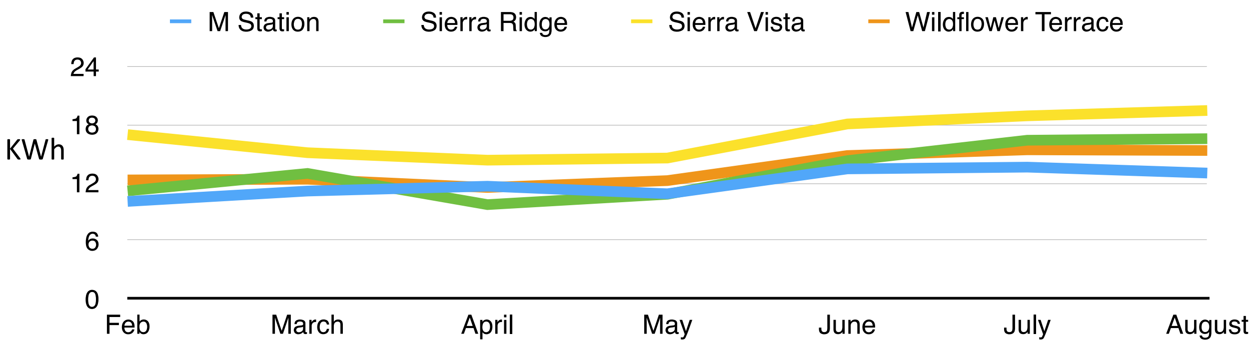


Figure 18. Average daily use per month by property

While resident demographics, such as size of family, and behaviors play a significant role in energy consumption, building attributes are also an important driver of energy use. Utility bills of tenants living in low-income housing should be considered as part of the overall affordability of the property. Investments in energy efficiency retrofits and green building measures by the building owner is an important component in providing truly affordable housing.

Table 17. Multifamily Research Groups

Research Trial Group	PlotWatt Portal Access	Smart Thermostat with External Control	Mobile App Access
Group A	Yes	Yes	No
Group B	Yes	Yes	Yes
Group C	Yes	No	Yes
Group D	Yes	No	No
Control	No	No	No

Project data also revealed that participants in Group C — those with the mobile app, smart thermostat and portal access - appear to be practicing energy conservation behaviors on a scale that exceeds the other test groups and the control group. Group C also accessed the PlotWatt web portal at a greater frequency than other user groups with 58% of Group C participants accessing the portal weekly, while Group A saw only 18%, Group B saw 33%, and Group D saw 22% of participants visiting the portal weekly.

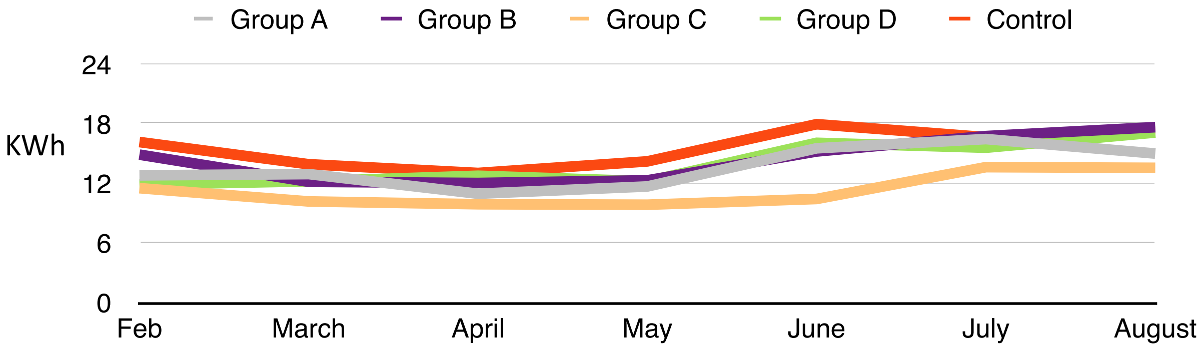


Figure 19. Average daily use per month by research trial group

Distributed Solar PV Energy

To encourage the adoption of solar among research participants, Pecan Street offered additional rebates in partnership with Austin Energy's rebates for installation of residential PV. Prior to Pecan Street's enhanced solar rebate offering, 11 homes in Mueller had installed PV systems. At the end of September 2011, when Pecan Street's solar rebate expired, over 200 homes in Mueller had installed rooftop PV systems.

To determine if solar is cost-effective for homeowners, the Savings to Investment Ratio (SIR) and Return on Investment (ROI) were calculated for participants in Pecan Street's study in 2013. The analysis used PV cost data from the time period of the installations, most of which occurred in 2012. PV component prices have fallen since that time so the project team expects that the SIR and ROI of distributed solar systems in Austin will improve over time if utility rebates remain constant or decrease commensurate with the decrease in PV system costs.

SIR equals total energy savings over the lifetime of an improvement in Net Present Value. A SIR value of greater than 1 means the system will pay for itself over its lifetime. Higher SIR scores indicate greater cost effectiveness and a shorter payback period. SIR value is calculated as:

*SIR = (Annual Energy Delivered * Cost of Electricity * Present Worth Factor) / System Cost*

The analysis drew upon the following data:

- Regression analysis of retrofit measures and energy savings
- Retrofit cost data obtained from Austin Energy
- Austin Energy's rate structure
- Solar PV attribute and cost data from Pecan Street

- PV Watts online solar generation calculator

Estimated saved kilowatt hours (kWh) per day from the regression were analyzed with Austin Energy's rate structure. Figure 20 shows average monthly power and it reveals that for the entire study period, the marginal power for the average home in the study fell between 501 and 2,500 kWh, an interval equivalent to tiers 2 and 4 of Austin Energy's rate structure. In the calculation, it was assumed that the energy savings would be spread throughout the year. Therefore summer rates as well as non-summer rates were applied for the correct number of days respectively.

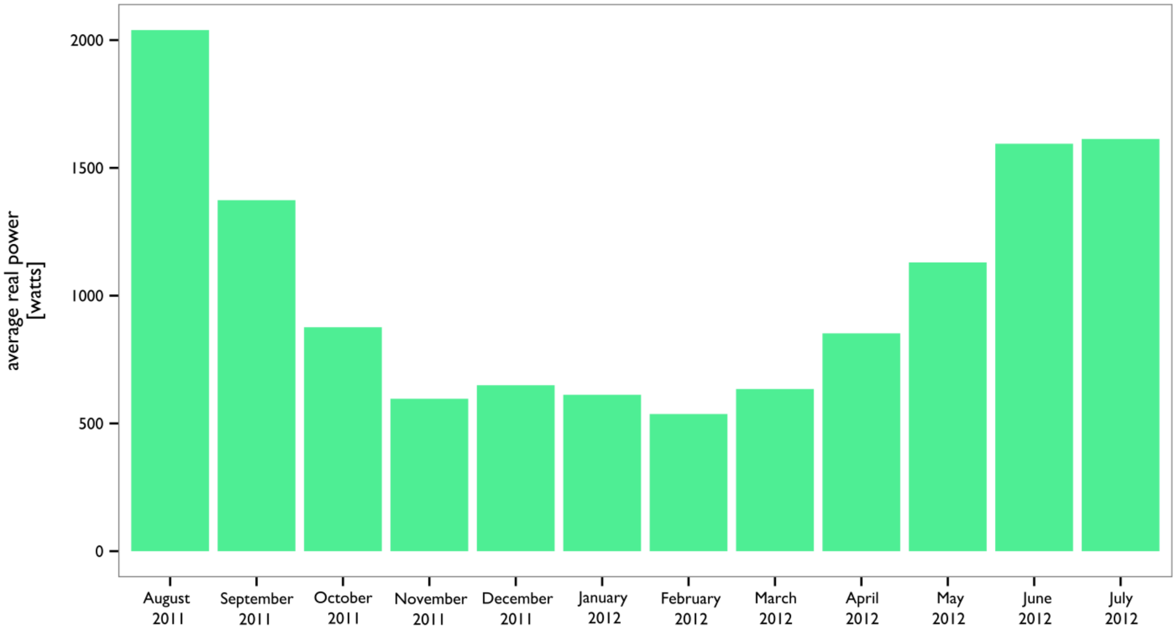


Figure 20. Average monthly whole home power, all participants

To calculate savings from solar, PV systems were analyzed based on three different orientation options:

- PV system with both south- and west-facing panels
- PV system with only south-facing panels
- PV system with only west-facing panels

For this analysis, total system size was held constant as the average system size from the study (5.52 kW). Values for tilt and azimuth were based on averages for each orientation. For systems with both south- and west-facing panels, a two-part analysis was conducted for both orientations. All values were entered into PV Watts, a program that can estimate energy generated by PV systems for a typical meteorological year based on the system's location and attributes. PV Watts delivered figures for annual AC energy generated, which were converted to daily values.

Cost data for PV systems was provided by the solar installers as part of the requirement to receive Pecan Street's rebate. Average cost per watt for each orientation as well as average rebate per watt were calculated separately for each orientation. Cost per watt values were adjusted to the normalized system size of 5.52 kW to estimate costs for each system.

Another value that is required for the analysis is the lifetime of the system. The figure used for solar PV systems was 25 years, equivalent to the time that the typical system is under warranty.

Currently, homeowners in Austin Energy territory investigating the possibility of installing solar panels must receive an inspection from an approved solar installer to determine whether the home qualifies for an Austin Energy rebate. Pecan Street's analysis of SRI and ROI found that PV is a cost-effective option for homeowners seeking energy improvements and it is one that is scalable to the size of the home.

The Pecan Street Data Team analyzed the data collected from south and west facing PV, compared to whole-house consumption. Figure 21 illustrates that while south-facing panels may produce more overall energy, the west-facing panels actually match more directly with peak demand.

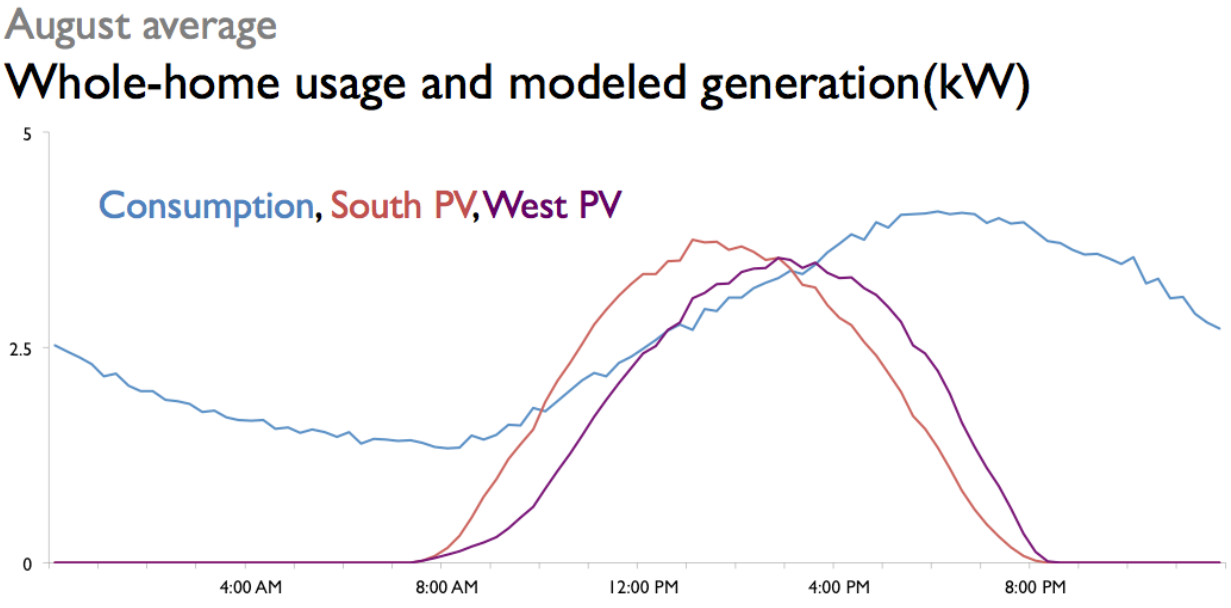


Figure 21. Comparison of whole home consumption to south- and west-facing PV, August 2013 daily average

The whole-home net electricity use was also calculated from the data collected during the solar PV study, and those results are shown in Figure 22.

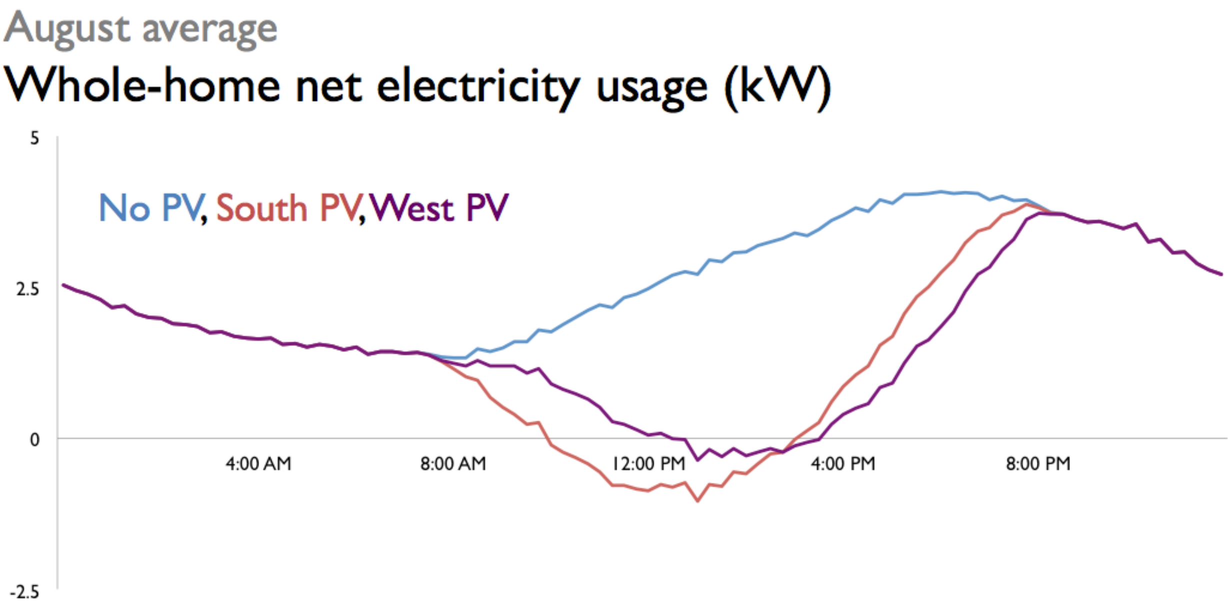


Figure 22. Comparison of whole home net electricity use, August 2013 daily average

Since the whole-home net electricity use is reduced with solar PV, this will have an effect of reducing a customer bill. Figure 23 shows the price implications of solar compared to those of homes with no PV, south-facing PV and west-facing PV.

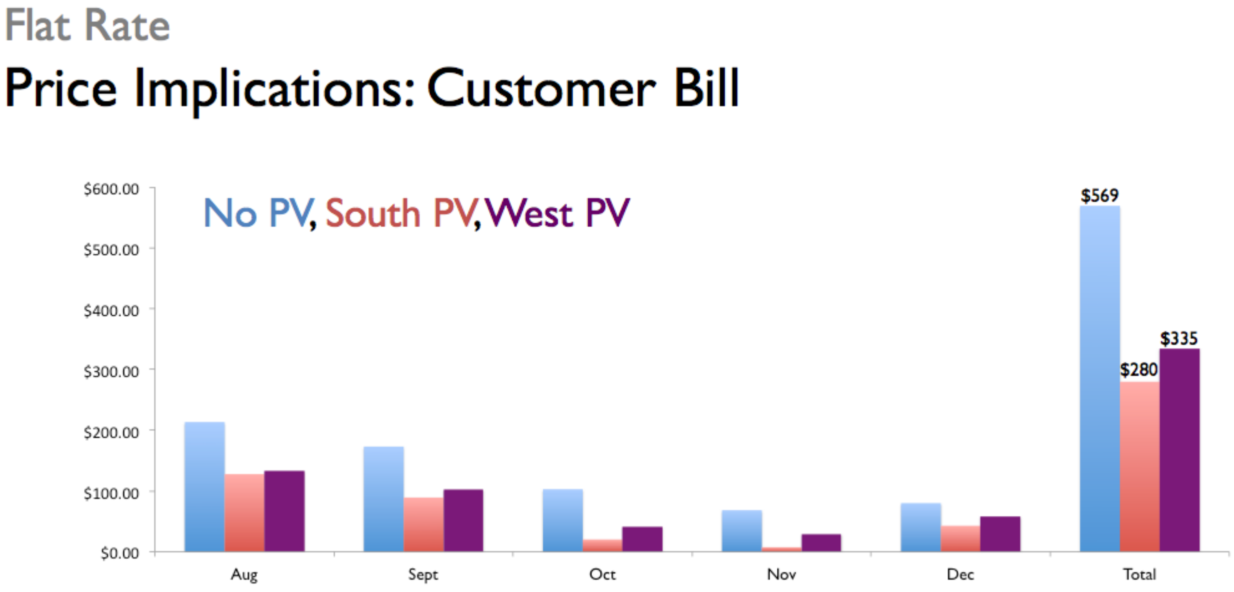


Figure 23. The price implications of a customer bill with solar

Table 18 shows detailed utility bill savings and the annual savings that are expected with varying solar panel orientations.

Table 18. Utility Bill Savings

Retrofit	Saved kWh per day	Annual savings	Lifetime (years)
PV system with only south-facing panels	20.57	$961	25
PV system with south- and west-facing panels	19.33	$903	25
PV system with only west-facing panels	18.14	$847	25

Table 19 calculates the Savings to Investment Ration (SIR) for varying solar PV system orientations.

Table 19. Savings to Investment Ratio Analysis

Retrofit	Lifetime savings	Cost before rebates	Cost after rebates	SIR with Rebate	SIR no rebate
PV system with only south-facing panels	$18,765	$24,741	$4,479	4.19	0.76
PV system with south and west-facing panels	$17,635	$24,983	$3,878	4.55	0.71
PV system with only west-facing panels	$16,543	$24,196	$3,234	5.12	0.68

Installing solar PV can have a positive effect on the profitability of the utility at certain times of the year. During the hottest times of the year, most often in August, the price per kWh is so high that the utility loses money during peak demand; however, with solar PV installed, facing either south or west, the utility is able to remain profitable with a flat rate, as shown in Figure 24.

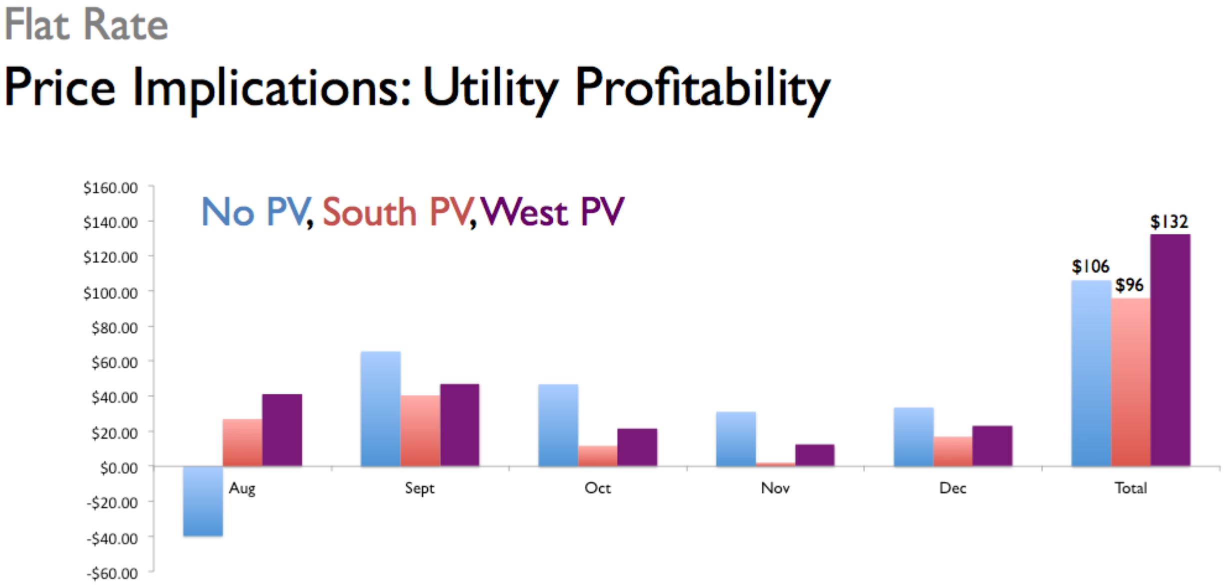


Figure 24. The price implications for utility profitability

While it was once thought that south-facing panels was the best scenario for solar panel installation to generate as much electricity as possible, the project team found that to combat peak electricity demand, the key is west-facing solar panels, which more directly aligns with peak demand. However, using current Austin Energy net metering pricing, south-facing systems are more profitable to customers.

Energy Storage

Pecan Street data has shown that the traditional utility view of a residential load has become inadequate. Residential loads, instead of being a minimally dynamic, high power factor load have changed. Modern technology has resulted in residential loads that can vary from peak to base level demand of 10:1. Total current harmonic distortion can exceed 40% on a daily basis. Instead of lagging and resistive loads, switch mode power supplies present high harmonic distortion and a leading impedance to the AC system. Traditionally, a building's electricity "load" meant the structure had nearly resistive consumption. With the emergence of dense networks of distributed generation (DG), a "load" now includes power consumption and power generation that is put back onto the grid.

To test the interoperability of battery storage, Pecan Street installed a battery storage system at the Pike Powers Lab. Installation of the batteries demonstrated the system integration requirements for an energy storage system that meets the following specifications:

- Output AC and DC power simultaneously or either one independently
- Integrate distributed generation

- Receive power from the grid or directly from the solar system
- Directly charge an electric vehicle
- Shift loads off the grid during peak
- Directly power individual loads in the building
- Integrate a natural gas generator or other on-site power source

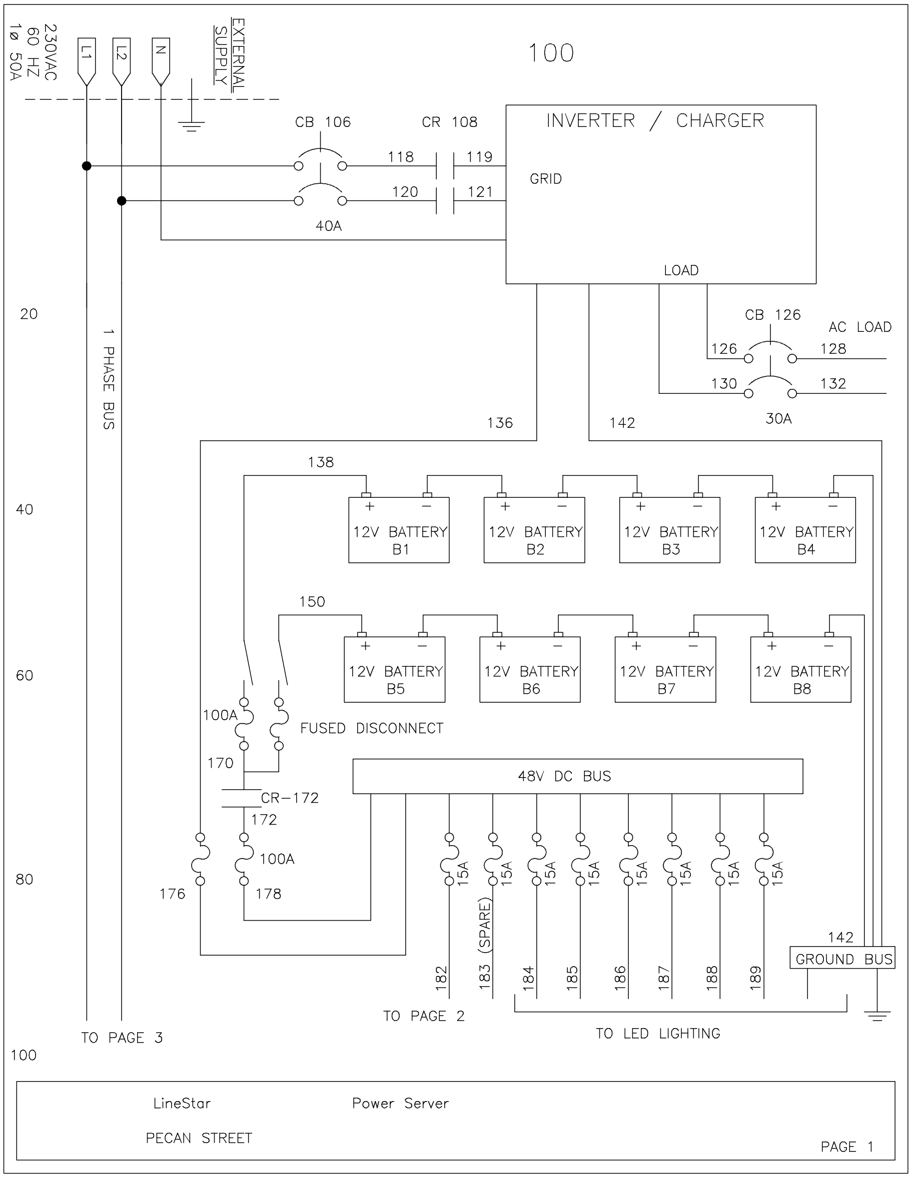


Figure 25. Line diagram showing integration of battery storage at Pike Powers Lab

Currently the energy storage system operates as a pico-grid within the facility because the AC output is not in parallel with the Austin Energy grid. Operating the energy storage as a pico-grid enabled the organization to bypass the jurisdiction's permitting requirements, reducing balance of system costs. Separate circuit beakers were installed in the energy storage system to enable loads under 4500 watts to directly receive power from the batteries.

The most significant system integration challenge involved communications between the battery charger and the batteries. The commonly available battery chargers on the market are designed for lead acid batteries. Pecan Street's lithium iron magnesium batteries required custom software development to enable the battery charger to communicate with the batteries, allowing charge from the grid, the on-site distributed generation, or the on-site natural gas generator.

Over the course of the project duration, the energy storage system has been used to power individual circuits in the building and charge a Volt electric vehicle to full charge, helping to shift significant loads off the grid during peak consumption hours. Using the data collected through its field trials and testing of the lab's energy storage system, the project team created an open-platform product specification that provides enhanced value to customers and utilities.

To many utilities, the emerging prevalence of distributed generation and disruptive technologies, such as energy storage and electric vehicles, constitute a risk to grid stability and a threat to traditional business models. Pecan Street leveraged its industry and consumer preference insights in tandem with its product development capabilities to develop, test and refine a customer-side-of-the-meter product, called the Energy Switch, that converts distributed generation and other consumer-owned systems into a valuable asset for the utility rather than a liability.

The Energy Switch is an open-sourced, interoperable intelligent home load controller and aggregator that provides a single point of interface from the home to the utility. As prototyped at the Pike Powers Lab in Austin, the Energy Switch is scalable so that as the price of storage and PV systems come down, more distributed resources can be added to buildings, resulting in less pressure on the grid over time. A distributed management system that aligns with the emergence of distributed power assets enables utilities to holistically manage distributed resources, thereby increasing the hosting capacity of the grid.

High density of local solar generation and high penetration of inexpensive energy efficiency products such as compact fluorescent lighting can have unexpected negative system consequences. Pecan Street's research has found that residential structures are moving from leading power factor to lagging 70 times in one day. In areas of high solar penetration residences grouped on a distribution transformer comprise a single load that supplies real power to the utility but must sink reactive power, leading to a negative power factor. On these transformers distribution voltages are 2% higher than the utility intends. At this point the impact appears to be localized by the engineering overhead in the system. Continued adoption of these desirable technologies will require upgrades to the existing distribution system or result in reduction to the reliability of the legacy systems already in place.

In Figure 26, the grey line represents the baseline residential load profile characterized by high volatility in the load, harmonics and power factor. The Energy Switch, represented by the green line, levels the baseline load profile, creating a more stable and manageable load. The one-minute interval data is collected by Pecan Street's home energy management system. The blue line is the load profile as depicted by a smart meter collecting data at one-hour intervals. The smart meter data masks much of the variability occurring within the home. Through access to one-minute interval, circuit-level data, Pecan Street was able to design a system that identifies and addresses these issues.

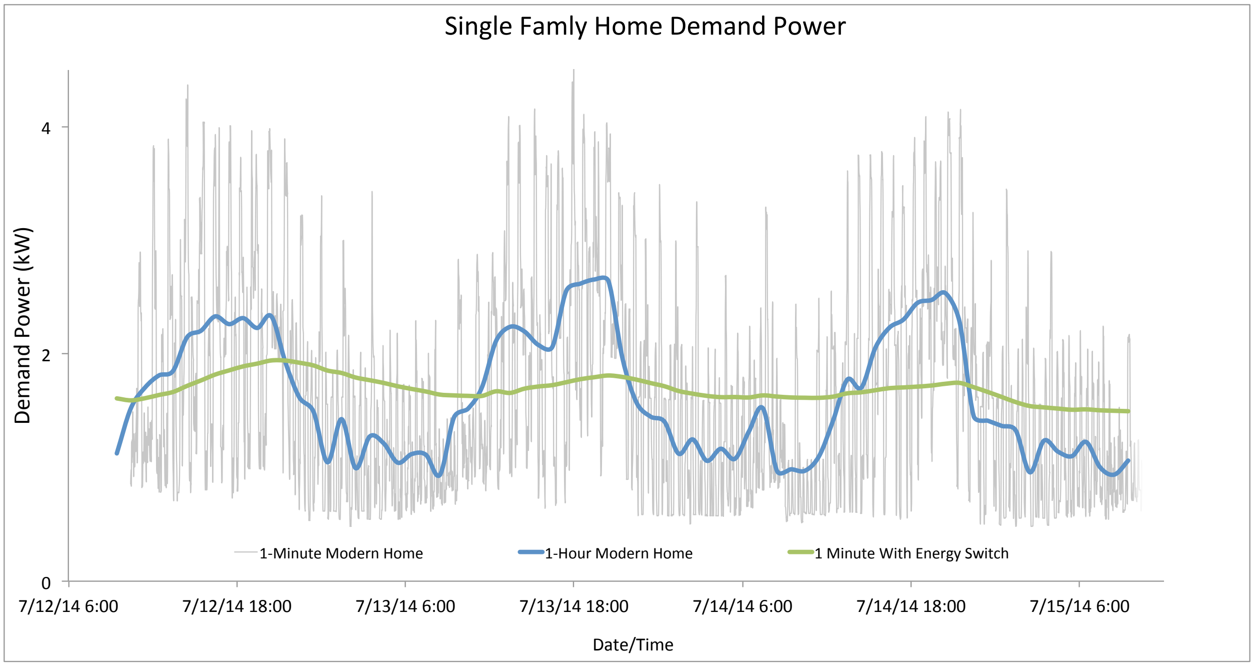


Figure 26. Single-family demand power

Traditional system integration approaches are yielding economically poor solutions for utilities and consumers. Utilities end up having to shutter renewable resources as is occurring in Southern California with the well-published duck curve. Private individuals end up paying increased permitting fees, or astronomically high system integration fees to have a solar system with energy storage connected to the grid. Any system that is more advanced than an emergency backup power requires engineering resources from the utility and monetary resources from the customer. The energy switch addresses all of these issues in an open-source scalable solution.

Integration Specifications

Through novel integration of mature technologies with OpenADR-compliant communications, the Energy Switch provides the following grid services and functionality:

- Abstracts all residential generation and load to a simple, aggregated single load resource for the utility
- Provides intelligent local control of legacy devices and new, smart devices
- Automates standard compliant islanding/reconnecting that minimizes safety concerns and customer interruption during an outage
- Simplifies two-way communications between utility and customer through the utility communications path of choice: Smart Meter, M2M direct communication or cloud services
- Provides utility customers the easy ability to manage and identify critical loads to be maintained during a demand response or outage event
- Acts as a single point for distributed and emergency generation connection permitting
- Enables operation of distributed grid-tie solar during outage by maintaining local frequency and voltage while disconnecting from utility grid.
- Provides energy input ports and local safety disconnect for local generation sources including PV, natural gas generators, co-generation systems and mini wind turbines
- Provides built-in distribution with safety current limiting, energy monitoring and load control on each circuit
- Will publish ICT source code on SourceForge or GitHub
- Serves as a Virtual End Node (VEN) or Virtual Top Node (VTN) providing the functionality to scale to a campus-wide solution

The Energy Switch forms a distributed management system that aligns the emergence of distributed power assets with smart local control and enables utilities to holistically manage distributed resources. This increases the hosting capacity of the grid and enabling new classes of energy systems and services to enter the marketplace. The Energy Switch provides a pathway for current and future sustainable energy systems operating at various scales to achieve the homeowner's sustainability and economic objectives while helping the utility maintain profitable and reliable electric service.

System Architecture

Within the Energy Switch, CTs are attached to all circuits to monitor individual loads or remotely-controllable breakers are installed that allow for monitoring and control. The ICT gateway connects to the residential broadband connection and based upon the consumer's prioritized preferences for sustainability and economic optimization, the gateway controls energy distribution within the property. A manual override feature enables islanding in the event of grid outage or cyberattack to provide power to critical circuits. The integration also allows a default grid connect mode in case of local hardware failure. Personally identifiable information and control/configuration commands will always be protected through encrypted communication channels.

The Energy Switch interfaces to the utility and ensures higher energy reliability for the consumer and an easier load for the utility to manage. It also allows the utility to disconnect the customer from the grid for a short duration of time if the customer can provide their own energy and it allows the customer to also initiate a disconnect if pricing signals are unacceptable to the customer. This new level of prosumerism enables the utility to offer different service levels to its customers with varying guarantees of power quantity and power quality delivered to the building, depending on the distributed resources within each property.

System Components

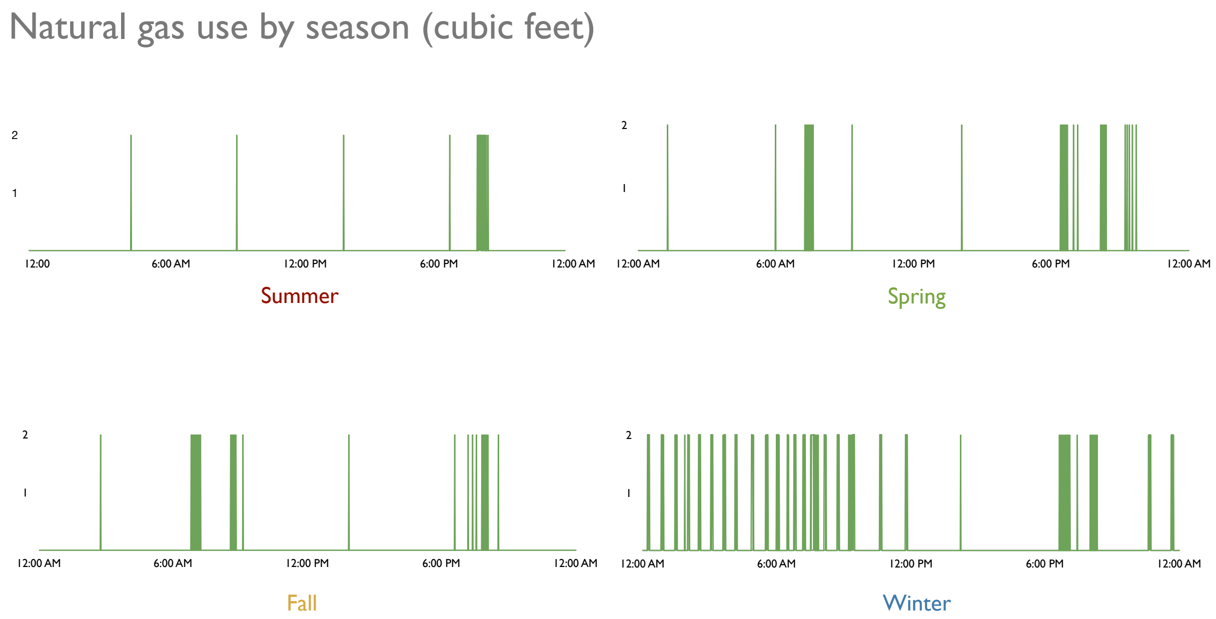
The components required to build an Energy Switch system are currently available in the marketplace:

- CTs and contactors that allow for monitoring and control of individual loads
- Open source ICT management system reference platform that communicates with the utility and provides third party access and control of the Energy Switch hardware
- 2 kWh of energy storage for minimal functional operation in all modes (scalable up to 40 kWh of storage)
- Home gateway that connects to circuit controller, which manages individual loads within the home (any off-the-shelf system)
- Control API based on OpenADR standards
- Energy management configuration templates
- Online user interface

Natural Gas and Water Metering

In partnership with Texas Gas Service and Austin Water Utility, Pecan Street installed smart gas and water meters along with a third-party ERT reader that transmits data over the participant's wireless network in 50 participating homes. These homes also have HEMS installed that enable the project team to disaggregate gas and water use within the home.

Pecan Street analyzed original research data it developed through its consumer research supported by Texas Gas Services to develop a seasonal load profile for natural gas consumption.



Source: Pecan Street Research Institute

Figure 27. Natural gas consumption by season

By synchronizing the signals from two independent data acquisition systems (its installed natural gas and electricity data acquisition systems), Pecan Street was been able to measure and correlate home electricity and gas use at the appliance level. The gas and electric data collected through two independent systems was combined to unambiguously determine information such as the timing of gas furnace and electrics blower operation in a specific residence.

The project team analyzed the electricity savings that could be derived by switching to gas-powered appliances. The analysis of opportunities to save electricity by switching to a gas-powered clothes dryer was performed by taking the electric signal for the gas dryer, captured by the home's eGauge, and overlaying it against the electric dryer electricity demand. Pecan Street gas data from that time period was used to determine how much gas the dryer used during the drying cycle.

Through this analysis, Pecan Street was been able to calculate and demonstrate with actual data that running a load on a gas dryer takes half the time as drying clothes with an electric dryer, (23 minutes versus 46 minutes). Assuming national average electricity and gas rates from the U.S. Energy Information Administration of $0.11.72/kWh and $0.00456/c.f., the cost of a load of laundry using the electric dryer under this real world observation is $0.36 versus $0.06 for gas dryers. By switching to a gas-powered clothes dryer from an electric clothes dryer, the project team found that on average, a household could save about 450 kWh of electricity over the course of a year, which equates to approximately $54 per year in savings.

Through analysis of energy consumption across the time of day, the research team found that gas-powered clothes dryers save approximately 154 kWh of electricity during peak demand times (3-7pm). A representative load of clothes uses approximately 3.2 kWh of electricity for an electric-powered clothes dryer. Electricity use for a gas-powered dryer is approximately 0.11 kWh plus approximately 8 cubic feet of gas.

Behavioral Research Trial

Dr. Raghunath Singh Rao, along with Xing (Mike) Lan and Zhuping Liu, all with the University of Texas at Austin, analyzed the results of the behavioral intervention groups. For their analysis, they focused on the initial 12 CPP events taking place in 2013. The exact dates of the events are as follows: June 20, June 26, June 28, July 24, July 26, August 1, August 7, August 8, August 29, August 30, September 5 & September 13. Dr. Rao, along with his colleagues, created a 3-day event window for each CPP event.

In analyzing the data, Dr. Rao and his graduate students took an observation sample size of approximately 6,820,218 observations spanning the portal group, generic text group, actionable text group, and a control group. The number of observations present allowed for intense research with a limited number of homes within the studies.

Table 20: Observation Counts and Average Usage

	Observations (Non-CPP period)	Average Use (Non-CPP period)	Observations (CPP period)	Average Use (CPP period)
Portal group	1,468,688	2.036	77,580	3.339
Text group	1,698,220	2.266	89,463	3.676
Actionable text group	1,780,040	2.058	93,511	3.276
Control group	1,873,270	1.807	98,702	3.041

Source: Dr. Rao, The University of Texas at Austin

Using trend analysis, Dr. Rao was able to calculate the average power usage using the observation window. The windowed average power usage shows a lower average use of power for the control group versus the portal group, text group, and actionable text group for times not within a CPP period. Also, during the CPP period, there is a higher average usage as well. As such, it was necessary to measure the effect of program difference—in-difference – taking into account pre-existing differences between the control and non-control group.

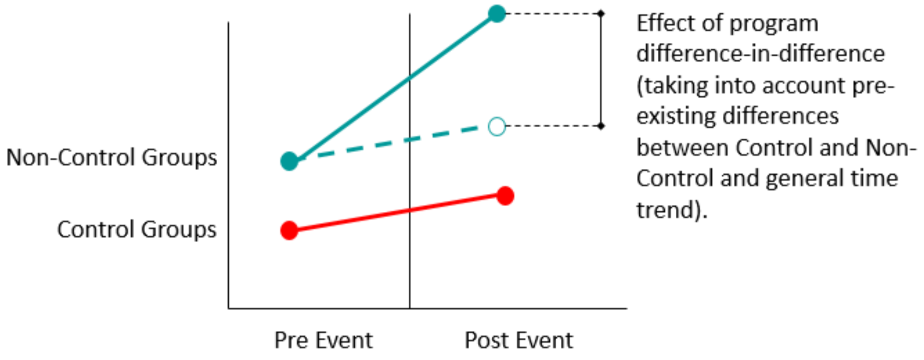


Figure 28: Measuring the effect of behavioral trial program differences using control and non-control groups (source: Dr. Rao, University of Texas at Austin)

The basic specification of the use was determined to be as follows:

$log(usei,j)$

Where is the household fixed effect, is the time effect, and are the treatment effects.

The individual CPP results for the first six CPP days, shown below, show a strong R2 values for the for the Actionable Text group.

Table 21: Individual CPP Results – CPP Days 1 through 6

	CPP1	CPP2	CPP3	CPP4	CPP5	CPP6
Portal R^2	0.0372	- .01215	- .231032	0.0292	-.00464	0.0449
Generic Text R^2	0.0514	-.09583	-.19447	-.03935	-.0877	0.0535
Actionable Text R^2	-.1749	0.0244	-.3097	-.02098	-.0824	-0.0508

Source: Dr. Rao, University of Texas at Austin

The aggregate results of the models created by Dr. Rao and his team are described below. Model 1 was the results of looking at neither the household fixed effect, nor the time effect. The second model was created using a time effect, but no household fixed effect. The third model run included the household fixed effect, but not time effect. The fourth, and final model, included both the household fixed effect and the time effect. The correlation in the fourth model showed an astounding 9% reduction in power use for a non-monetary incentive (the Actionable Text group).

Table 22: Aggregate Model Results for All Days

	Model 1	Model 2	Model 3	Model 4
Portal R^2	0.2469782	0.2468995	-0.014403	-0.014106
Generic Text R^2	0.3195427	0.3194095	-0.041533	-0.041503
Actionable Text R^2	0.1525115	0.1523223	-0.091125	-0.090916
Household FE	Not Included	Not Included	Included	Included
Hour-of-Day FE	Not Included	Included	Not Included	Included

Source: Dr. Rao, University of Texas at Austin

Further findings from Dr. Rao's analysis show a reduction in energy usage of approximately 4% for generic texts and almost no reduction (1%) for the portal group.

Dr. Rao ran significant robustness checks pertaining to his analysis, including a placebo check, where a set of known dates not included in the CPP trial was evaluated in the models created. The outcome of the placebo check was that there was no correlation between the model and the placebo dates, thereby substantiating the model correlation.

Conclusions

The initial Smart Grid Demonstration Program design and execution was validated during implementation of the program. Using data from Pecan Street's field trials, the project team has found the following conclusions for customer impacts from the Energy Internet.

Best Practices

- Any system that acquires data to provide customer services needs to have on-board data caching. This is due to inevitable intermittencies in even the most robust Internet and cellular networks.
- Even highly motivated customers quickly lose interest in their home energy data. To achieve any kind of behavioral response, such data needs to be analyzed through software applications to produce useful recommendations to customers that are highly tailored to their specific situations. Recommendations should move beyond "how to save money on your electric bill," which has limited enduring interest for customers. Rather, recommendations should focus on using home energy use to make home highly tailored home maintenance, appliance maintenance and home retrofit recommendations.
- Moving from electric versions to gas versions of clothes dryers, space heating, water heating and ovens offers an overlooked pathway to reduced carbon emissions, reduced operating costs, peak demand reduction and lower total energy costs.

Lessons Learned

- Pecan Street's initial research challenge lay in the reliability of continuous data reporting from HEMS deployed in the field. To solve this problem, the Project team developed two methods to protect against data loss. First, the team found a data collection device that locally caches data for up to one year. If data is not transmitted correctly at a given time, the database is able to fill data gaps with this feature. Second, Pecan Street uses an offsite web-based backup system as well as long-term archival storage for raw data to prevent data losses.
- At one hour intervals, AMI smart meters do not provide sufficient data to enable meaningful algorithmic disaggregation and the consumer services that could be made possible by such disaggregation.

- Residential air conditioning technology improvements represent the most promising area for achieving high impact in peak demand reduction. Such technology improvement, however, must move beyond technologies that produce greater levels of occupant discomfort and higher temperatures. Instead, innovations should focus on how to provide current or even greater levels of home cooling through greater system efficiencies. One promising area of air conditioning innovation is in zonal, mini-split systems, which are common in parts of Europe and Asia but rare in the U.S.; such systems empower occupants to cool individual rooms while leaving unoccupied rooms uncooled or set at much higher temperatures.

Program 2: Demonstrate impacts of the Energy Internet on utility infrastructure

Distributed PV Energy

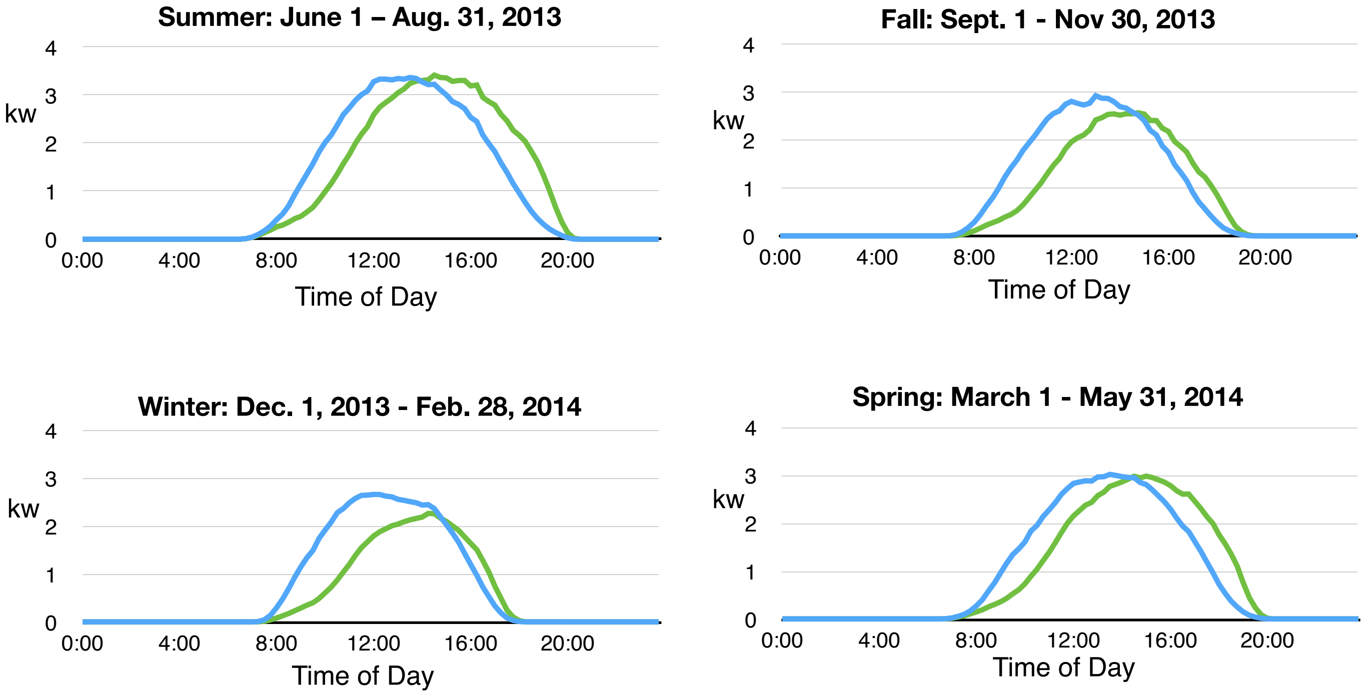
Austin Energy has provided $37 million in solar incentives for 2,740 residential solar projects and 141 commercial solar projects since its Solar Program's inception in 2004. In August 2014 the Austin City Council increased the Renewable Portfolio Standards (RPS) solar carve-out by setting a goal for Austin Energy of 600 MW of new utility-scale solar by 2017 and 200 MW of "local solar" by 2020, of which at least 100 MW is to be customer-controlled (behind the meter) solar. Pecan Street sought to evaluate how customer-owned solar could provide greater value to the utility and contribute to overall grid reliability and resilience.

To evaluate the impacts of dense deployments of residential rooftop PV systems on utility infrastructure, Pecan Street evaluated the overlap between PV generation by variable system orientations and on-site energy consumption, by season. Austin Energy will derive greater benefit from distributed generation that meets demand during peak consumption hours. By producing energy when it is needed on-site, less power is fed back onto the grid, which reduces the current and energy requirements for that grid infrastructure. Reduced loading on the local infrastructure should result in longer life for that equipment and an ability to manage additional loads.

Furthermore, Austin Energy — a vertically-integrated utility — is regularly forced to purchase power in the Texas Nodal Market in the summertime when it does not have enough generation capacity to meet local peak demand. In peak demand times, wholesale electricity prices may reach many multiples of their off-peak value. The ERCOT wholesale price cap is currently $7,000 per MWh and will rise to $9,000 per MWh on June 1, 2015. In 2013, the total load for Austin Energy's service territory was 13,056,430 MWh and total local generation was 11,128,145 MWh, leaving 1,928,285 MWh that had to be purchased on the Nodal Market. In 2014, the total load for Austin Energy's service territory was 12,628,517 MWh and total local generation was 10,829,326 MWh, leaving 1,799,191 MWh that had to be purchased on the Nodal Market.

The project team found that west-facing solar produces more power during the ERCOT peak demand hours of 3-7pm in all seasons, with the greatest difference in peak alignment occurring in the summer, when peak demand is highest. Figure 29 shows average daily generation (in kW) for south- and west-facing residential rooftop PV generation.

The study sample consists of 50 homes for which there was continuous data throughout the project period.


Summer: June 1 – Aug. 31, 2013

Fall: Sept. 1 - Nov 30, 2013

Winter: Dec. 1, 2013 - Feb. 28, 2014

Spring: March 1 - May 31, 2014

Figure 29. PV generation by season and directional orientation

In Fall 2013, west-facing systems generated 10 percent more electricity per day than south-facing systems (on a normalized basis). [6] This was due primarily to June generation; by August, south-facing systems produced more per day than west-facing systems. During peak demand hours (3-7 pm), west-facing systems generated 68 percent more electricity than south-facing systems. This level of difference persisted throughout the three-month period.

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[6] Normalized generation is the amount of generation that a solar PV system would have produced if it was the same size as all other systems in a sample. To determine how much electricity each system would have produced if each system was sized at 5,500 watts, normalized generation was calculated by dividing generation by the size of the system, then multiplying that value by 5,500.

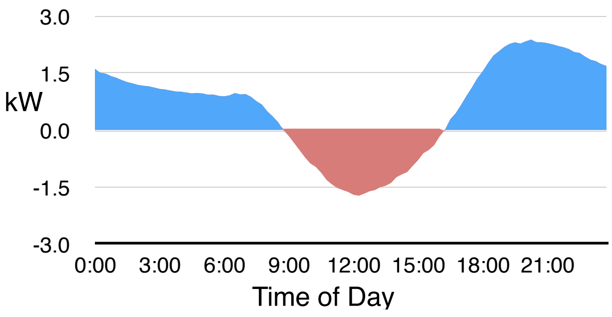
In Summer 2013, west-facing systems generated 10 percent more electricity per day than south-facing systems (on a normalized basis). [7] This was due primarily to June generation; by August, south-facing systems produced more per day than west-facing systems. During peak demand hours of 3-7pm, west-facing systems generated 68 percent more electricity than south-facing systems. This level of difference persisted throughout the three-month period.

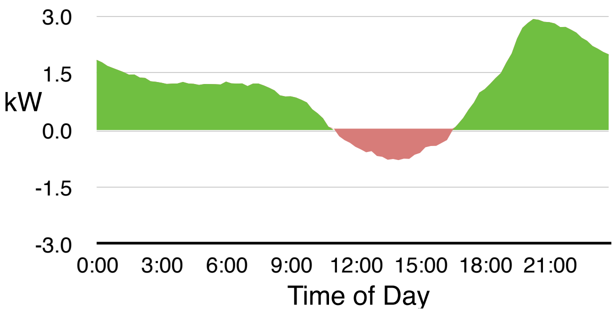
In Winter 2013-14, south-facing systems generated 34 percent more electricity per day than west-facing systems (on a normalized basis).[8] During the 3-7 pm peak consumption period, west-facing systems generated 35 percent more electricity than south-facing systems.

In Spring 2014, south-facing systems generated 4 percent more electricity per day than west-facing systems (on a normalized basis).[9] By May, west-facing systems were outproducing south-facing systems. During the 3-7 pm peak period, west-facing systems generated 42 percent more electricity than south-facing systems. West-facing systems out-produced south-facing systems during the late afternoon hours throughout the period.

The project team next looked at average daily net grid impact (kW) for homes with south-facing PV by analyzing electricity drawn from grid and PV generation sent to grid and for homes with west-facing PV by analyzing electricity drawn from grid and PV generation sent to grid.

Summer 2013 (June 1- August 31, 2013):





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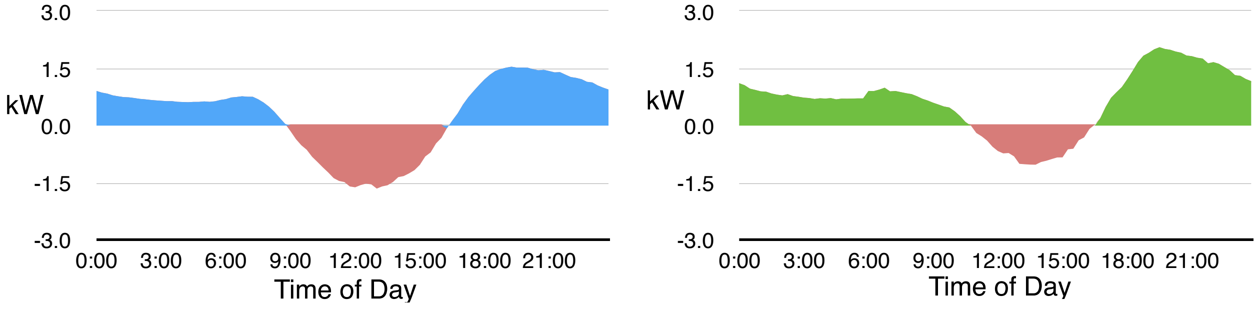
[7] Normalized generation is the amount of generation that a solar PV system would have produced if it was the same size as all other systems in a sample. To determine how much electricity each system would have produced if each system was sized at 5,500 watts, normalized generation was calculated by dividing generation by the size of the system, then multiplying that value by 5,500.

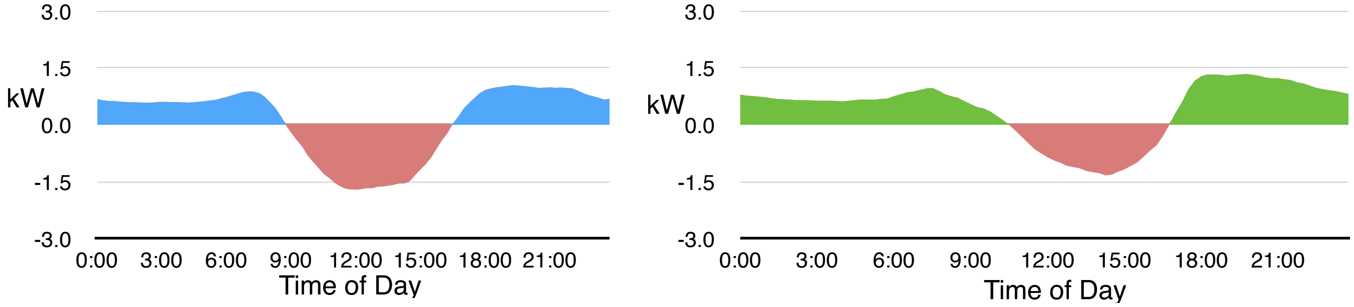
[8] See footnote 2

[9] See footnote 2

Fall 2013 (September 1 - November 30, 2013):



Winter (December 1 - February 28, 2014):



Spring (March 1 - May 31, 2014):

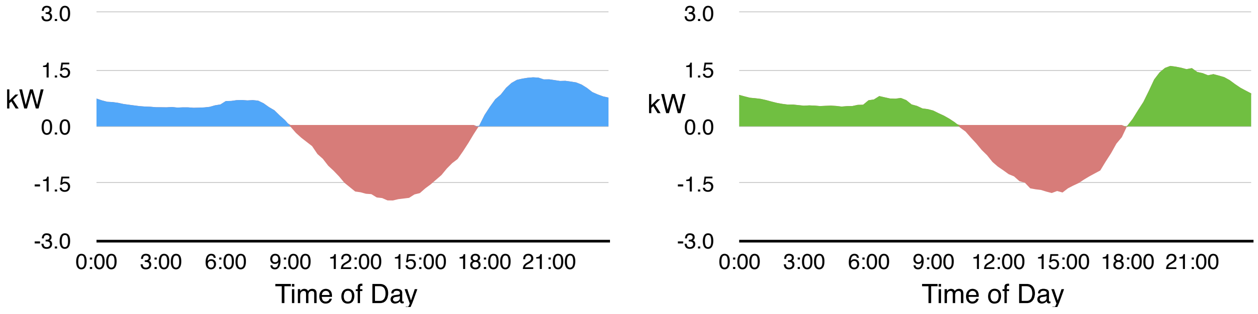


Figure 30. Average daily PV generation and on-site consumption by season

In Summer 2013, during peak demand hours, 78 percent of generated electricity was used in the home. Peak demand reduction from rooftop PV was robust during the most intense hours of system-wide peak. From 4-5 pm, PV systems averaged an 87 percent peak demand reduction. From 5-6 pm, systems provided a 64 peak demand reduction. The project team found that because so much of their production occurs during summer peak demand hours, rooftop solar panels, particularly west-facing, could play a helpful role in managing summer peak demand.

In Fall 2013, between noon and 5 pm, rooftop systems on average put about one kilowatt hour per hour back on to the grid. Over the course of an average day, 48 percent of generated electricity was used in the home. While home electricity use decreased from summer to fall (driven almost exclusively by reduced HVAC use), the amount of electricity that PV systems put back on distribution systems during the fall shoulder months also declined.

In Winter 2014, between noon and 5 pm, rooftop systems on average put slightly more than one kilowatt hour per hour back on to the grid. Over the course of the average day, 34 percent of generated electricity was used in the home. The project team observed that generation from rooftop solar panels has a low level of alignment with winter home electricity use patterns, particularly for homes whose occupants are not home during the day. Even so, PV systems have a lower level of impact on utility distribution systems than in other seasons due to overall reduced generation during winter months.

In Spring 2014, between noon and 5 pm, rooftop systems on average put about 1.6 kilowatt hours per hour back on to the grid. Over the course of the average day, 38 percent of generated electricity was used in the home.

Energy Storage

Pecan Street's energy storage research undertaken through Program 2 evaluated the impacts of energy storage solutions implemented alongside a single transformer, known as "community energy storage," and designing systems integration specifications for multi-fuel, islandable pico- and micro-grids.

The potential impacts of energy storage solutions were hypothesized in the Mueller Community in Austin, TX through a theoretical and mathematical model developed by Dr. Fabian Uriarte from the University of Texas's Center for Electromechanics. The entire community is fed from a single three phase lateral where each phase inside the community serves 20 to 40 transformers. For the model, the PV generated energy storage unit would be installed on only one transformer.

An overview of the Mueller Community's distribution network is illustrated below:

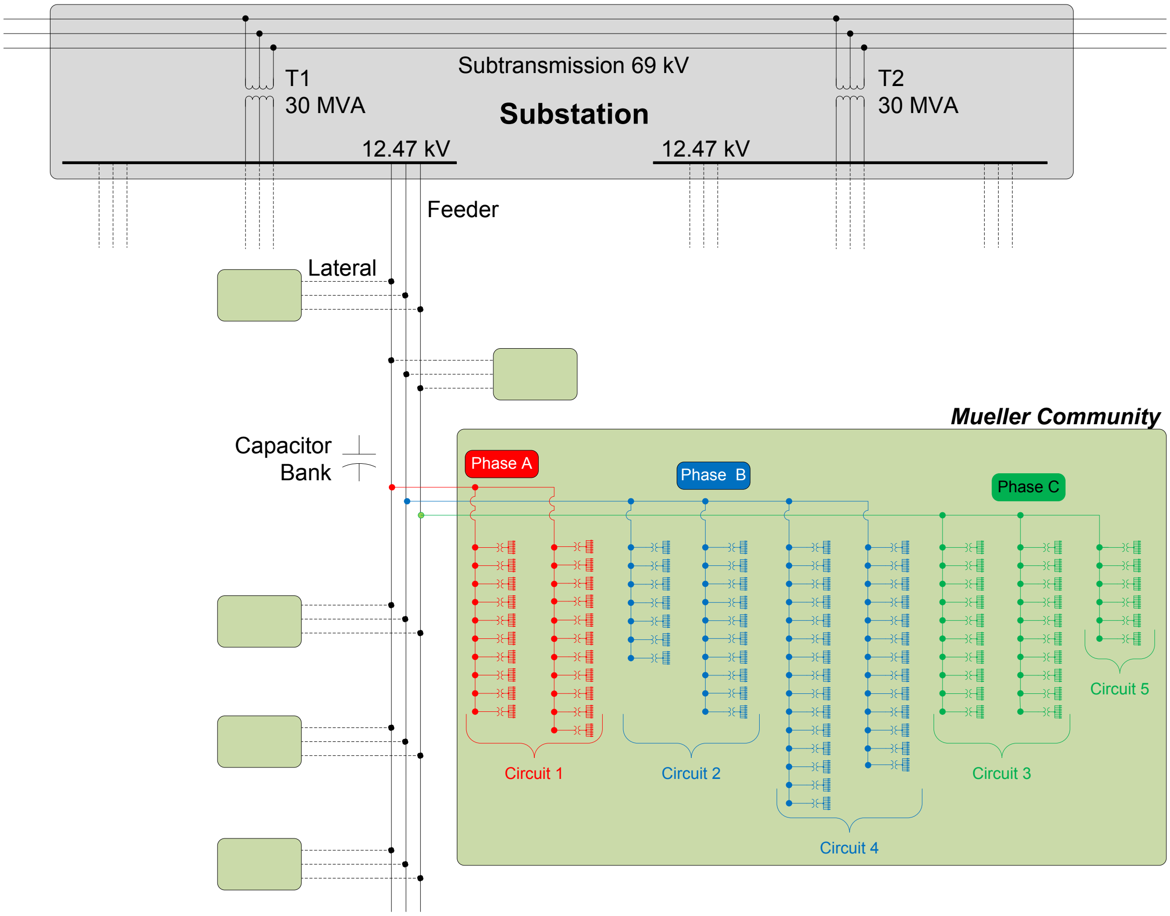


Figure 31. Mueller distribution network [10]

Charging of the energy storage batteries is set to occur in this model under the following conditions:

a. When transformer load is low (< 30 kW)

b. When sun is out (PV > 5 kW)

c. When state of charge (SOC) reaches 10 %

d. Charge logic: (a OR b) AND c

Discharge of the energy storage units is set to occur under the following conditions:

a. When PV output fluctuates

b. When transformer load is high (≥ 30 kW)

c. When SOC reaches 90 %

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[10] Dr. Fabian Uriarte et. al. Community Energy Storage: 7-Day Forecast. Presentation at June 2012 Pecan Street Inc. Industry Advisory Council Quarterly Workshop.

d. Discharge logic: (a OR b) AND c

The community energy storage unit consists of a single-phase transformer stepping down from 7.2 kilovolts (kV) to 240 volt (V) split phase. The unit includes a disconnect switch at the community energy storage that permits entering island mode. Inside the storage unit, there is a connection from a 25 kW PV and a 25 kWh, 25 kW battery unit. The PV and the battery are interconnected to an internal 240 V AC Bus. The residential loads, including solar panels and electric vehicles, are connected from this internal AC Bus as shown.

A diagram of the unit is illustrated in the figure below:

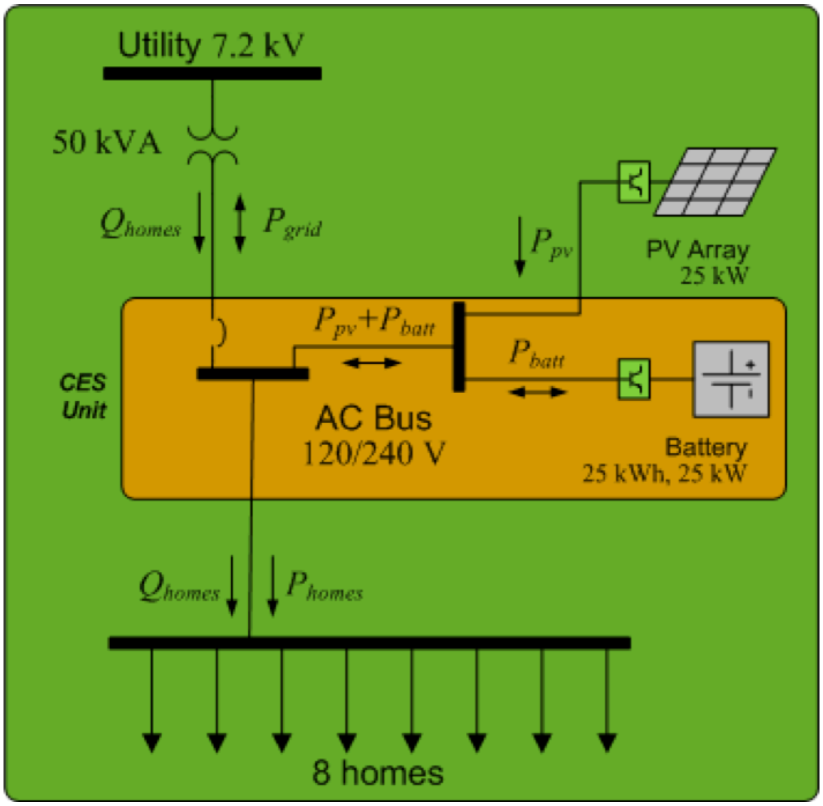

Figure 32. Community energy storage diagram.[11]

Three hypothetical case studies were considered as part of this research. The first case study focused on charging and discharging the battery when the state-of-charge reaches its threshold. This scenario demonstrates how long the battery can support the residential load of 10 homes.

The second study charges the battery at midnight, but only discharges it during PV outage. This scenario demonstrates whether the battery can compensate for the 25 kW PV fluctuations that occur when local PV generation is disrupted.

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[11] Dr. Fabian Uriarte et. al. Community Energy Storage: 7-Day Forecast. Presentation at June 2012 Pecan Street Inc. Industry Advisory Council Quarterly Workshop.

The third case study charges at midnight, and discharges when the residential load is greater than 15 kW. This demonstrates whether the storage unit can effectively serve to level the transformer load.

Each case study was analyzed using MATLAB/Simulink to simulate the single transformer with community energy storage. The source, transformer and main disconnect blocks were taken from the SimPowerSystems library. The residential load, the 25 kW PV and battery storage models, were custom subsystems.

Preliminary observations from the research conclude that community transformers appear to be sized appropriately and maintain an average load of 6 kW. The PV installed alongside the storage unit peaks at 20 kW, but can fluctuate intermittently.

Supplemental battery storage can support residential load for up to two hours and can compensate for PV fluctuations. Additionally, the battery can level the transformer's load by providing real power. Reactive power support is also possible, but is not part of this study.

Additionally, a financial model was evaluated for battery storage combined with PV. The criteria was if a residential battery could improve power quality, assist with peak shaving, encourage time shifting or allow the customer to go off-grid. Using the installed cost of PV (Figure 33), combined with the battery cost, a model was run to evaluate the projected total installation cost of the community energy storage system.

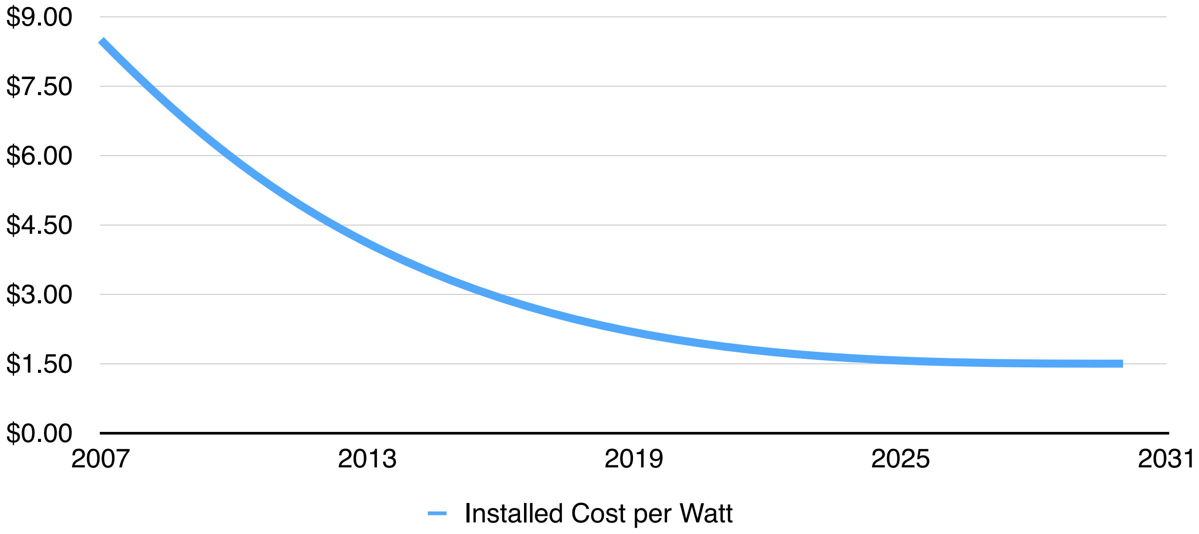

Figure 33. Installed cost of PV per what over time

A simple cost model for storage for one cycle per day suggests that the cost per kWh discharged is currently cost prohibitive for main-stream residential adoption at $0.48, based on current battery costs. However, battery costs continue to decline and may result in financial feasible over the next few years.

Figure 34 was generated by converting the previous PV cost curve (Figure 33) to $/kWh for power delivered over the life cycle of the PV, and by converting the cost of kWh of storage to $/kWh for power delivered over the lifecycle of the battery. This curve suggests that an islanded PV power system with storage could produce energy at a cost of $0.25 per kWh by 2020, and $0.12 per kWh by 2030. These costs would be the natural result of a rapid shift to PV. After 2030 the cost of energy from combined PV-battery systems will continue to drop.

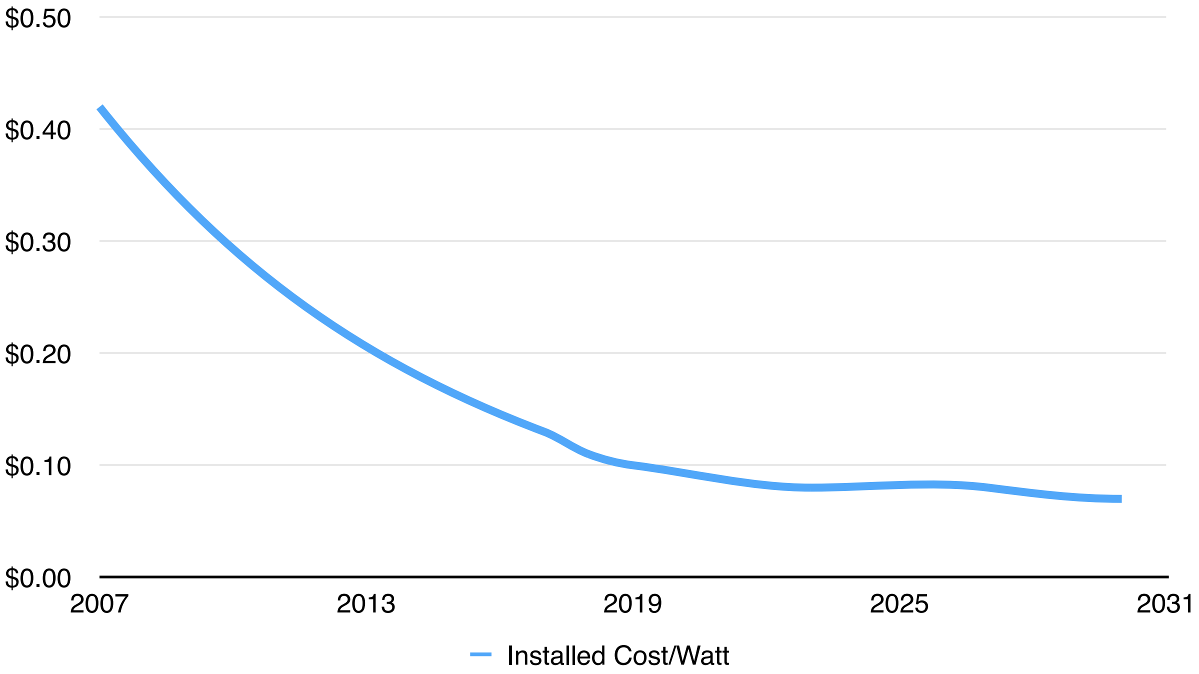

Figure 34. Project installed cost per kWh for PV and storage

Residential Power Quality

To gain insight into the current status of residential power quality, pQube measurement systems were installed at seven different residences for a period of four weeks, two weeks during heavy AC usage and two weeks during periods of low AC usage. The pQube device measures:

- L-L voltage
- L1 Current
- L2 Current
- Neutral Current
- Voltage THD
- Current THD
- Real Power
- Apparent Power
- Reactive Power
- Frequency

Other three-phase specific parameters are measured, but since the devices were installed in a split phase residential service they will be ignored for the purpose of this analysis.

Several devices were examined for this work from Fluke, Yokogowa and Dranetz/BMI. The Power Standards Laboratory product was significantly less expensive while providing the exact same or improved capabilities.

The device also can be programmed to take time-domain snapshots either at specific interval or during events. The pQubes were programmed to take snapshots of the voltage and current every three hours. The snapshots provide a high resolution, high speed data capture of 16 cycles of AC waveform data measured at an 8kHz sample rate, sufficient to capture up to the 50th harmonic of a 60Hz system if present.

Previous work by Dr. Grady (Proc. of the EPRI Power Quality Issues & Opportunities Conference (PQA'93), San Diego, CA, November, 1993) measured typical appliances and found that the power factor for all but the smallest devices was a high 0.98 or better.

At the time of the work the total load inside the home served by switched mode power supplies was relatively low. Efficiency and cost requirements have meant that increasingly switched mode power supplies and variable speed drives are being used for residential devices.

Figure 35 shows an example whole home voltage and current snapshot for a Mueller participant during the study period. Note that the current waveforms show visible distortion, and are not a clean 60Hz sine wave. For this home during this snapshot period the power factor for L1 was 0.91 and L2 was 0.94. It is common to see a power factor as low as 0.8 or even 0.7 without solar production.

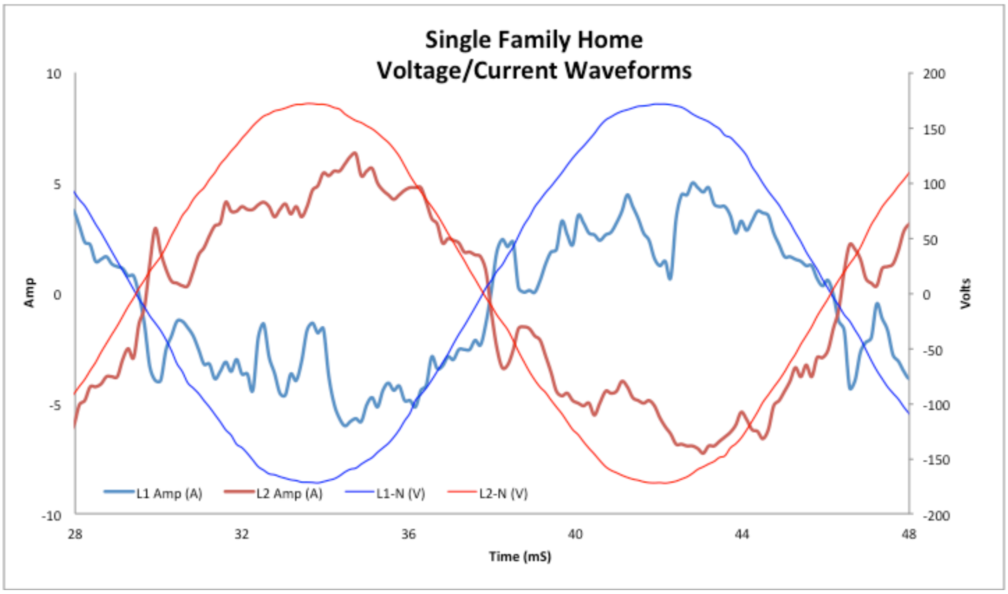

Figure 35. Whole home voltage and current waveforms

Figure 36 shows the the apparent (kVA) and reactive (kVAR) power for a single-family home during a typical summer evening. An examination of the individual circuits on at this time from the eGauge data for this home shows that the home load consisted of a base load of exterior and interior lighting and devices that are "always on" in a typical residential structure, such as electronics in power save mode, refrigeration, etc.

The three periods of high demand shown in Figure 36 correspond to cycles of the air-conditioner for the structure.

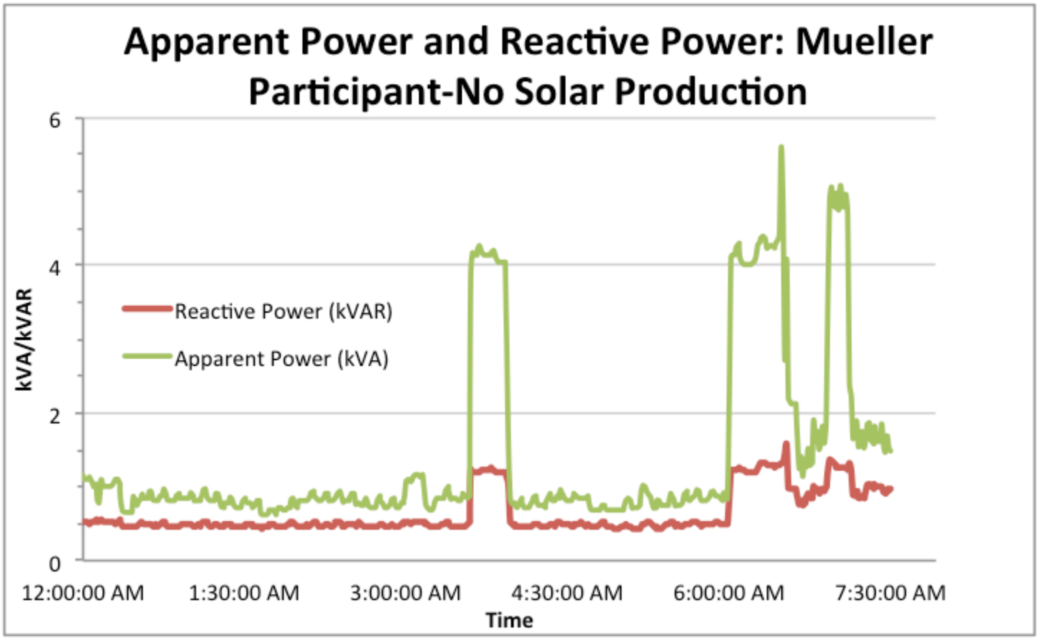

Figure 36. Single home reactive and apparent power

Figure 37 shows the power factor during the same period, which averages 0.82. The cause of the low power factor appears to be devices either with switching power supplies or switched mode motor drives. Older induction motor devices, or devices with linear power supplies/resistive heating, have very high power factors and corresponding low current distortion. An examination of the individual loads, as show in Table 23, makes a strong case that this is the cause of the low power factor.

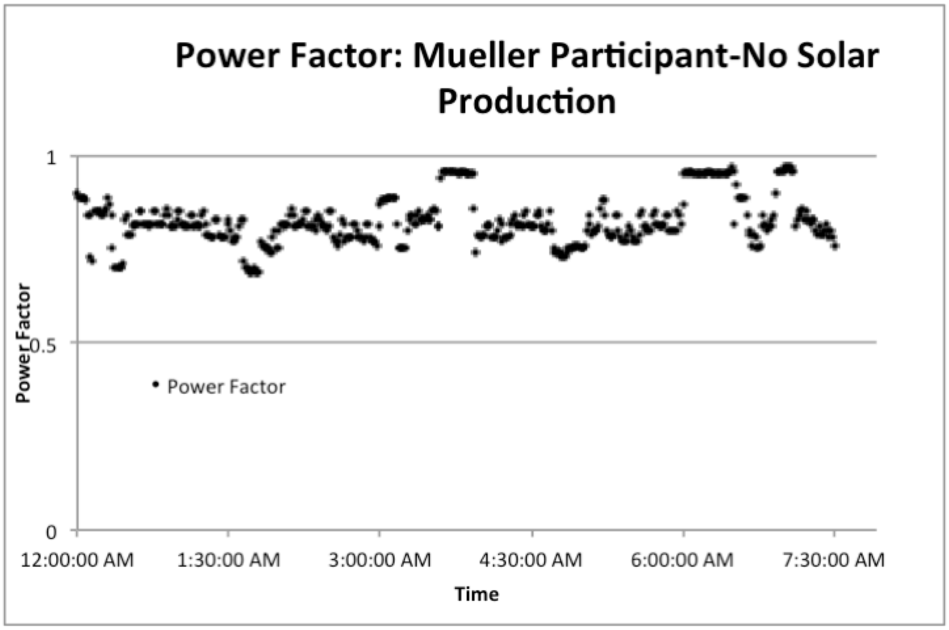

Figure 37. Residential power factor, no solar production

Table 23. Power Factor of Residential Devices

Item	HVAC System	Electric Vehicle	12-Year Old Refrigerator	PF Corrected Computer	Flat Panel TV	CFL Light Bulb	LED Light Bulb	Electronic Drive Blower Motor	Induction AC Blower Motor
Power Factor	0.94	0.99	>.99	>.97	>.96	0.56	0.675	0.56	0.94
Current THD	14%	10%	<7%	16%	25%	121%	109%	N/A	10%

Figure 38 shows the voltage and current for a typical well maintained HVAC condenser unit. This is the portion of the AC unit placed outdoors and is responsible for the majority of the energy usage. The power factor for this unit is approximately 0.94 and the majority of the term comes from lagging displacement in the current. This is what one would expect in an induction motor. In a poorly maintained unit, where the "run/start" capacitor is at the end of its service life, or in need of replacement the power factor may drop as low as 0.6 or lower.

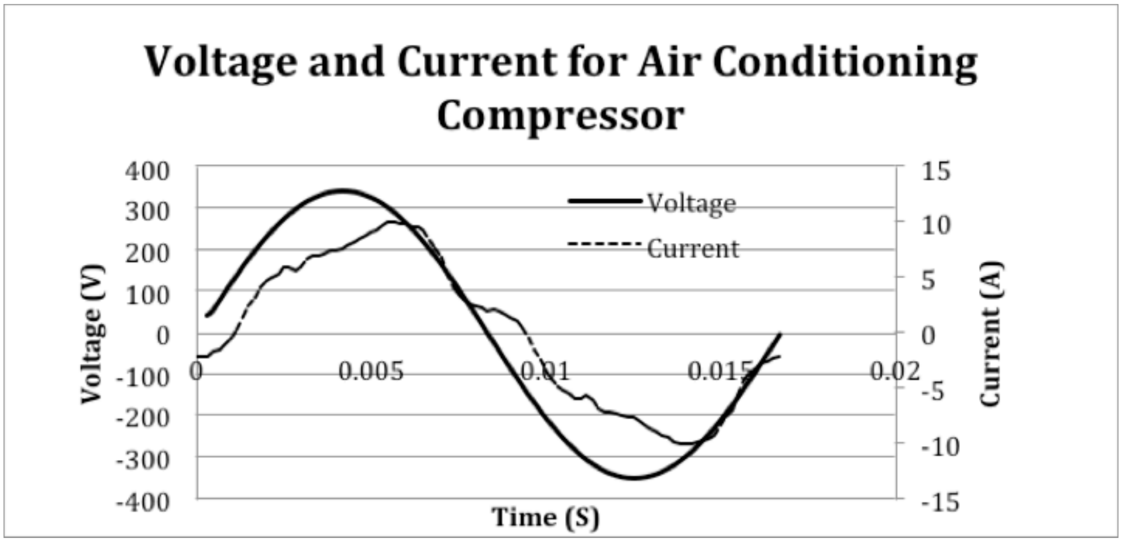

Figure 38. Voltage and current for HVAC compressor

Figure 39 shows the voltage and current waveforms for an electric vehicle, in this case a 2011 Chevy Volt using a Level 2 EVSE from Schneider Electric. The EVSE has no impact on power quality as the design consists of a two pole electric contactor and safety circuitry to detect ground faults. The vehicle however does an excellent job of power factor correction providing a power factor of 0.99 and less than 7% THD for the current.

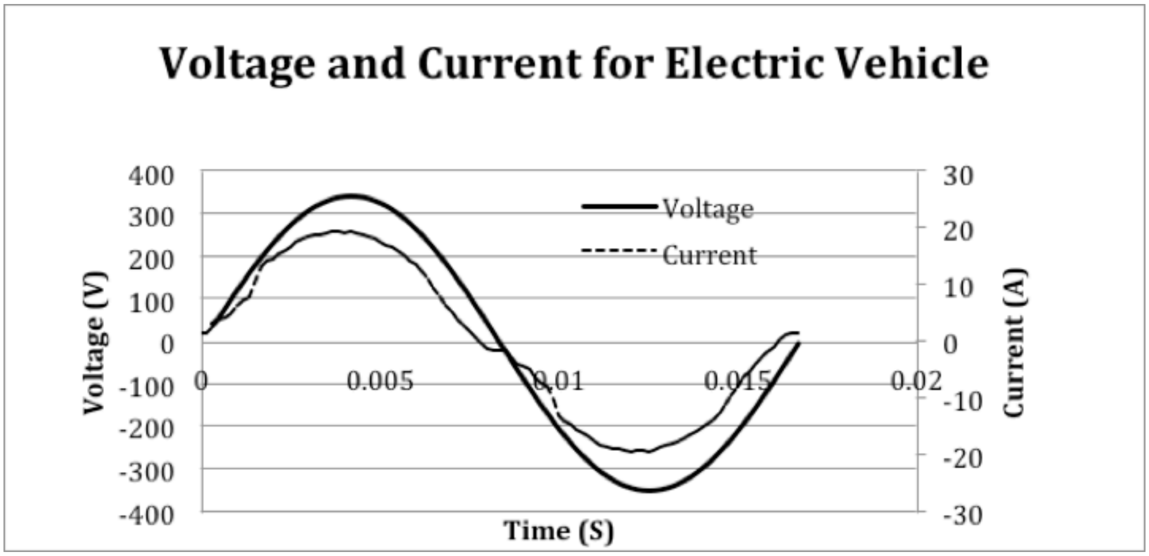

Figure 39. Voltage and current for electric vehicle

Figure 40 shows the voltage and current for a "silver" rated Energy Star power factor corrected computer. The power factor for this computer is 0.97, but is starting to show some of the distortion current characteristic typical for switching power supplies.

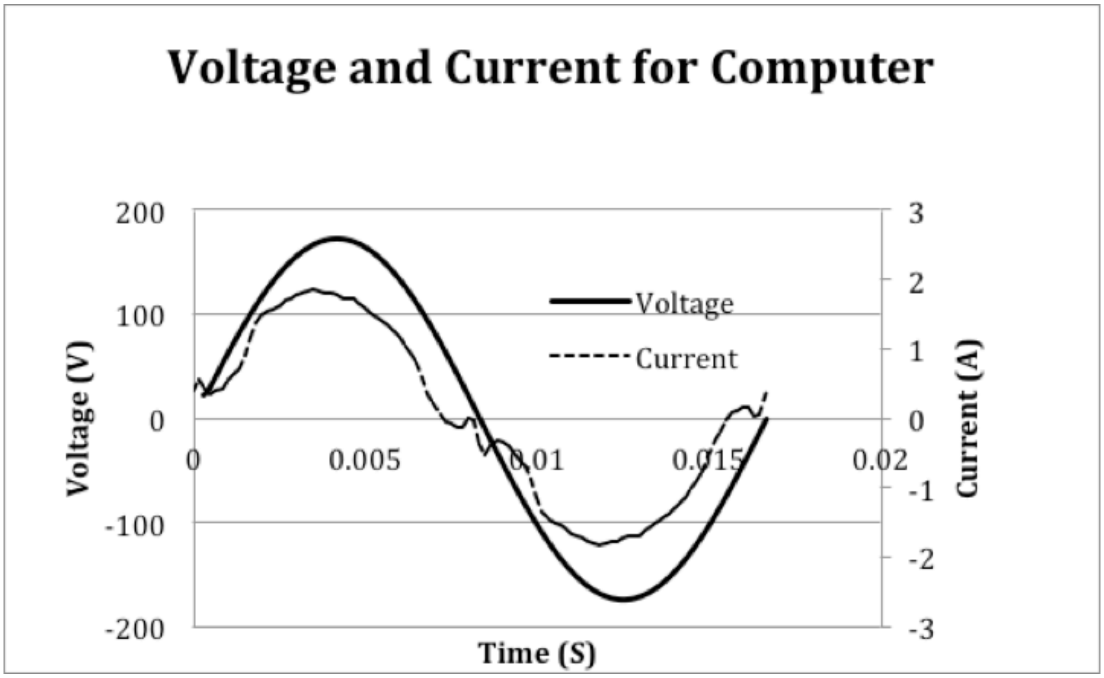

Figure 40. Voltage and current for computer

Figure 41 shows the voltage and current for an Energy Star-rated CFL light bulb. In this case the tPF for the device is a low 0.56 (the minimum to achieve the Energy Star rating is a 0.5) with 121% current THD. Therefore, this particular device has more harmonic current than fundamental current, with heavy amounts of 5, 7, 9 and 13th order harmonics. It should be noted that a Fourier analysis of the current waveform shows that the fundamental 60Hz current leads the voltage by almost 20 degrees. This means that a residential structure with large amounts of CFL light bulbs can actually put leading VArs onto the distribution system. Historically residential structures have only put lagging VArs onto the distribution system, coming from inductive motors.

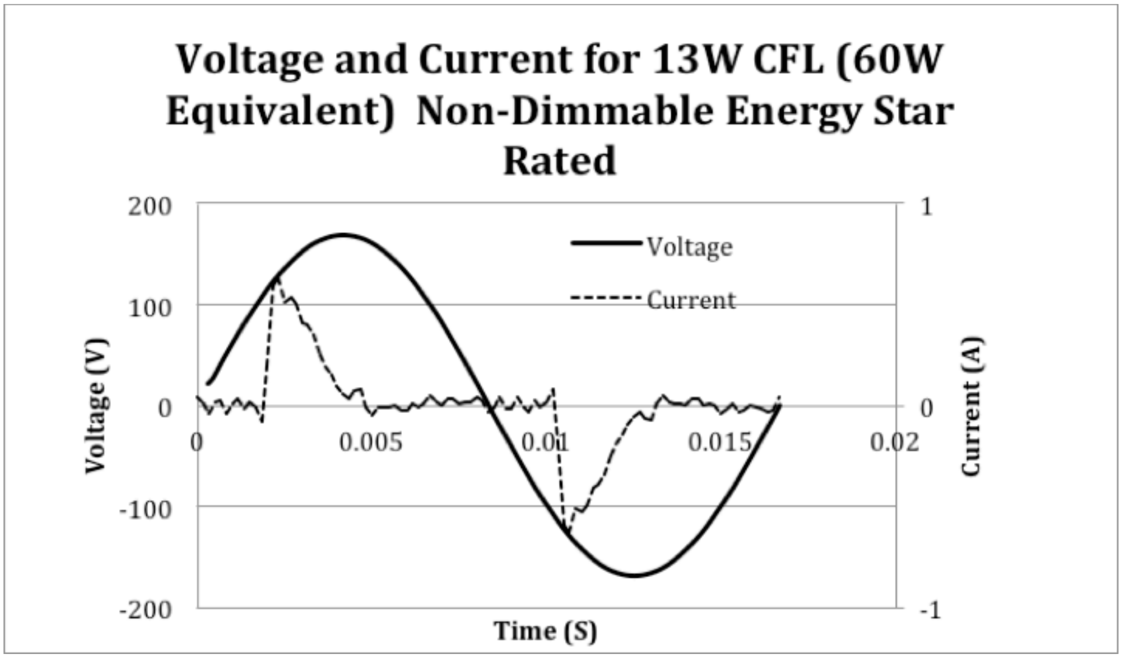

Figure 41. Voltage and current for CFL light bulb

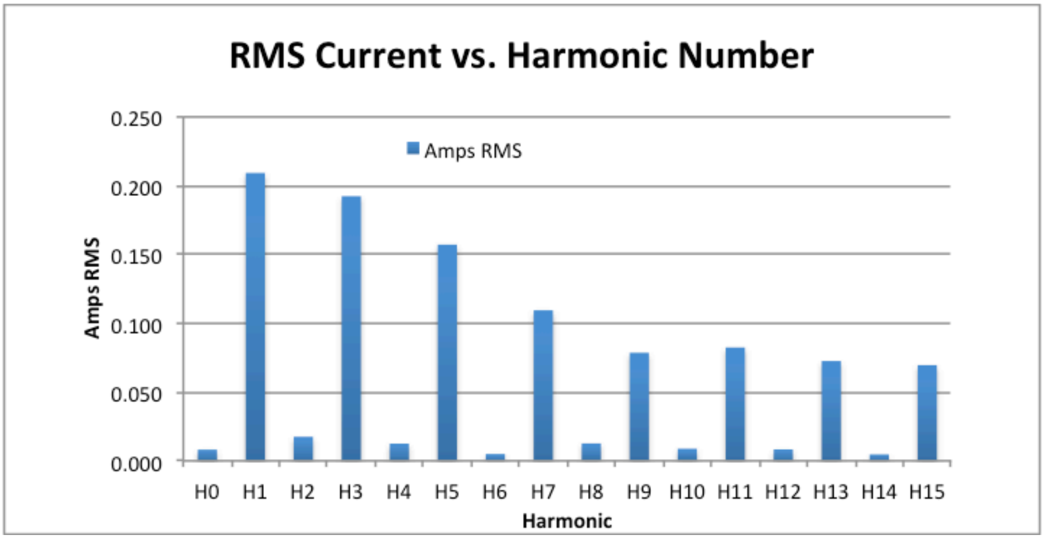

Figure 42. RMS current vs. harmonic for CFL light bulb

Figure 43 shows the voltage and current for an Energy Star-rated LED bulb. This particular bulb measured at 0.65, or just under the 0.7 requirement in the Energy Star standard. It has similar waveforms to the LED bulb, but does not present quite the amount of fundamental leading VArs to the system.

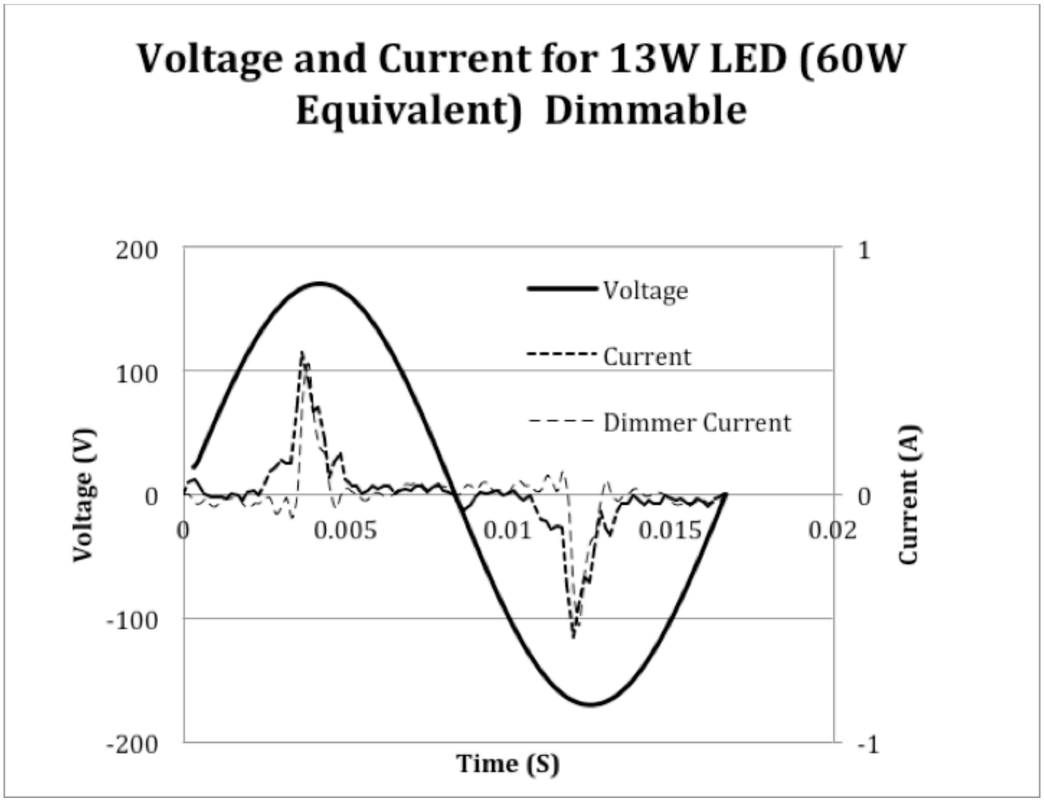

Figure 43. Voltage and current for LED light bulb

The power factor for many other devices, including set-top boxes, DVR units, televisions, power tools and others were measured as well. In general, units with smaller switching power supplies, such as set-top boxes and DVR units, to medium-sized switching power supplies, such as variable speed drive units, showed very high current distortion. The current distortion for these devices explains the high level of current distortion shown at the residential service entrance. The presence of solar can complicate the picture for utility service providers.

Power Quality in the Presence of Solar

In the presence of solar, it is possible and quite common in the Mueller community for the solar system to produce more power than the residential structure consumes. Grid-tied solar inverters produce a very high quality (typically less than 3% THD) sine wave output that provides real power only. These devices do not to provide any reactive power support for loads requiring either phase correction (leading or lagging loads) or distortion cancellation.

This output puts the utility in the unusual situation of needing to provide reactive power support to an individual structure or geographically close homes if they all have grid-tied solar.

The definition of power factor is defined as the ratio of real power to total apparent power. Historically loads would never generate real power, so there was no real need to track the direction of the power, or the sign of the numerator.

$$PF = P/S$$

Where:

P = *Real Power*

S = *Apparent Power*

In the case where the load generates power, the most common way to denote the phase reversal is to assign a negative value to the P term, leading to a Power Factor that is negative.

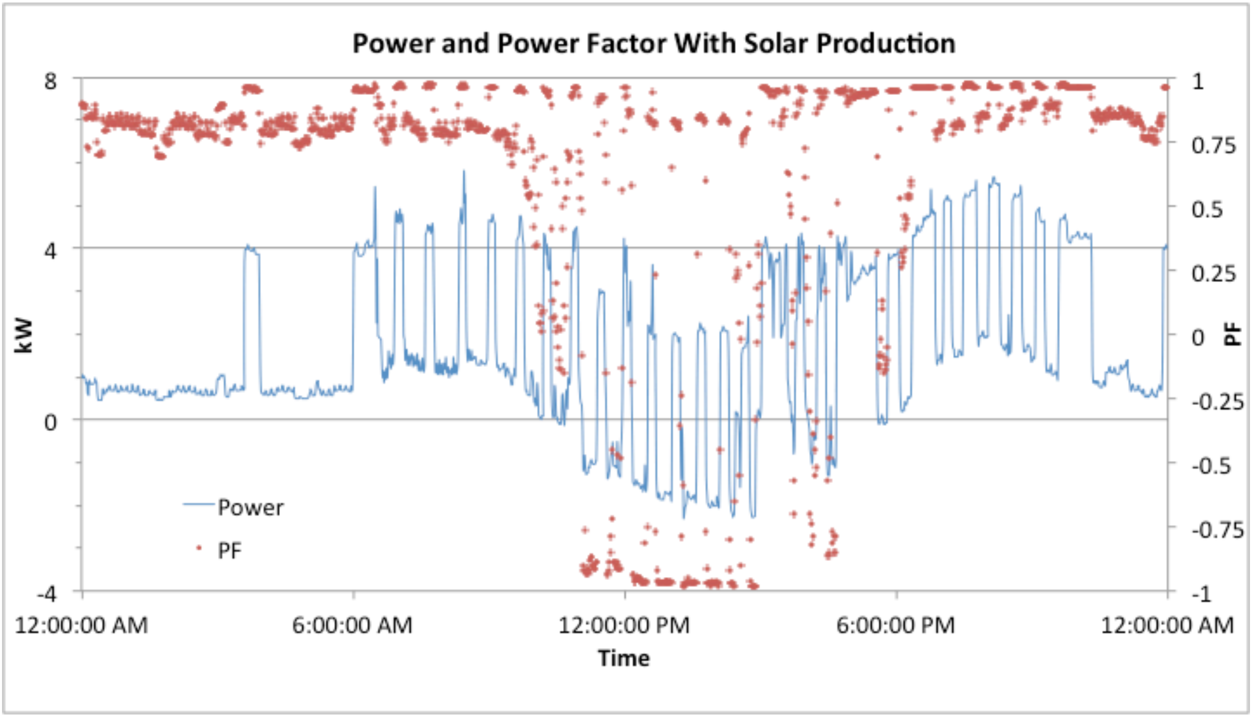

Figure 44. Power and power factor with solar production

Figure 45 shows the typical power factor and power for a house with grid-tied residential solar. A negative power indicates power being supplied to the utility.

While studying the residential structure a high correlation between residential current THD and solar production was observed. One interpretation might be that the solar caused the THD, but this is not the case. If the grid-tie solar inverter meets the specifications and requirements from both Underwriters Laboratories/ANSI and the IEEE than the current distortion from the inverter must be under 5% THD. Several inverters were measured directly from a variety of large international manufacturers such as Fronius, Schneider and SMA. All units were typically better than the standard at under 3%.

The cause of the correlation is the fact that the units all supplied fundamental 60Hz current, in phase with the utility voltage as the sole energy output. They did not perform any power factor correction by providing leading/lagging VArs or distortion power factor correction by supplying cancellation distortion current.

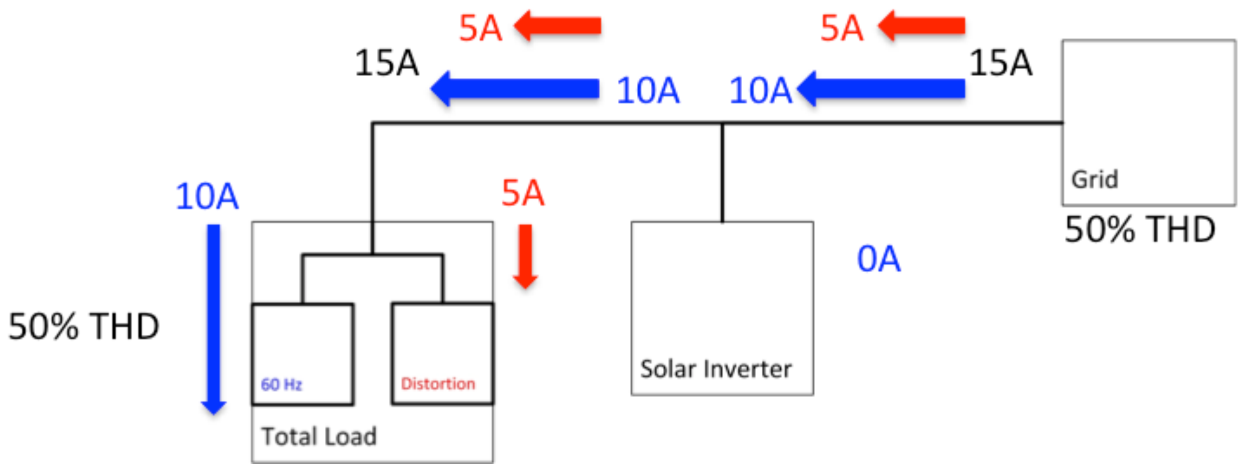

Figure 45. Example home load, no solar production

Figure 45 provides an example home load condition under no solar production. In this case the home requires 15A total current, with 10A of fundamental 60Hz current. In addition the home requires 5A distortion current support from the utility.

The utility sees 50% THD as does the home.

Figure 46 shows the same home, with the same loads, this time with solar production. In this case the solar is producing 8 amps of the 10 amps fundamental 60Hz current required in the home. However, it provides no support for any of the distortion current. In this case the THD of the current in the home is still 50%. However, the utility now only supplies 2A of fundamental current and is still needed for 5A of distortion current support. In this case the utility sees a total THD of 250%.

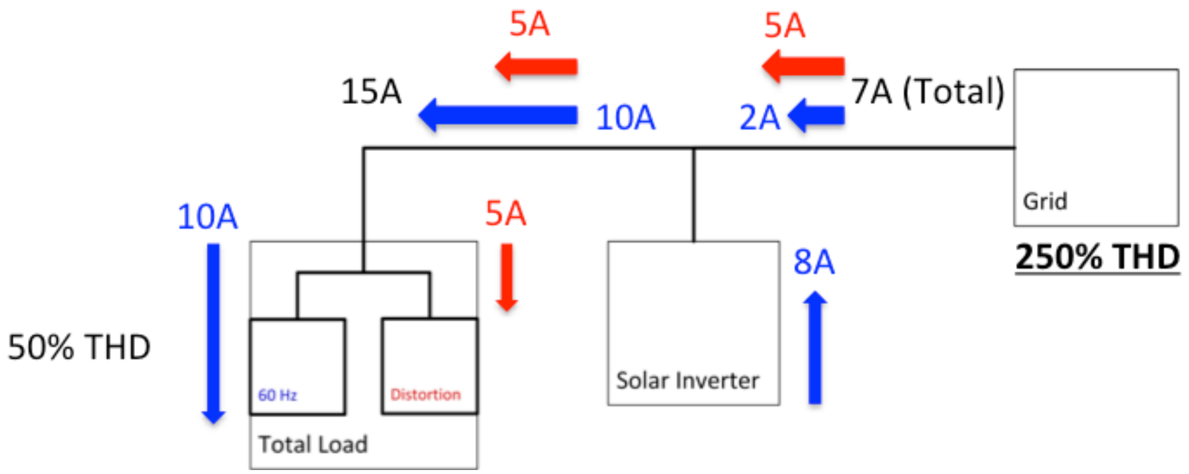

Figure 46. Example home load, solar production

The green line in Figure 47 shows the fundamental 60 Hz current for a Mueller participant with grid-tied solar. A negative number indicates that the residence is supplying power back to the distribution grid while a positive number indicates that the customer is using power from the distribution grid. The red line plots the distortion current support provided by the utility during the day, ranging between 1-2 amps RMS. Note that the magnitude of the distortion current changes relatively little during the day, with only a few very short excursions to over 5A RMS. The distortion, however, shoots up to over 1000% in the morning and evening, when the solar production most completely cancels the fundamental current load in the home.

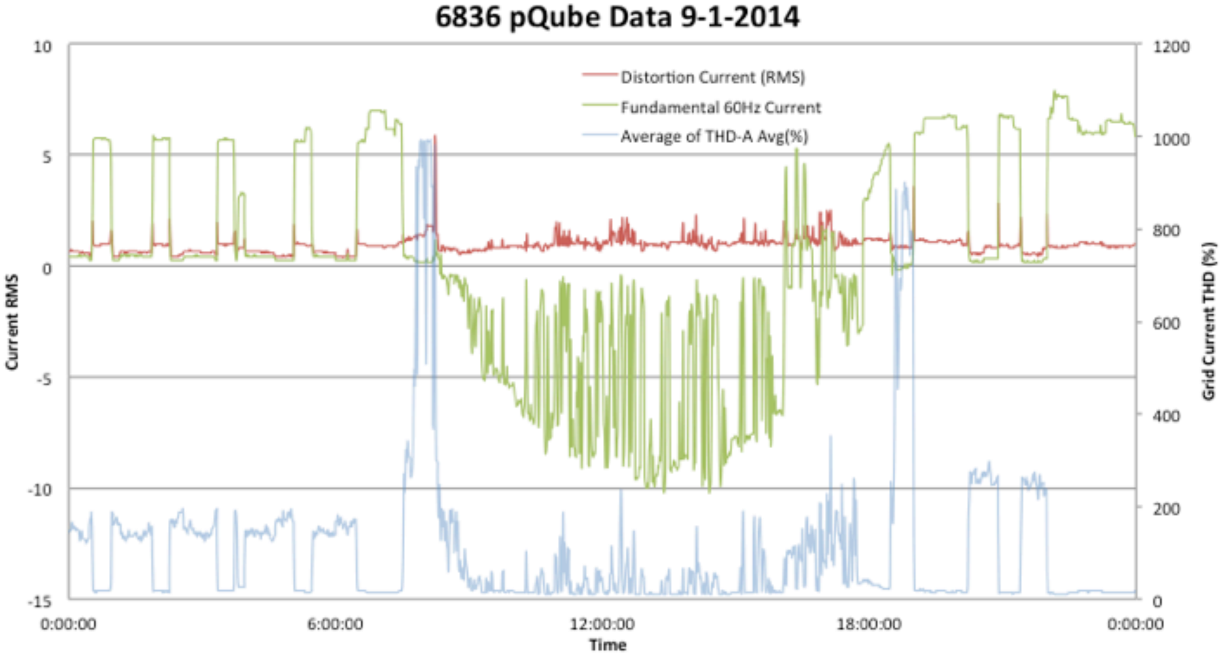

Figure 47. Distortion and fundamental currents during solar production

Residential Solar Impacts on Utility Distribution Transformers

During the study period four transformer monitors made by Gridsense were installed in distribution transformers serving residential customers in the Mueller neighborhood. Three of the four transformer monitors successfully collected data over the entire installation period, from February of 2012 to the end of 2014. The fourth unit collected data correctly for approximately nine months and then failed to report data. Unfortunately, the vendor has not yet successfully repaired the unit.

Data from the remaining three transformers was analyzed to determine what impacts the high density of solar, plug-in electric vehicles and other devices at the distribution transformer level.

The utility service for these residential customers is Austin Energy, which uses conservative design guidelines for sizing residential transformers. On average in the Mueller neighborhood, eight 200A residential structures are served by a single 50kVA transformer. By comparison, the T&D utility Oncor, servicing areas just north of Austin, will commonly put 12-16 200A service level residential structures on the same size/rating transformer.

Power Quality Impacts

Power factor is the ratio of real power divided by the total apparent power. For grid operation and control it is desirable to maximize power factor. A power factor of 1.0 is considered perfect, and values lower can cause issues. Commercial customers are typically penalized through demand charges or power factor charges if the power factor at the site drops too low. Typical trigger points for these charges are a power factor of 0.8 to 0.9.

During the study period Pecan Street worked with The Center for Commercialization of Electric Technology to study the impact of residential solar on the power quality seen on a feeder in the Houston area. In the Houston area a low power factor of 0.6 was measured on a feeder with a high penetration of residential solar during solar production hours. The concern was that the solar was adding distortion current to the distribution system thereby lowering power factor.

Pecan Street measurements indicate the solar systems do not add distortion, but only provide real power generation and provide no displacement or distortion reactive power support. Measurements were made at the home level and transformer level.

With grid-tied solar production the electric customer can supply power to the grid. In this case the amount of real power demand will drop to very low levels, or even go negative. The reactive power component for power factor is not provided by the solar and must be provided by the utility. It is possible with high penetration of solar for power factor to be a negative number since the real power is headed in the opposite direction of the load.

For this study period Pecan Street examined the power quality for a group of homes on the same transformer, monitored by the Gridsense Transformer IQ product. A full year of data was analyzed with no significant gaps in data availability (96% data availability for the year). The transformer serves seven homes totaling 18,700 square feet of conditioned space. Five of the seven homes have grid-tied solar arrays.

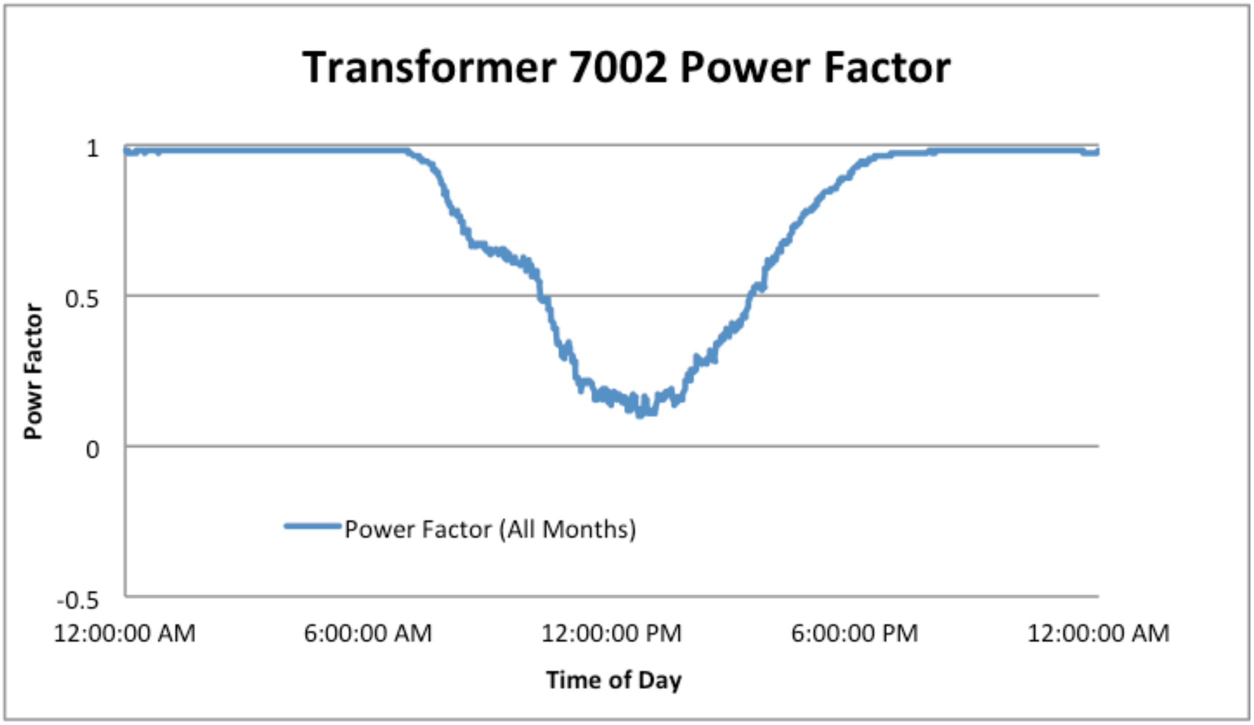

Figure 48. Transformer total power factor-12 month average

Figure 48 shows the average power factor measured at the distribution transformer where 5 of the 7 houses have grid-tied solar. In the Houston neighborhood studied by CCET the power factor would drop as low as .6 during the winter months. The Houston neighborhood had an average of ~1kW of solar on each of the houses.

The Mueller study area has an average of 5.5kW of solar on participant houses, and when the solar penetration hits five of seven homes or 71%, even lower power factors can exist at the distribution level.

In this case the yearly average power factor in the middle of the day is approximately 0.2.

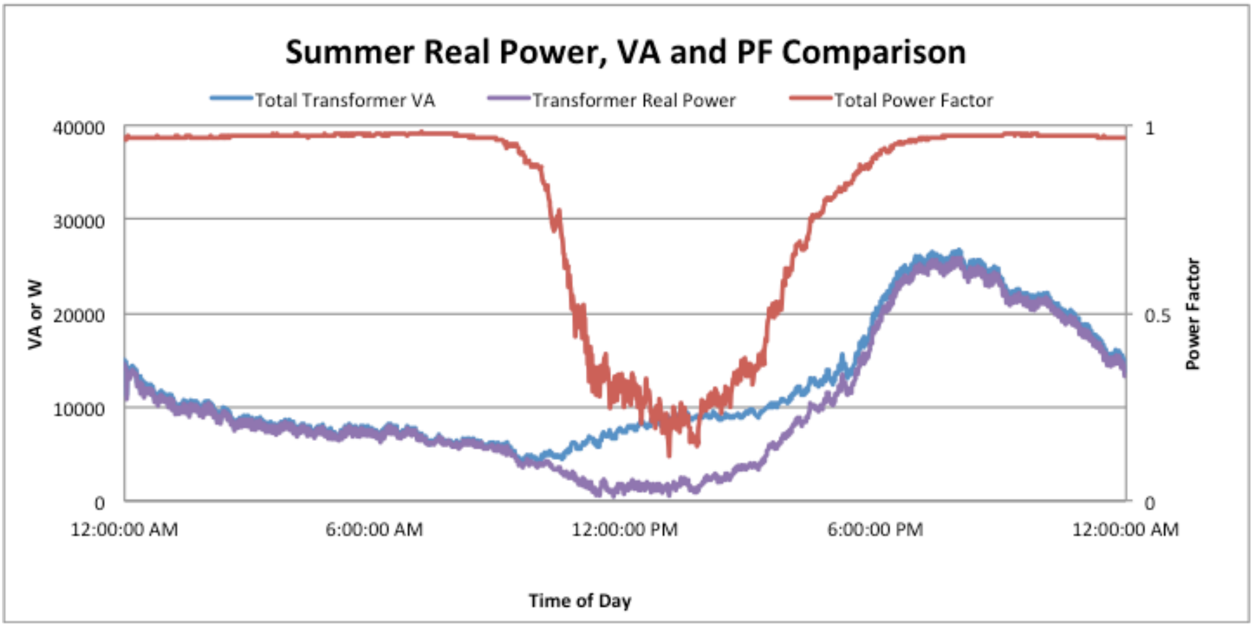

Figure 49. Real and reactive power, distribution transformer

Figure 49 shows the real and reactive power requirements for summer months at the same transformer as Figure 48. During the summer the power factor at the transformer drops to 0.25 during the middle of the day. The utility, on average must provide 10kVAR of reactive power support to these homes while the total billed load is almost zero.

Discussions with several utilities indicate that they may not be recovering the full cost of this reactive power support through interconnection and service fees. Since this level of solar penetration has not been historically common there was no need to calculate the cost of this type of service. Data suggests that residential solar adoption growth rates are approximately 40% per year, meaning this situation may become more common in the future. Power factor correction technology is available that would fix the issue at the residential level but there is currently no economic incentive or code requirements for the residential customer to install this equipment.

Local Voltage Control Impacts

Pecan Street also looked at the impact of local voltage control in the presence of high penetration solar. In this case the Gridsense Transformer IQ data was paired with data collected by a Power Standards Laboratory pQube device. The pQube is a power quality measurement system typically used by commercial entities to examine power quality and power quality correction system performance for industrial loads.

One of the concerns for high penetrations of solar on the grid is that during periods of high intermittency caused by fast moving clouds that the utility would lose control over the line-to-line voltage levels at customer premises. In cases where there is generation the utility may not know the voltage at the end of long feeders or distribution systems. The common method for controlling voltage are multiple-tap transformers with switching networks at the utility substation, known as tap changers. These tap changers typically have 12 voltage steps from low to high to maintain a narrow band of voltage control at the customer service entrance.

Pecan Street does not have access to the load flow information from Austin Energy or the ERCOT grid operator to determine what the utility thought the voltage should be at the transformer and participants being studied. However, Pecan Street does have very high resolution time stamped data over many months. At the transformer and specialized data collection for periods as the residential service entrance for those transformers.

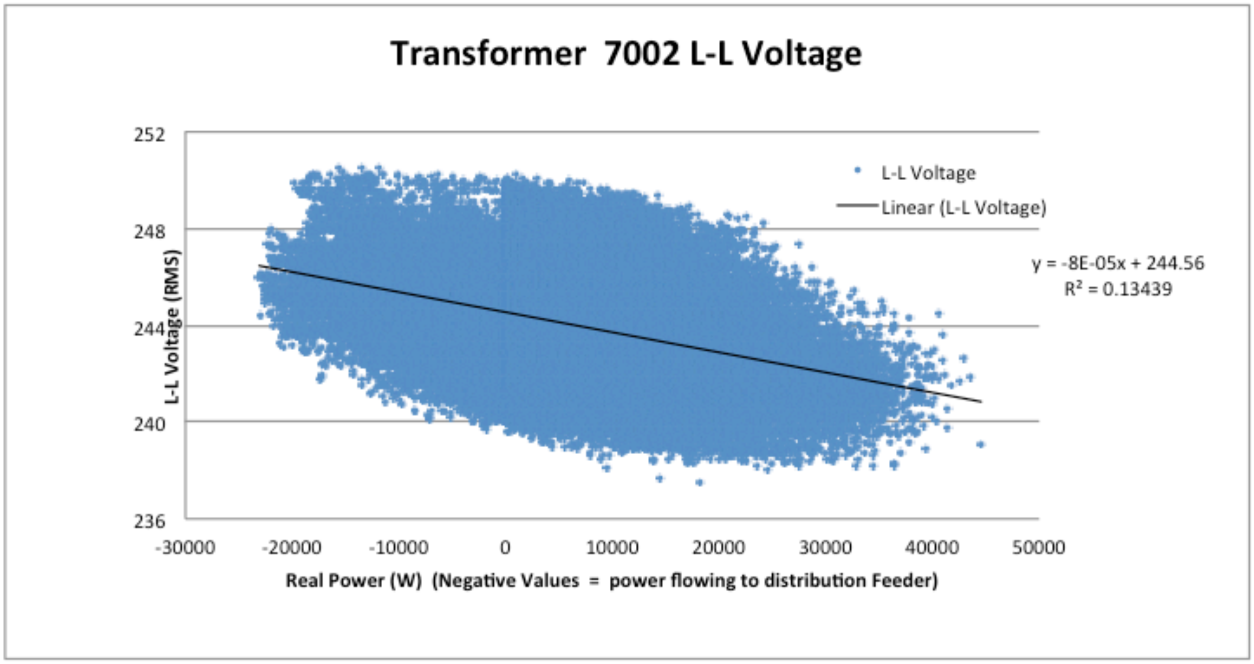

Figure 50. L-L voltage levels

Figure 50 shows over 122,000 data points for a year of transformer data. A negative value means there is real power flow from the homes on the transformer to the distribution feeder. The linear regression of the data has a relatively low R^2 value indicating that power alone is not responsible for all of the variation of voltage. This is not surprising since the voltage at the service entrance can be caused by both the variation of distribution system voltage caused by load balancing and the operation of the voltage control tap changers at the substation.

A closer examination of the voltage at the premise in the time domain shows there may be local voltage instability caused by high levels of residential solar.

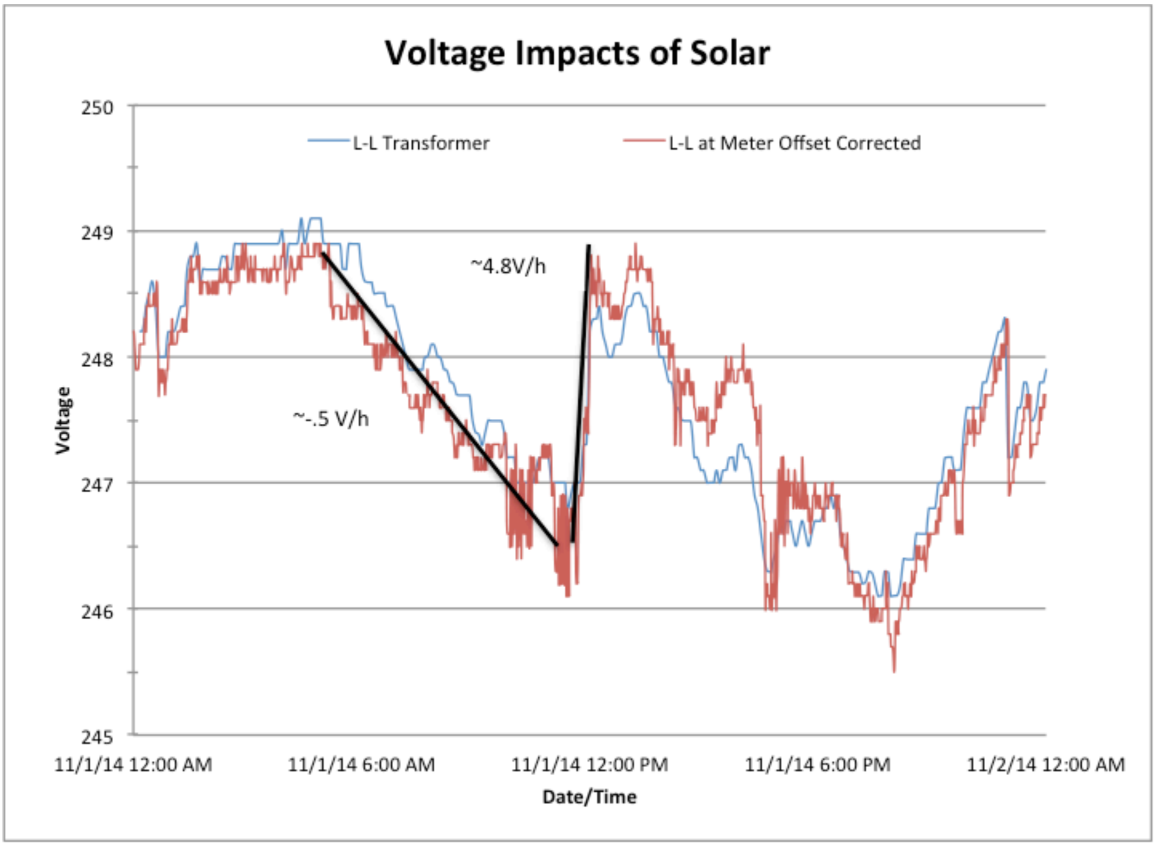

Figure 51. Voltage at residential service entrance

Figure 51 shows the voltage at the distribution transformer and the residential service entrance for the same 24 hour period. The residential voltage level was measured using a pQube and the transformer voltage level was measured using the Gridsense TransformerIQ.

This particular day shows local behavior that explains some issues commonly discussed with solar arrays, where the solar array trips offline due to an over-voltage condition. In the Mueller neighborhood the distance between service entrances and transformers are considered short, typically less than 100 feet and often under 20. The neighborhood zoning dictates that there is less than six feet between the residential structures.

Since two different instruments were used, there was 1.7 volt offset between the two instruments. The offset was corrected by applying a correction factor to the residential service entrance measurement so that during periods of zero power consumption at the residence the voltage at the transformer matched the voltage at the service entrance. By definition there can be no voltage drop when no current is flowing.

The corrected voltage shows exactly the behavior one would expect. At night and during periods of power consumption in the residence the voltage is higher at the transformer than it is at the service entrance from the voltage drop through the impedance of the service wiring. The morning of this particular day was cloudy with almost no solar production. At noon the cloud cover moved out rapidly and the neighborhood solar arrays all turned on to nearly full power over a couple of minutes. During periods of power production the voltage at the service entrance is higher than the voltage at the transformer.

Most telling about this event is that the voltage variation due to grid balancing operations during the evening shows the expected slow variation. A linear fit line shows the variation to be about 5V per hour, and no sudden changes indicate that there was no tap changing operations at the substation.

During the period ramping solar production a linear fit shows that voltage rate of change was 4.8V/hr or nearly 10 times the rate of change from the grid balancing operation the night before. What is not known is if any tap-changing events at the substation occurred at this time. In the evening, cloud cover again moved into the area and the voltage dropped quickly, again at about 5V/hr. It is unlikely that both events also coincide with a tap-change at the substation.

Without synchro-phaser data or time stamped tap-changer information on voltage control operation at the transmission level or substation, it is not possible to definitively attribute the time domain data in Figure 51 solely to solar production. However, the data does indicate that further study with high resolution, high sampling rate equipment at both the substation and residential premise is warranted. The data seems to indicate that even in distribution areas with short distances resulting in low distribution impedance, local voltage instability is possible with the rapid change in load conditions caused by solar intermittency.

Energy Impact at Transformer Level

One of the main concerns regarding solar and electric vehicles is that the technologies would overload the distribution transformers serving the residential structures. As previously mentioned, the Mueller Demonstration is a good place to check the impact on transformers because Austin Energy, the utility serving the neighborhood, has very conservative specifications for the transformers. On average, eight homes are served by a single transformer rated at 50kVA.

Using data from a subset of the total study participants, 42 homes with both plug-in electric vehicles and grid-tied solar as well as a full year of high availability (~99%), the project team was able to analyze the impact of these technologies at the transformer level. The homes have a combination of south-facing and west-facing solar. The average size of the solar arrays is 5.5 kWh nameplate, and the average utility service connection size is 200A. As previously shown the west-facing solar has a much greater load coincidence with generation and will be helpful to the transformers.

The project team performed analysis and modeling using data from the 42 homes to create scenarios looking at total energy load transmitted through a transformer serving a group of 8 homes with 0 to 8 plug-in electric vehicles and 0 to 8 solar arrays.

The study shows that the impact of solar arrays varies by season and overall-coincidence with load. It can also be used to show the impact of electric vehicles on average peak demand for the transformers during the summer months when electric usage is highest due to air conditioning.

Table 24. Impact on Transformer Loading-Full Year

Full Year		**Solar Arrays**								
		0	1	2	3	4	5	6	7	8
Number of Electric Vehicles (3.3kW)	0	0%	-8%	-15%	-23%	-31%	-31%	-29%	-25%	-21%
	1	2%	-6%	-13%	-21%	-29%	-29%	-27%	-23%	-18%
	2	4%	-3%	-11%	-19%	-26%	-27%	-25%	-21%	-16%
	3	7%	-1%	-9%	-17%	-24%	-25%	-22%	-19%	-14%
	4	9%	1%	-7%	-14%	-22%	-23%	-20%	-16%	-12%
	5	11%	3%	-4%	-12%	-20%	-20%	-18%	-14%	-10%
	6	13%	6%	-2%	-10%	-17%	-18%	-16%	-12%	-7%
	7	16%	8%	0%	-8%	-15%	-16%	-14%	-10%	-5%
	8	18%	10%	2%	-5%	-13%	-14%	-11%	-8%	-3%

Table 24 shows the total energy transmission change over a calendar year based on the 42 study homes. The reported values are the percent increase/decrease in total energy transmission regardless of direction, representing the differences in total cumulative VAh through the transformers. The losses in a distribution transformer are for all intensive purposes identical regardless of direction of power flow.

The case where no homes have solar and no homes have a plug-in electric vehicle represents the base case for a traditional home. As one might expect the absolute worst case scenario for the model would be 8 electric vehicles and no solar. Interestingly there is a localized minimum case for the total energy transmission of solar, which is a combination of solar arrays and electric vehicles that results in the lowest possible energy transmission through the transformer, possibly extending the service life of the unit.

In the case of no electric vehicles and either 4 or 5 solar arrays, the load on the transformer is at a minimum. The total load on the transformer is reduced by 31% compared to the reference case of no PV and no PEV. As the penetration of solar is increased from the 50%-62.5% penetration rate the benefit to the transformer begins to decrease, ultimately falling between the benefit seen by 2-3 solar installations on the 8 home cluster.

This behavior was examined further. At any point in time during the high PV production period there is some likely hood that even if the residential structure with the PV is operating as a net generator the other homes on the transformer are providing some amount of load. As the number of PV systems increases the other homes are also more likely to be net generators simultaneously given the close geographical proximity. Once the penetration rate is over 50% to 62.5% the solar generation, on average for the year is high enough to cause the cluster of homes to become net generators. In this case, all of the solar is not used locally and starts to reverse the benefit to the localized grid infrastructure.

For this study there was no case where the addition of cars benefited the transformer, in all cases they add to the total load. The coincidence of electric vehicle charging with PV production is almost zero.

In order to look at what might happen in other areas, the data was split into two seasonal groups: high cooling AC use months (May, June, July, August, September, October) and low cooling AC use months (November, December, January, February, March, April). It is difficult to find months with no AC usage in the Austin area as it is possible to have days in January and February with highs in the mid to high 80s, which can induce some individuals to turn on air conditioning to keep their house under 80 degrees.

Table 25. Impact on Transformer Loading-Low-AC Months

Low-AC Months		**Solar Arrays**								
		0	1	2	3	4	5	6	7	8
Number of Electric Vehicles (3.3kW)	0	0%	-10%	-20%	-26%	-23%	-17%	-11%	-3%	5%
	1	3%	-7%	-17%	-23%	-20%	-14%	-7%	0%	8%
	2	7%	-3%	-13%	-20%	-16%	-11%	-4%	3%	11%
	3	10%	0%	-10%	-16%	-13%	-7%	-1%	7%	15%
	4	13%	3%	-7%	-13%	-10%	-4%	3%	10%	18%
	5	17%	7%	-3%	-9%	-6%	-1%	6%	14%	21%
	6	20%	10%	0%	-6%	-3%	3%	10%	17%	25%
	7	24%	14%	3%	-3%	1%	6%	13%	20%	28%
	8	27%	17%	7%	1%	4%	10%	16%	24%	32%

Table 25 shows the impact on the transformers during low AC usage months. Again there is a "sweet spot" for transformers with 3 solar connected homes the optimum. Also repeated from the full year average, there is no case where the addition of an electric vehicle lowers the energy transfer through the transformer. Interestingly, there are cases where the heavy addition of solar (either 6, 7, or 8 PV systems depending on the number of EVs) adds to the transmission of energy. The worst case is 8 EVs and 8 PV homes, in which case the load on the transformer is increased by 32%. This is significantly different from the full year data where the transformer load is decreased by 3%. The difference between the two scenarios indicates that the coincidence of use and solar generation play a critical role in the stresses that could be added to the edge of grid infrastructure.

Table 26. Impact on Transformer Loading AC Usage Months

AC Months		**Solar Arrays**								
		0	1	2	3	4	5	6	7	8
Number of Electric Vehicles (3.3kW)	0	0%	-7%	-13%	-20%	-27%	-33%	-35%	-35%	-32%
	1	2%	-5%	-12%	-18%	-25%	-31%	-34%	-33%	-31%
	2	3%	-3%	-10%	-17%	-23%	-30%	-32%	-31%	-29%
	3	5%	-2%	-8%	-15%	-22%	-28%	-30%	-30%	-27%
	4	7%	0%	-7%	-13%	-20%	-26%	-29%	-28%	-26%
	5	8%	2%	-5%	-12%	-18%	-25%	-27%	-26%	-24%
	6	10%	3%	-3%	-10%	-16%	-23%	-25%	-25%	-22%
	7	12%	5%	-2%	-8%	-15%	-21%	-24%	-23%	-21%
	8	13%	7%	0%	-7%	-13%	-20%	-22%	-21%	-19%

Table 26 shows the same data but for high AC usage months. In this case the minimum transformer usage is with either 6 or 7 solar arrays and no electric vehicles. The high coincidence of combined south/west facing solar generation and AC usage means that the solar is being used in the home during these months. Again EVs have only a negative impact on the transformer in terms of total energy transfer.

Table 27. Impact on Transformer Loading: Peak Demand

June Demand		**Solar Arrays**								
		0	1	2	3	4	5	6	7	8
Number of Electric Vehicles (3.3kW)	0	30.4	28.6	28.4	28.2	28.1	27.9	27.7	27.6	27.4
	1	30.7	28.9	28.7	28.6	28.4	28.3	28.1	27.9	27.8
	2	31.0	29.2	29.1	28.9	28.8	28.6	28.4	28.3	28.1
	3	31.3	29.6	29.4	29.3	29.1	29.0	28.8	28.6	28.5
	4	31.6	30.0	29.8	29.6	29.5	29.3	29.1	29.0	28.8
	5	31.8	30.4	30.1	30.0	29.8	29.6	29.5	29.3	29.2
	6	32.1	30.8	30.5	30.3	30.2	30.0	29.8	29.7	29.5
	7	32.4	31.1	30.8	30.7	30.5	30.3	30.2	30.0	29.9
	8	32.8	31.5	31.2	31.0	30.9	30.7	30.5	30.4	30.2

Table 27 shows the impact on peak demand through the transformer. On average the 50kVA transformer shows a 30.4kW with no PV or EVs. This nominally increases to 32.8kW with no solar arrays and 8 electric vehicles. Compared with an 18% increase in total energy, the 7.8% peak demand increase does not appear to represent a signficant issue. Separate studies of charging behavior indicate that charge times vary over many hours of the day between participants. Interestingly, there is no local minimum with solar; the more solar arrays, the more the transformer peak load is reduced.

Power Factor Correction Benefits of Energy Storage

The energy storage system installed at the Pike Powers Lab is currently used to provide DC power to the lab's advanced LED lighting systems, which can accept either AC or DC power. One of the expected benefits of using DC power from the energy storage system is that the entire day's worth of lighting energy can be stored in the system in a few hours during off-peak times.

One of the unexpected benefits witnessed was the inherent power factor correction provided by the system. The system was prevented from charging the batteries for a full 24-hour period. The lighting for the lab was operated normally at that time. When the storage system was allowed to recharge the batteries the following morning the instantaneous load presented to the electrical grid was 1.9kW at a total Power Factor (tPF) of 0.98.

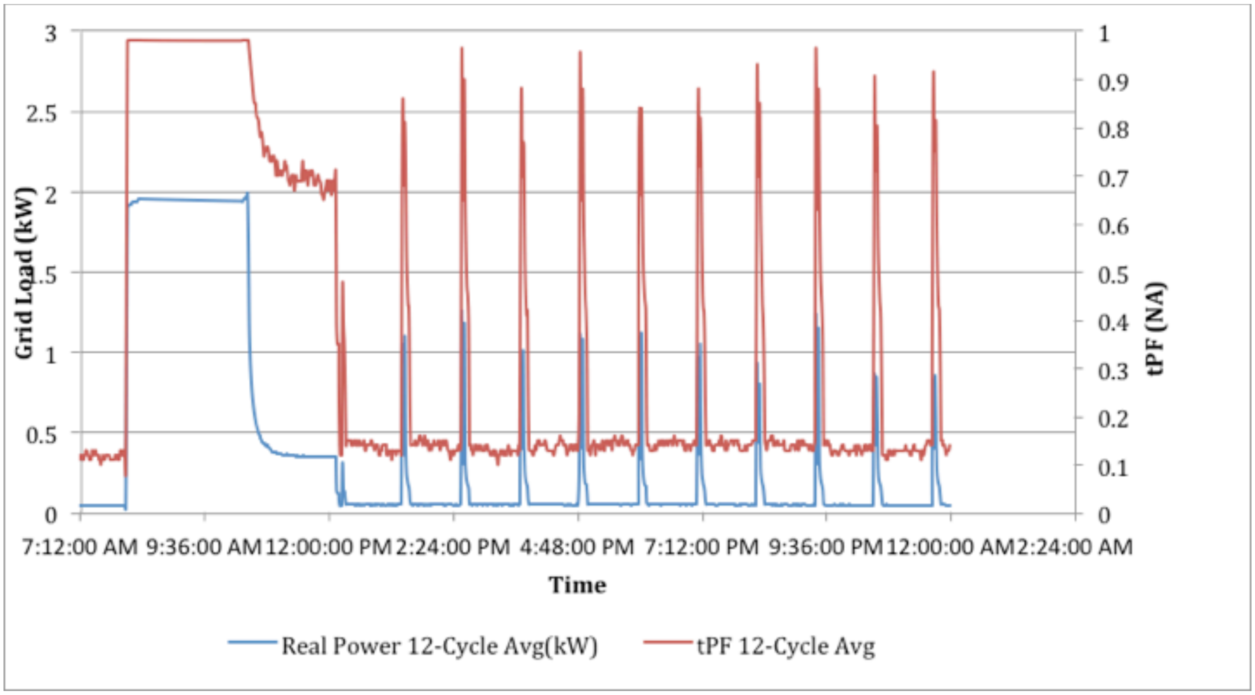

Figure 52. Power factor correction

The system was then allowed to recharge the batteries after a nominal 2% capacity drop as needed for the next 12 hours. During that time the batteries needed to be recharged 10 times, each time drawing approximately 1kW off the grid for a few minutes at a tPF typically above 0.9.

Contrast this performance with Energy Star-rated CFL or LED light bulbs. The Energy Star requirements only specify a minimum of a tPF > 0.5 for CFL bulbs and a tPF >0 .7 for LED bulbs. In practice the CFL bulbs measured at the lab typically have a tPF between 0.56 and 0.7, while LED bulbs range from 0.75 to 0.95. Most LED bulbs are 0.8 or better. Compared to the LED bulbs the less expensive CFL varieties typically measure at the bottom end of the minimum spec, around 6.

Even if the lab lighting system was not a DC distribution system the energy storage system could be used to power factor correct and time shift lighting circuits in a building. The resulting distribution system current would be shifted to an easier to handle time (late night or early morning) and the overall system losses would be reduced since the reactive power would not be required on the distribution system.

Table 28. Current Reduction from Energy Storage

Energy Storage System Load tPF	Corrected tPF Distribution System Current Reduction
0.5	49%
0.55	40%
0.6	33%
0.65	26%
0.7	21%
0.75	16%
0.8	12%
0.85	8%
0.9	5%
0.95	2%

The total current reduction for lighting load on the distribution grid could be lowered by approximately 40% when the typical tPF of a CFL light bulb is considered.

Conclusions

Through observation of near real-time consumption and generation data as well as transformer performance data, the project team was able to draw the following conclusions about impacts of the Energy Internet on utility infrastructure.

Best Practices

- West-facing rooftop solar PV is more load-aligned than south-facing and therefore may provide greater system benefit and overall higher utility for demand reduction purposes.
- The lack of load alignment of generation from south-facing solar PV results in higher operational loads and operating temperatures for utility transformers during shoulder months, when PV generation increases but midday residential electricity use is typically low.

- Areas without significant cooling loads, such as coastal California, could experience challenges at lower penetrations of residential PV during late spring when electricity use did not increase in step with solar panel generation.
- Utilities that provide solar rebates to customers may want to consider providing a higher rebate for west-facing systems.
- Home energy storage systems with individual circuit load control and independent energy source capability have the ability to turn demand response into a customer financial benefit instead of the typical unwanted change to an air conditioning/heating setting change.
- Actionable recommendations to consumers can have a measurable impact on energy usage even without monetary incentive.
- High density installation of residential solar arrays have the potential to cause more energy to flow through the distribution transformers serving the entrance to the homes depending on the load profile of the homes.
- Storage installed at the point of use and generation where distributed generation can have the greatest impact on grid operations. Grid scale solutions installed at the substation or generation station still expose the grid assets nearest the residential customer to the variability of distributed generation.

Lessons Learned

- The impact of energy efficiency technologies such as compact fluorescent lighting, variable speed drives and switching mode power supplies have unintended power quality consequences when paired with high density of residential solar. Transformers and neighborhoods operating at a power factor of 0.2 are possible and may present challenges to traditional operations and grid stability.
- Residential smart meters rarely have the power factor measurement turned on and even if they did the 15 minute or 1 hour averages may not be able to inform the utility of dynamic events at the residential service entrance.
- Home energy storage systems provide potential to reduce variability and intermittency in residential load and residential solar generation. However, Pecan Street's efforts with utilities show resistance and an inability to accommodate these systems within the utility generation and interconnection rules. This is partially due to the lack of market definition provided by the public utility commission. These systems, with an appropriate communication interface and functionality, and appropriate market regulations can turn intermittent distributed resources into a utility and customer asset.

- Behavioral modification that relies on manual actions by customers (as opposed to automated, "set and forget" structures) will face significant headwinds in producing predictable customer response. This has implications for the structures of pricing and demand response programs. This situation is analogous to the "blinking VCR clock" syndrome in that significant numbers of customers will not undertake manual actions, even when they receive constant, visible alerts.

Program 3: Demonstration of electric vehicle integration onto the Energy Internet

Plug-in electric vehicles represent the most significant new electric load to appear in homes in half a century. Uncertainty surrounds the rate and extent of customer adoption. However, the experience of hybrid vehicles—where adoption has clustered in handfuls of urban neighborhoods—suggests the possibility that clusters of electric vehicles in percentages exceeding 15 percent could begin to appear in a number of urban distribution feeders in the coming years. The Mueller community has experienced elevated levels of electric vehicle adoption, which occurred in tandem with a significantly higher adoption rate of solar PV than the population at large.

These observed conditions raised important research questions:

- In a neighborhood where electric vehicle clustering does occur, what is the charging behavior pattern?
- How does the presence of rooftop solar PV impact electric vehicle owners' peak load and distribution system impact?

Pecan Street incentivized the purchase or lease of 69 electric vehicles all with Level 2 charging stations located in and near the Mueller community, with almost all homes also having rooftop PV systems. Over 4,000 charging events were measured between June 1, 2012 to January 15, 2013. As shown in Figure 53, the distribution of charge duration in minutes by the number of charges that occur for the seven-month time frame indicates that the majority of charges last between 41 and 80 minutes.

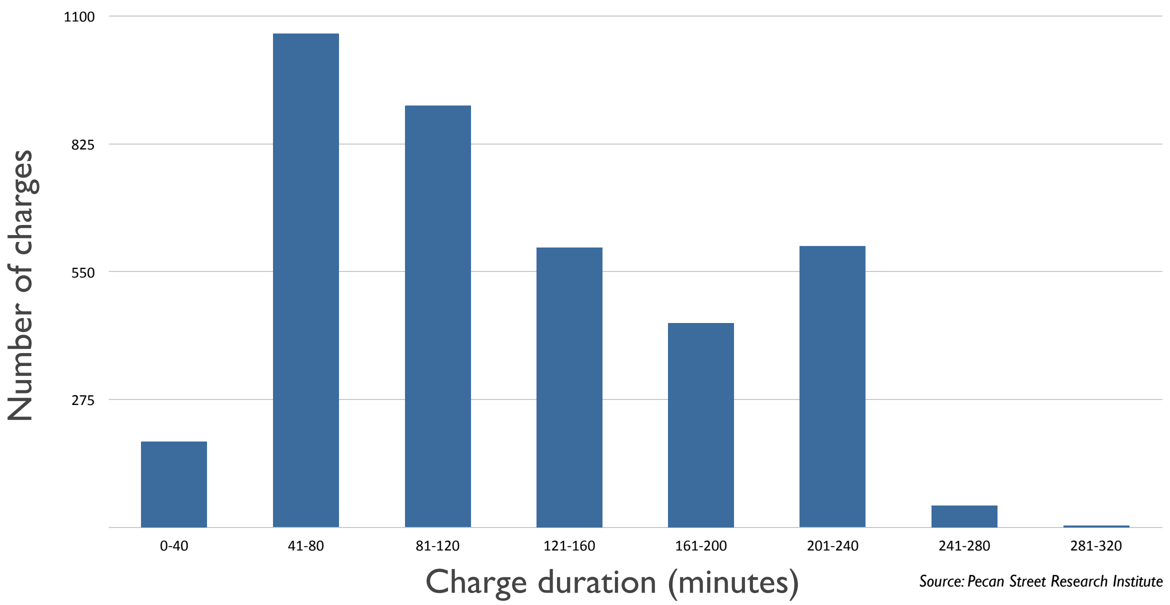

Figure 53. Electric vehicle charge duration in minutes, from June 1, 2012 to January 15, 2013

Analysis of electric vehicle start times suggests that 12% more charging occurs on a workday versus on a weekend and that 35% of charging start between 4:00 pm and 8:00 pm. The analysis also suggests very few participants have their vehicles set for delayed charging, which is a common EV feature, but requires a degree of user intervention. Figure 54 shows electric vehicle charge start times for weekdays, where the Y-axis is number of recorded instances and the X-axis is the start time of a charge event.

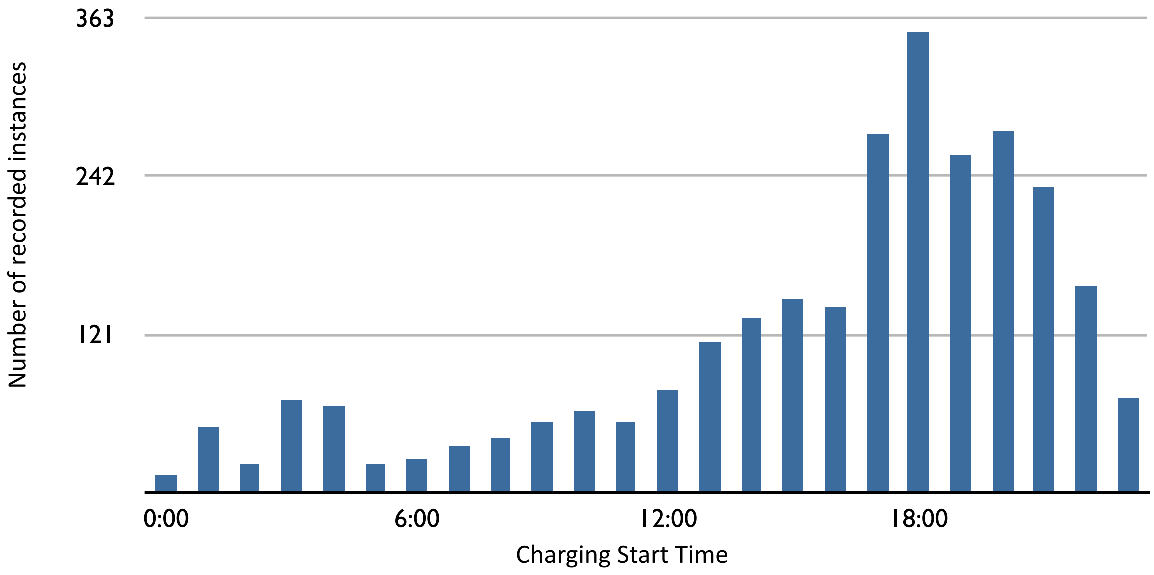

Figure 54. Electric vehicle charging start times from June 1, 2012 to January 15, 2013

As shown in the Figure 55, peak PV generation corresponds with customer electricity use. Effective PV energy storage solutions may help offset peak demand. PV generation provides more than enough energy to fully offset electric vehicle charging demands; average additional peak load due to electric vehicle charging is 600-1,000 watts. However, during the summer months the electricity used to charge the EV is only a small portion of the energy used in the home. This may be different in other geographical areas where cooling electric load is small, and if the vehicles purchased have significantly higher charge rates than the 3.3 kW used by most participants in the study.

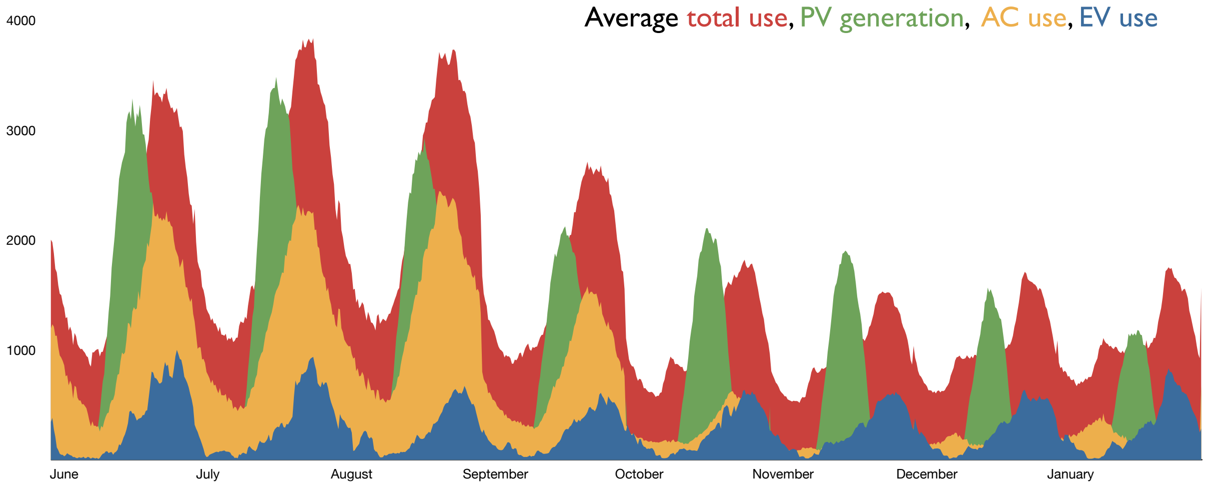

Figure 55. Average energy use over time (in watts)

Electric Vehicle Charging Control: HVAC Systems

With a number of participants charging during peak demand period a prototype hardware effort was undertaken in 2012 to study commercially available systems that would prevent the simultaneous use of residential HVAC systems and level-2 (3.3kW) PEV charging.

Several manufacturers were contacted, but no one had a system that was available for immediate testing. All systems were still under development or being used for in-house testing.

To demonstrate the change on the residential load that such a system would have Pecan Street undertook a small scale demonstration in a volunteer participant home in Mueller with prototype hardware developed by Pecan Street staff.

The system could not use a HAN system directly connected to the utility smart meter since the utility had not enabled that functionality on the electric meter monitoring the residence.

The residence did have an eGauge system installed by Pecan Street, which has an API for getting high resolution electrical usage. At the time the eGauge firmware updated the values for power measurement every 10 seconds.

The hardware used open-source hardware/software from Arduino to communicate with the eGauge home energy monitoring system installed in the residence. The algorithm for vehicle charging was very simple:

- Total Home Electricity Demand <2.3kW allow charging to start.
- Total Home Electricity Demand <5.8kW but greater than 2.3kW, allow charging to continue, but don't disable charging.
- Total Home Electricity Demand >5.8kW disable electric vehicle charging.

A commercially available Electric Vehicle Support Equipment (EVSE) device was partially disassembled to gain access to the J1772 pilot signal. The Arduino microcontroller accessed the home energy data from the eGauge every 15 seconds over a Wi-Fi connection. Depending on the total energy usage the pilot signal was disconnected with a relay or connected. If connected and a vehicle was present, the vehicle would begin charging. If a vehicle was present and disconnected the vehicle would cease charging.

It is important to note that this disconnect sequence does not follow the established J1772 standards and was done for demonstration purposes. At the time of the demonstration only a small number of EVSE models advertised charge curtailment or interruption according to the J1772 standards. The two identified manufacturers were contacted and asked to participate in the demonstration. They declined and none of the EVSE models were available for the demonstration dates. The decision was made to move ahead with a demonstration system that physically interrupted the J1772 pilot signal in order to collect data on the energy impact of avoiding vehicle charging while the HVAC system was running.

The vehicle interpreted the interruption of the pilot signal as an external act of vandalism and the car horn honked to alert the owner of the vehicle that someone had tampered with their charge event. Most manufacturers allow this notification feature to be turned off now, since a power outage would also be interpreted as tampering and would also cause the car horn to honk. An early production 2011 Chevy Volt could not be used as the software did not allow tamper notification to be disabled. Every time the pilot signal was removed on the vehicle, it did stop charging, but it also honked the horn in an alarm mode.

A later production year 2011 vehicle had the ability to remove that alarm feature and was the vehicle used for the test. Figure 56 and Figure 57 show pictures of the prototype hardware solution.

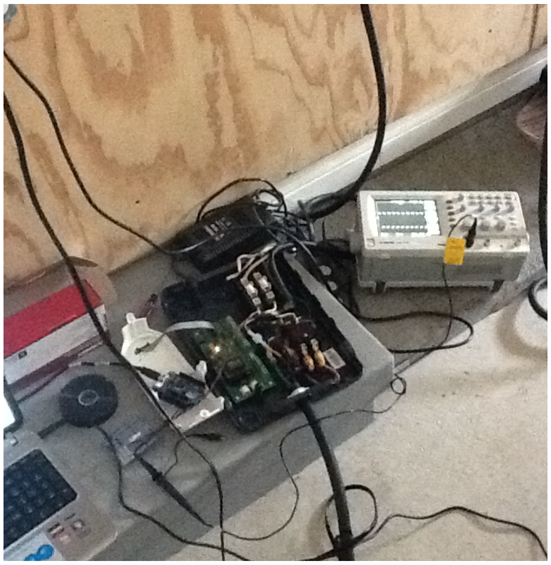

Figure 56. Prototype system hardware photo

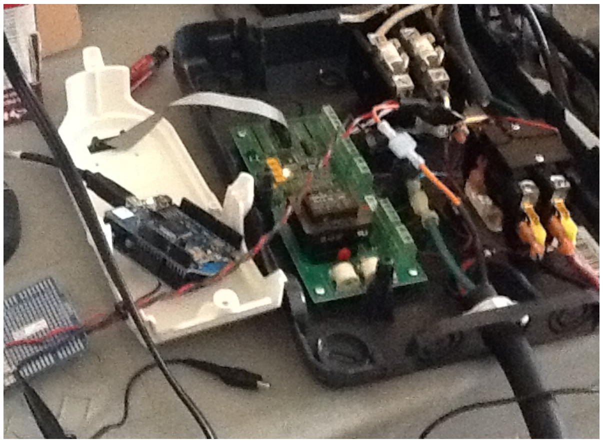

Figure 57. Prototype system hardware photo

The system was tested over the course of two days in late September of 2012. The first day the EV was charged in the middle of the day while the AC was running to establish a baseline electric load and demand for the day.

Figure 58 shows the whole home usage for the entire day. Vehicle charging occurred between 1:00 PM and 2:45 PM representing a ~50% charge for the Chevy Volt. Note that the peak demand for the house exceeded 7 kW on two occasions and was over 5 kW a majority of the charging time.

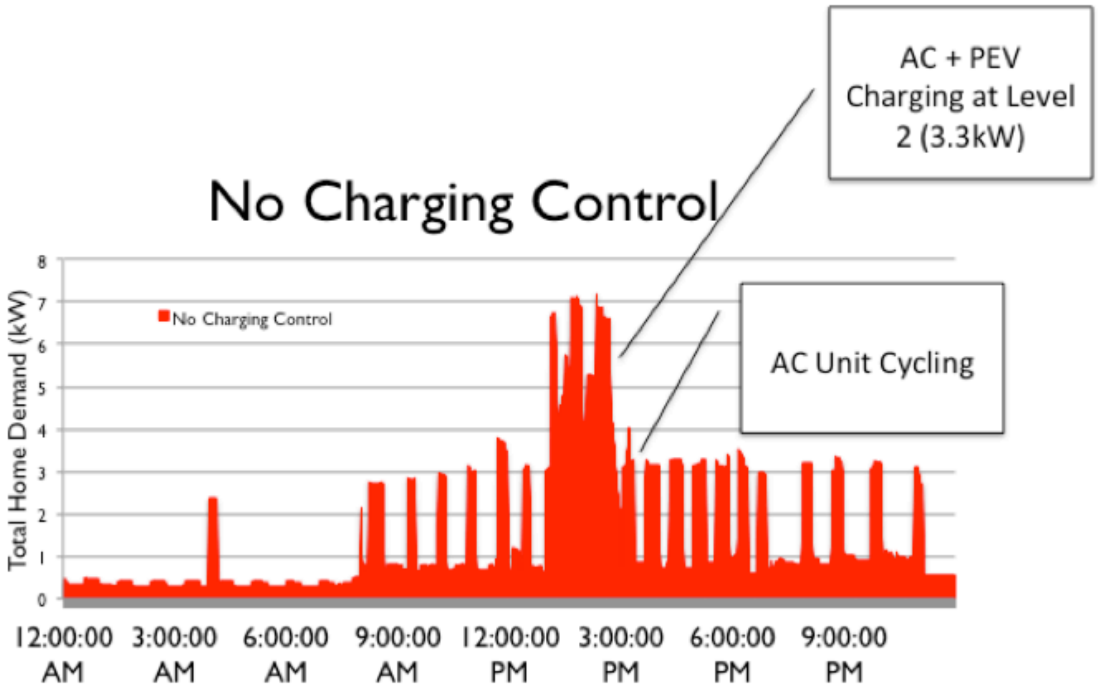

Figure 58. Home electricity usage with EV; no charge control.

Figure 59 shows the same home, with the charge control algorithm enabled for the next day.

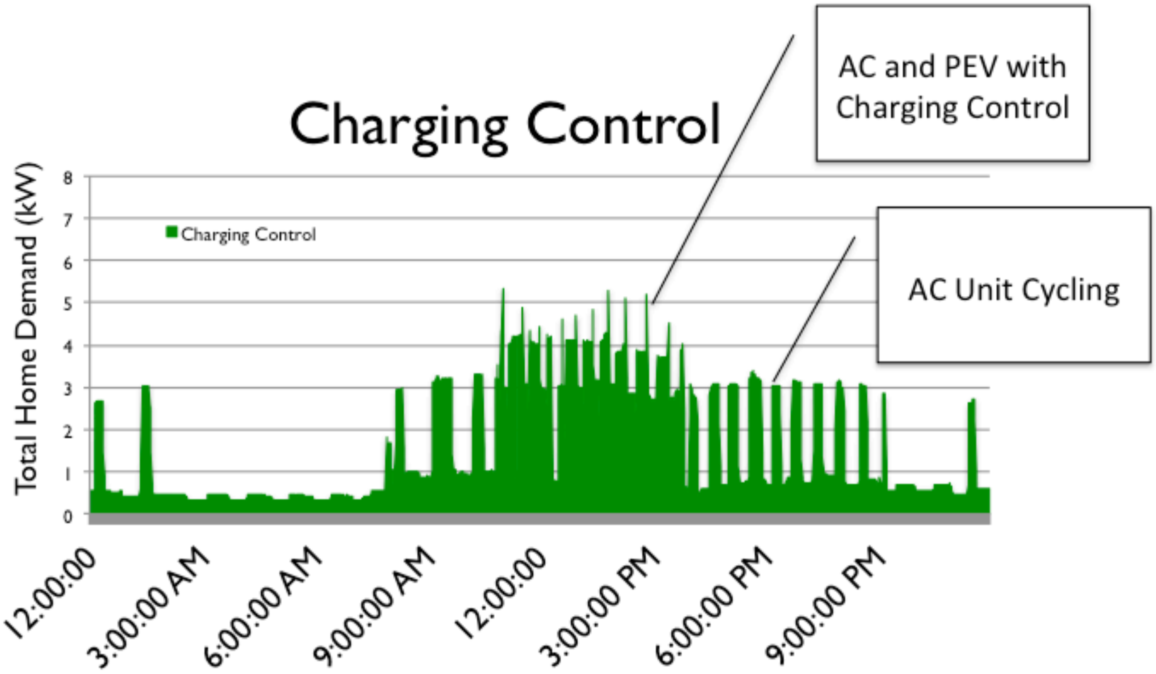

Figure 59. Home electricity usage with EV; with charge control

Charging occurred between 11:45 AM and 4:00 PM. It represented a ~50% charge for the vehicle. In this case there are very short peaks over 5kW and no demand peaks over 7kW. The system effectively limited the peak demand of the home.

Figure 60 shows the two days of electricity usage overlaid to more clearly demonstrate the impact that charge control had on the peak demand in the home. The total energy usage between the two days was similar (the second day was slightly warmer, so there was more AC usage) but the peak demand was reduced from 7kW to just over 5kW.

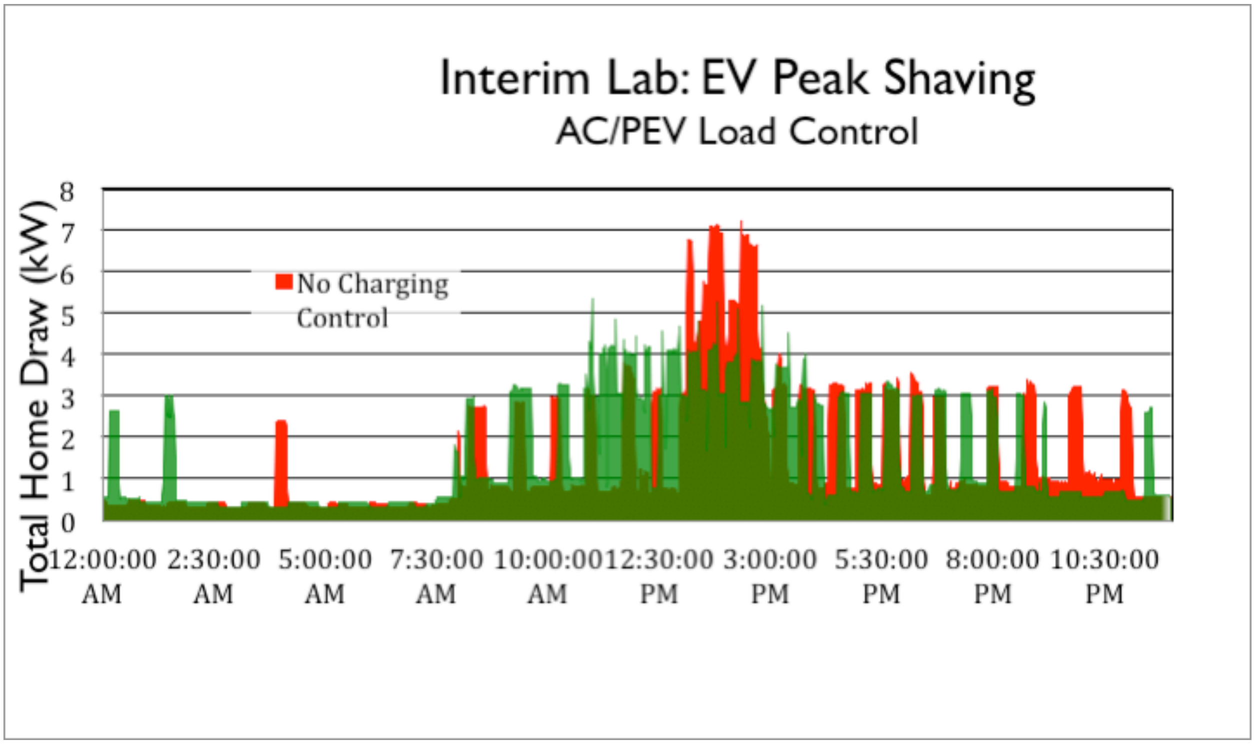

Figure 60. Comparison of residential demand with and without load control

Electric Vehicle Charging Control: Solar Systems

In May of 2014, a second prototype system was developed in co-operation with Enervalis, a technology partner of one of our corporate consortium members. The Enervalis system used electricity pricing information and local solar production information to control the charge rate for a PEV. In this case Schneider EVSE with RS-485 serial connection was used to change the duty cycle of the J1772 pilot signal and control on/off/rate of charging.

The system used devices supposedly compatible with the standards, but as is the case with many new technologies there were unexpected and unintended consequences of operating the system with load control.

The demand response/energy management protocol the system would prevent charging until the output of the solar array reached 1500 watts. The vehicle would then charge at the minimum allowed rate of 6 amps, or roughly 1500 watts. The vehicle would then be signaled to ramp up charging to whatever level the solar array was producing up to the maximum draw of the vehicle/EVSE whichever was the limiting factor. In the demonstration system case, there was ~6kWp of solar available and the Chevy Volt used for the test caps charging at 3.3kW.

The system used a wireless gateway made by Enervalis, connected to the Schneider EVLink EVSE through RS-485. The solar energy monitoring was performed by an eGauge.

The issue with the system operation was that the EVSE did not negotiate the shut down protocol correctly with the electric vehicle. The SAE J1772 standard specifies the physical and electrical signals but the messaging protocol and function for an EVSE and electric vehicle is specified in SAE J2953. There are quite a few paragraphs detailing the startup sequence for charging, but very little time is spent on the handshaking required for shutdown.

When the signal for shutting down charging was sent to the EVSE, the EVSE should have changed the pilot signal to signal the vehicle that the EVSE needed to stop charging, then disconnect the AC mains going to the vehicle. Instead the EVSE stopped the AC mains before the pilot signal was changed to a steady state high condition.

A work-around was found and Schneider was informed of the issue so they could correct it in later releases of system firmware.

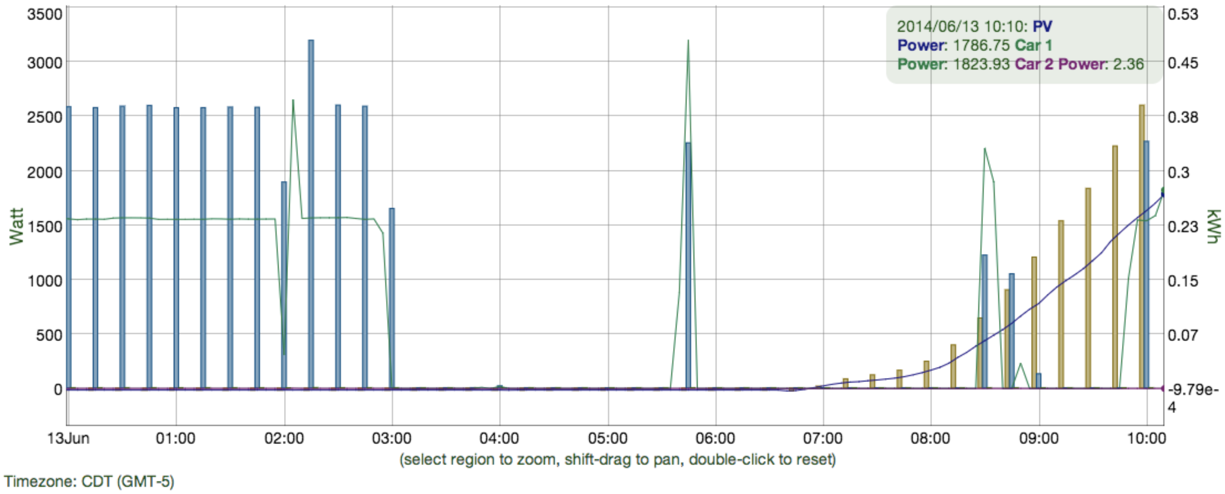

Figure 61. EVSE-Solar charge control

Figure 61 shows the Enervalis system operating at the Pecan Street Lab. One vehicle was charged overnight (vertical blue bars) and a second vehicle was plugged in during the morning, before the control system was operational. At 10:00 AM the solar production (purple line) reached 1500 watts and the car charging commenced at the minimum level allowed by the Chevy Volt ~2kW.

Conclusions

Best Practices

- Electric vehicle residential charging is concentrated during peak demand hours, which coincides with when people arrive home. However, the portion of peak coincident charging does not rise to the level assumed in previous research models by other organizations. This has significant implications on the level of EV adoption that would begin to trigger negative distribution system impacts; i.e., EV adoption can likely rise to higher penetration levels without negative impacts for most distribution systems than has been assumed in many EV impact models.

Lessons Learned

- There is a lack of commercially available, cost-effective residential hardware products that would integrate the EV into the existing home residential electric infrastructure in a useful way. Prototype systems are relatively easy to build, but there is not an effective method to compensate the consumer for the purchase and use of these products.
- Electric vehicles do not appear to significantly add to the total energy usage in a residential structure for the participants in the study area because the total energy spent on charging the car is small compared to total use during the summer months when air conditioning load is highest.

V. Metrics and Benefits Analysis

Build Metrics

Pecan Street's monetary investments to build the Energy Internet Demonstration include:

Table 29. Monetary Investments by System: Summary of Sources

Item	DOE Funded	Pecan Street Funded	Partner Contributions	Total Project Cost
Smart Meters	$ 688,696.50			$ 688,696.50
Smart Water Systems	$ 7,486.79	$ 3,270.00	$ 6,000.00	$ 16,756.79
Distributed Energy	$ 626,990.81			$ 626,990.81
Energy Storage	$ 100,000.00		$864,197.40	$ 964,197.40
Electric Vehicles	$ 566,097.93		$ 7,699.00	$ 573,796.93
Pricing Models & Behavioral Interventions	$ 22,275.00			$ 22,275.00
Other (computing, printing, servers, backhaul, e.t.c)	$ 164,801.53		$ 49,498.63	$ 214,300.16
Total	$2,176,348.56	$ 3,270.00	$927,395.03	$3,107,013.59

Funding provided by the Department of Energy through the Smart Grid Demonstration Grant Program and resources provided by cost share partners were utilized for the procurement of equipment required for the three Energy Internet Demonstration programs.

Smart meters, including home energy monitoring systems that provide billing-grade data, were purchased and installed in the homes of participants. These systems provided the granular, near-real-time data that served as the backbone of this research program. The energy monitoring systems enabled all of the hardware, software, and behavioral testing that was undertaken, and have resulted in the world's most significant dataset on residential energy use. The majority of the smart meters will remain installed at the premises of participants, in accordance with agreements that Pecan Street has executed with its research participants, to enable on-going research.

Smart water monitoring systems were purchased to collect data on water use within homes of participants who also have dual-socketed electricity meters. The water data was made available for free to university researchers for analysis on opportunities to save energy through water conservation. The water monitoring systems will remain installed at the premises of participants, in accordance with agreements that Pecan Street has executed with its research participants, to enable on-going research.

Pecan Street provided incentives to participants in the Energy Internet Demonstration to encourage installation of rooftop PV systems. The incentives were very successful and resulted in over 1MW of distributed generation spread across 163 homes. The data collected on PV generation, energy consumption and transformer performance enabled original research on the impacts of dense deployments of distributed generation as well as opportunities to optimize PV configurations to optimize benefits to the utility and the system owner. The available incentive funding was fully subscribed to, with a waiting list of participants who wanted to take advantage of the rebate program if additional funding became available. Pecan Street also installed a rooftop-mounted PV system at its lab to enable analysis of distributed generation-connected products and services. The participants in the PV field trial own their solar systems and will retain ownership and control of those systems after conclusion of this program.

Pecan Street provided incentives to participants in the Energy Internet Demonstration, who had previously purchased PV systems, for the purchase or lease of an electric vehicle. This incentive program was also very successful and resulted in 69 participants procuring electric vehicles. Pecan Street purchased and provided to these participants a Level 2 EVSE to allow for analysis of utility infrastructure impacts from geographically dense adoption of EVs with Level 2 charging. The participants in the EV field trial own their electric vehicles, and will retain ownership of the vehicles upon conclusion of this program.

To enable analysis on the impacts of the behavioral trials on participant behavior, Pecan Street purchased and installed 99 Nest thermostats. The Nest thermostats provided data on internal set temperature, time of adjustments to set temperature and enabled remote control of the thermostats.

Table 30. Monetary Investments by System: Detailed Accounts

Item	Count	Amount	Total
Smart Meters			
eGauges	1132	$ 462,588.27	
CTs	4700	$ 141,060.23	
Homeplugs	328	$ 9,854.00	
Sequentric gateway	106	$ 10,602.00	
Transducer modules	212	$ 15,132.00	
4-way wired DHCP router	26	$ 414.00	
110-120 v outlet doubler	26	$ 136.00	
Installation	106	$ 10,750.00	
Monthly maintenance and support	106	$ 38,160.00	$688,696.50
Smart Water Systems			
Badger Meters	45	$ 7,486.79	
Capstone Meters	5	$ 3,270.00	
AE Irrigation equipment	1	$ 6,000.00	$ 16,756.79
Distributed Energy			
Solar PV rebates	163	$ 612,441.00	
Solar Array	1	$ 14,549.81	$626,990.81
Energy Storage			
Sony batteries plus battery servers	67	$ 964,197.40	$964,197.40
Electric Vehicles			
EV Rebates	69	$ 476,750.00	
EV charge cards	25	$ 1,225.00	
PSI EVs (Volts)	2	$ 87,273.93	
Car Chargers	4	$ 7,699.00	
Charger wall mount	1	$ 849.00	$573,796.93
Behavioral Interventions			
Nest thermostats	99	$ 22,275.00	$ 22,275.00
Other			
Printers	2	$ 40,300.00	
Servers	3	$ 20,134.04	
Other computing & data storage equipment	various	$ 153,866.12	$214,300.16
Total			$3,107,013.59

Impact Metrics

To analyze the Impact Metrics of Pecan Street's Energy Internet Demonstration, Pecan Street and the Environmental Defense Fund undertook an emissions analysis to determine the carbon emissions savings that resulted from system demonstrations.

The first step in the analysis was calculation of Austin Energy's (AE) carbon intensity over the course of fiscal year 2013, the most recent year for which data was reported by AE, using the following equation:

$$c = e / (a - g)$$

where

c = average carbon intensity (lbs CO_2 equivalents/kWh)

e = total greenhouse gas emissions at the point of combustion (lbs CO_2 equivalents)

a = net generation in kWh from all AE resources, including coal, natural gas, nuclear, renewable, and both renewable and non-renewable purchased power

g = GreenChoice® energy sales

GreenChoice® is Austin Energy's renewable energy program that allows residential and commercial customers to meet their electricity needs by purchasing 100% renewable Texas wind power.

The project team was able to find numbers in Austin Energy's annual report for the variables c, a, and g, so those numbers were used to calculate e in order to properly recalculate the average carbon intensity of the Austin Energy grid.

While the report lists the average carbon intensity for each calendar year (CY), the remainder of the relevant numbers used were reported for each fiscal year (FY). While the calendar year is defined as January 1, 2013 – December 31, 2013, Austin Energy's fiscal year is defined as October 1, 2012 – September 30, 2013. This means that three months of CY 2012 and nine months of CY 2013 are included in FY2013. Making the simplifying assumption that the carbon intensity of the Austin Energy grid was uniform over the course of each calendar year, the equation was modified slightly so that all numbers are expressed in FY2013 terms. The value for a was calculated based on a few separate values. The equation used to calculate a is:

$$a = s(100/p)$$

where

s = total kWh from renewables, as well as AE coal, natural gas, and nuclear plants

p = the percentage of a accounted for by the resources included in s

The value *s* is the total energy from Austin Energy resources excluding what was categorized in the report as Purchased Power, for which the project team could not find clear numbers. This value was calculated by adding the total renewable energy purchased in fiscal year 2013 (2,656,952,000 kWh) to the fiscal year 2013 net generation for coal, gas, and nuclear plants owned by Austin Energy (8,256,118,000 kWh):

$$s = 2{,}656{,}952{,}000 + 8{,}256{,}118{,}000 = 10{,}913{,}070{,}000\ kWh$$

By analyzing the percentage of total Austin Energy generation for which each resource type is responsible, the project team concluded that p = 85.06%, since every resource type was accounted for except for Purchased Power in *s*.

Having collected all of the information necessary to complete the equation, *e* can be calculated as:

$e = (0.25*1.03+0.75*1.05)(10{,}913{,}070{,}000*(1/85.06) - 861{,}972{,}633)$

$e = 12{,}506{,}431{,}344.811$ *lbs* CO_2 *equivalent*

This provides all of the values needed to recalculate *c to normalize for the fiscal year:*

$c = 12{,}506{,}431{,}344.811/(10{,}913{,}070{,}000*(1/85.06))$

$c = 0.974792$ *lbs* CO_2 *equivalent/kWh*

The calculations indicate that Austin Energy's average carbon intensity for FY2013 was 0.974792 lbs of CO_2 equivalent/kWh.

The second step was analyzing the reductions in electricity consumed from the grid as a result of the deployed systems. Because deployment of HEMS was not found to have a statistically significant impact on electricity consumption, the resulting emissions savings of this technology was zero.

Distributed Generation Analysis

The reduction in grid electricity consumption and corresponding carbon dioxide (CO_2) emissions from residential rooftop solar photovoltaic (PV) panels were analyzed to determine the environmental impacts of the research trial. Results are both cumulative and disaggregated for the direction for which solar panels face. Table 31, below, summarizes samples sizes, as well as other pertinent metrics, such as average array size, azimuth, and tilt, for all solar homes and disaggregated for the direction a home's panel(s) face.

Table 31 - Solar Panel Features, by Orientation for Mueller Homes with Complete Data Sets

	All Solar Homes	South- & East -Facing PV	South-Facing PV	South- & West-Facing PV	West-Facing PV	West- & East-Facing PV
# of Homes (% of Homes with PV)	110 (100%)	3 Homes (2.7%)	26 Homes (23.4%)	65 Homes (58.6%)	9 Homes (8.1%)	1 Home (0.9%)
# of Observations (% of All Solar Observations)	963,174 (100%)	26,271 (2.7%)	227,682 (23.4%)	569,109 (58.6%)	78,813 (8.1%)	8,757 (0.9%)
Average PV Array Size (KW)	5.642 KW	5.672 KW	5.088 KW	5.887 KW	5.371 KW	6.500 KW
Average Azimuth	210.26	158	174.08	219.25	268.44	200
Average Tilt (Degrees)	27.5	25.7	27.7	27.4	28.61	26.5

The analysis examines 110 unique data IDs from homes with solar panels in Austin's Mueller neighborhood during Austin Energy's FY2013, extending from October 1, 2012 through September 30, 2013. Data are measured at hourly intervals; and, each of the 110 homes has a complete dataset, meaning there are data for every hour of the year.

Methodology

This analysis follows a three-step approach:

1) **Calculation of the average hourly amount of electricity generated per 1 KW PV array for the average home in this sample.** For example, for all 110 homes in this sample with PV, average hourly generation is 0.884 kWh and average PV array size is 5.642 kW. Using these statistics, the average hourly generation per kW of panel size is 0.1567 kWh.

   = 0.1567 kWh of PV Generation per 1 kW PV Array

2) **Conversion of the rate calculated in step 1 to an emissions savings rate per 1 KW PV array.** Homes with solar PV were assumed to have used the same amount of electricity if they did not have solar panels; and, thus, all electricity from PV generation equates to savings of grid electricity and corresponding emissions. As calculated above, for all 110 solar homes in this sample, average kWh of PV generation per 1 kW PV array is 0.1567 kWh. Austin Energy's grid emissions rate is 0.974792 lbs. CO_2 e/kWh (see Appendix A

for information on how this metric was calculated). Using these statistics, the average hourly emissions savings per 1 kW PV array is 0.1527 lbs. CO_2 e, equivalent to an annual emissions savings per 1 kW PV array of 0.6690 short tons of CO_2 e (t CO_2 e).

3) **Applying this emissions savings rate to determine emissions reduced from solar panels for homes included in this sample.** As calculated in step 2, the average home in this sample saves 0.669 tCO_2 e annually per 1 kW PV array. Using this rate for this sample's 110 homes, which have an average PV array size of 5.642 kW, Austin Energy's FY2013 emissions savings from PV generation is 415.2 tCO_2e.

Results

Table 32, below, displays the findings for solar generation and corresponding emissions savings from PV, as well for homes disaggregated by the directional orientation of installed system.

Table 32. Solar Generation, Corresponding Electricity and Emissions Savings by Orientation

	All Solar Homes	South Facing PV	South & West Facing PV	West Facing PV
Average Hourly Generation (KWh)	0.884 kWh	0.8400 kWh	0.9018 kWh	0.7964 kWh
Ave. Hourly Gen. for a 1 KW PV Array	0.1567 kWh	0.1651 kWh	0.1532 kWh	0.1483 kWh
Ave. Gen (kWh) Assuming Ave. Panel Size of 5.642 KW	0.884 kWh	0.9315 kWh	0.8643 kWh	0.8367 kWh
Hourly Emissions Savings for a 1 KW PV Array (lbs. CO_2e)	0.1527 lbs CO_2e	0.1609 lbs CO_2e	0.0655 lbs. CO_2e	0.0925 lbs. CO_2e
Annual Emissions Savings for a 1 KW PV Array (lbs. CO_2e)	1,337.936 lbs. CO_2e	1,409.69 lbs. CO_2e	573.769 lbs. CO_2e	810.189 lbs. CO_2e
Annual Emissions Savings for a 1 KW PV Array tCO_2e)	0.6690 tCO_2e	0.7048 tCO_2e	0.6540 tCO_2e	0.6332 tCO_2e
Annual Emissions Savings Assuming Average Panel Size of 5.642 KW	3.77 tCO_2e	3.98 tCO_2e	3.69 tCO_2e	3.57 tCO_2e
FY2013 Emissions Saved from PV for Mueller Homes in this Study (tCO_2e)	415.2 tCO_2e	93.2 tCO_2e	250.3 tCO_2e	30.6 tCO_2e

For the sample used in this analysis, a 74% reduction of household grid electricity consumption and associated emissions resulted from installation of residential PV systems. Per 1 kW PV array, average hourly PV generation is 0.1567 kWh for all 110 homes in this study. Under the assumption that all PV generation offsets grid electricity consumption, the corresponding average hourly emissions savings per 1 kW PV array is 0.1527 lbs. CO_2e, equivalent to 0.6690 tCO_2e per year per 1 kW PV array. As the average home in this study has a 5.642 kW array, the average home offset 3.77 tCO_2e during FY2013. Together, the 110 homes in this study saved 415.2 tCO_2e.

Directionally, homes with south-facing PV generate 0.1651 kWh per 1 kW PV array, more than homes with south- and west-facing PV and west-facing PV with rates of 0.1532 KWh and 0.1483 KWh, respectively. These generation rates equate to annual emissions savings rates of

0.7048 tCO_2e per 1 kW PV array, 0.6540 tCO_2e per 1 kW PV array, and 0.6332 tCO_2e per 1 kW PV array for homes with south-facing, south- and west-facing, and west-facing panels, respectively.

While this study finds that south-facing panels offset more emissions per 1 kW PV array than other directions, this finding comes with caveats. For example, as shown in Figure 62, west-facing panels generate more power during the early evening, when the grid's peak demand usually occurs and the emissions rate in Texas is usually highest.

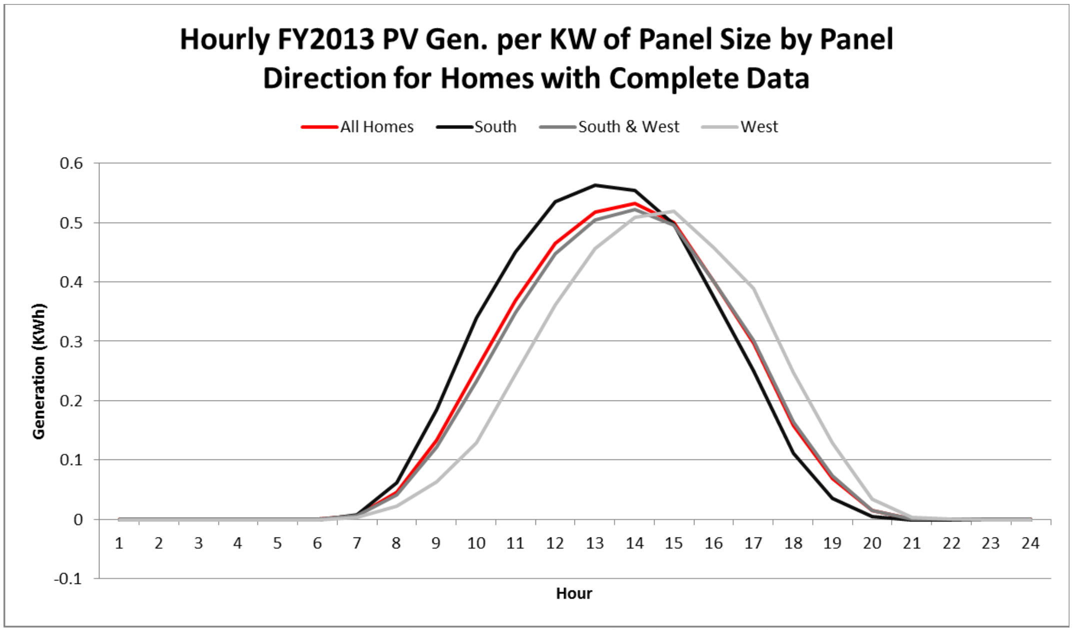

Figure 62. Hourly PV generation by directional orientation

Electric Vehicle Analysis

In this section, we compare carbon dioxide-equivalent (CCO_2e) emissions associated with the sum of household electricity and gasoline consumption from cars when the vehicle is an electric vehicle versus a traditional all-gas passenger vehicle. Table 33, below, summarizes sample sizes, as well as other pertinent metrics — such as the percentage of these homes that have PV and hourly average household power usage, grid electricity consumption, and car electricity consumption — for all homes with EVs and disaggregated for vehicle type (Chevy Volt and Nissan Leaf). Only homes without chargers at work and with complete data sets for FY2013 are included in the analysis.

Table 33. Features of Observations by EV Type

	All EVs	Chevy Volt	Nissan Leaf
Number of Homes without Charger at Work	25 Homes	20 Homes	5 Homes
% of Homes with EVs	100%	80.00%	20.00%
Number of Observations	218,877	175,092	43,785
% of Observations with PV	100%	100%	100%
Hourly Average Electricity Use (KWh)	1.329 KWh	1.321 KWh	1.362 KWh
Hourly Average Grid Electricity Consumption (KWh)	0.489 KWh	0.509 KWh	0.413 KWh
Hourly Average Car Electricity Consumption (KWh)	0.267 KWh	0.262 KWh	0.285 KWh

This analysis examines 25 unique data IDs from homes with EVs in the Mueller neighborhood during Austin Energy's fiscal year 2013. Data are measured at hourly intervals and each of the 25 homes has a complete dataset, meaning there are data for every hour of the year. Participants with EV chargers at work were excluded from this sample to ensure the data is from cars that are primarily charged at home.

Methodology

This analysis follows a four-step approach:

1. **Calculation of the average hourly EV electricity consumption for the average home in this sample and the corresponding emissions.** For the average charging hour on a Level 2 EVSE, electric vehicles in this sample consume 0.267 kWh of electricity. As previously calculated, Austin Energy's grid emissions rate is 0.974792 lbs. $CO_2{}^2e$/kWh. Using these statistics, the average hourly household electricity emissions from EV charging is 0.260 lbs. CO_2e, equivalent to 2,280.0 lbs. CO_2e/year and 1.11 tCO_2e/year. Because traditional vehicles do not consume electricity, 1.11 tCO_2e is the amount by which the household electricity emissions of EVs exceed those of traditional passenger vehicles.

2. **Calculation of the average EV emissions versus traditional vehicle gasoline emissions for the average home in this sample and the corresponding emissions**. For traditional all-gas vehicles, EPA gas consumption and emissions rates for the average passenger vehicle, as reported in the May 2014 report titled "Greenhouse Gas Emissions from a Typical Passenger Vehicle", were used. The average all-gas vehicle travels 11,400 miles per year using 528 gallons of gas, which equates to an annual emissions rate of 5.18 tCO_2e/year.

To reach a comparison of annual emissions from EVs and traditional gas-powered vehicles, two methods were used.

Method 1: According to the U.S. Department Energy's fueleconomy.gov, average annual tailpipe CO_2 emissions from a Chevy Volt and Nissan Leaf are 1.4 tCO_2e and 0 tCO_2e, respectively. As 80% of the vehicles in this sample are Volts and 20% are Leafs, the average EV in this sample emits 1.12 tCO_2e from gasoline.

Method 2: For six electric vehicles, Pecan Street monitored 1,984 car trips to accumulate data that reveal for which trips cars use only electricity and for which trips gas is used. Some gas was used for 13.22% of the distance travelled by these vehicles. The data collected did not reveal the amount of gas consumed, only that the vehicle switched from its electric transmission to the gas transmission. Assuming the EPA's annual average vehicle miles traveled of 11,400, 13.22% of this number is 1,507 miles; thus, it can be conservatively assumed that the average EV in this sample travels 1,507 miles/year using gasoline. Because all hybrids in this sample are Chevrolet Volts, which consume gas at 37 mpg, the EVs in this sample consume 41 gallons of gas annually, equivalent to 0.40 tCO_2e/year.

3. **Calculating the emissions savings from EVs.** This step sums results from steps 1 and 2.
4. **Applying the emissions savings rate for EVs over traditional vehicles to determine emissions reduced from EVs for the sample.**

Results

Table 34, below, displays the findings for emissions savings from EVs over traditional vehicles for the household electricity consumption and car gasoline emissions package, for homes without chargers at work and complete data sets for FY2013.

Table 34. Vehicle Energy Consumption & Emissions for Homes with EVs and Traditional Vehicles

	EV	Traditional Vehicle	Savings from EV over Traditional Vehicle
Hourly Household Car Electricity Consumption (KWh)	0.267 KWh	0 KWh	(-0.267) KWh
Hourly Vehicle Electricity Emissions (lbs. CO_2e)	0.260 lbs. CO_2e	0 lbs.CO_2e	(-0.260) lbs. CO_2e

Annual Vehicle Electricity Emissions (lbs. CO$_2$e)	2,280.0 lbs. CO$_2$e	0 lbs. CO$_2$e	(-2,280.0) lbs. CO$_2$e
Annual Vehicle Electricity Emissions (tCO$_2$e)	1.11 tCO$_2$e	0 tCO$_2$e	(-1.11) tCO$_2$e
Car Gas Use Methodology 1 - Using DOE Estimates for Annual Tailpipe CO$_2$ Emissions from Volts and Leafs			
Hourly Car Gas Emissions (lbs. CO$_2$e)	0.256 lbs. CO$_2$e	1.183 lbs. CO$_2$e	0.927 lbs. CO$_2$e
Annual Car Gas Emissions (tCO$_2$e)	1.12 tCO$_2$e	5.18 tCO$_2$e	4.06 tCO$_2$e
Hourly Vehicle Total Emissions (lbs. CO$_2$e)	5.23 lbs.CO$_2$e	1.183 lbs. CO$_2$e	0.660 lbs. CO$_2$e
Annual Vehicle Total Emissions (tCO$_2$e)	2.23 tCO$_2$e	5.18 tCO$_2$e	2.95 tCO$_2$e
FY2013 Emissions Savings from All 25 EVs in this Sample over Traditional Vehicles (tCO$_2$e)	NA	NA	73.75 tCO$_2$e
Car Gas Use Methodology 2 - Using Pecan St. Trips Data, Conservatively Assuming That Gas Fuels 100% Distance Traveled on Trips Gas is Used, or 13.22% of all Mileage is from Gas			
Car Gas Consumption	**41 Gallons^/ 1,507 Miles**	**528 Gallons^^/ 11,400 Miles**	**487 Gallons/ 9,893 Miles**
Hourly Car Gas Emissions (lbs. CO$_2$e)	0.092 lbs. CO$_2$e^^^	1.183 lbs. CO$_2$e^^^	1.091 lbs. CO$_2$e
Annual Car Gas Emissions (tCO$_2$e)	0.40 tCO$_2$e^^^	5.18 tCO$_2$e^^^	4.78 tCO$_2$e
Hourly Vehicle Total Emissions (lbs. CO$_2$e)	0.352 lbs. CO$_2$e	1.183 lbs.CO$_2$e	0.831 lbs.CO$_2$e
Annual Vehicle Total Emissions (tCO$_2$e)	1.51 tCO$_2$e	5.18 tCO$_2$e	3.67 tCO$_2$e
FY2013 Emissions Savings from All 25 EVs in this Sample over Traditional Vehicles (tCO$_2$e)	NA	NA	91.75 tCO$_2$e

^ Assuming Chevy Volt mileage per gallon of 37 mpg, according to the DOE, http://www.fueleconomy.gov/feg/Find.do?action=sbs&id=31618&id=30980&id=33398

^^ Assuming mileage per gallon of 21.6 mpg, according to EPA's estimate for the average passenger vehicle http://www.epa.gov/otaq/climate/documents/420f14040.pdf

^^^ Assuming 8,887 grams of CO_2 emissions per gallon of gasoline consumed, per EPA's estimate http://www.epa.gov/otaq/climate/documents/420f14040.pdf

The homes in this sample reduced their vehicle carbon emissions by 56.9% by purchasing an electric vehicle instead of a traditional gas-powered vehicle. Annual car-related household electricity emissions plus annual car gasoline emissions are 5.18 tCO$_2$e for the average traditional all-gas vehicle and 2.23 tCO$_2$e for the average EV in this study (with 80% of the EV sample having dual-transmission gas and electric engines and 20% being all-electric). Thus, the emissions savings rate from an EV over a traditional vehicle is 2.95 tCO$_2$e/year using Method 1 and 3.67 tCO$_2$e/year using Method 2. The emissions savings from an all-electric EV is 5.18 tCO$_2$e/year.

Annual household electricity emissions are 1.11 tCO$_2$ e from an EV and 0 from a traditional all-gas vehicle. Average hourly EV electricity consumption for the 25 cars in our sample is 0.267 KWh, which corresponds to an hourly emissions rate of 0.260 lbs. CO$_2$ e, equivalent to 1.11 tCO$_2$ e/year. Traditional vehicles consume zero KWh of electricity, so the annual household electricity emissions rate from traditional passenger vehicles is 0 tCO^{2}2e/year.

Together, the 25 homes in this sample saved 73.75 tCO$_2$ e during FY2013 (October 1, 2012 – September 30, 2013) using Method 1 and 91.75 tCO$_2$ e using Method 2.

Residential Energy Storage Analysis

Energy storage technologies can provide a number of benefits to utilities in terms of electric system resilience. For example, a several-kWh lithium-ion battery located at a home where solar panels are installed could store excess solar power on site for later use in the home rather than sending it to the grid. This would reduce the utility's need to increase the grid's capacity to manage the increased load from excess solar power in neighborhoods with a high penetration of solar panels, such as the Mueller community.

As utilities transition to more sustainable energy sources, energy storage technologies will play a critical role in ensuring electric system reliability. Both solar and wind power are intermittent in that they can only be generated at certain times of day, so energy storage will allow power from these sources to be used continuously. While these technologies may be useful to the utility if they are located close to the power source (on site at a solar power plant, for example), the Pecan

Street dataset is most informative at the level of the individual home rather than the level of the utility.

Pecan Street is uniquely qualified to examine what might happen if energy storage systems were located at individual homes, at the source of distributed generation production and local consumption. To analyze the emissions benefits of residential energy storage, the project team simulated the effects of installing a 20 kWh lithium-ion battery system at an average home in the Energy Internet Demonstration. The simulation utilized data on energy consumption across the time of day and by season that was collected by Pecan Street and it utilized data on energy storage system performance collected from the energy storage system installed at Pecan Street's lab. The simulation assumes the home does not have on-site distributed generation and that the energy storage system is charged by power from the grid.

A 20 kWh battery size was selected because this is the approximate average battery size of an electric vehicle — a 2015 Chevrolet Volt battery has a size of 17.1 kWh and a Nissan Leaf battery has a size of 24 kWh — which is likely to be recycled as a home energy storage system after the car is decommissioned. It is assumed that the energy storage system will charge by capturing power from the grid during night-time wind power production hours and release it during peak consumption times. Such a situation has the potential to reduce grid demand for coal- and natural gas-generated power during peak hours, thus reducing overall CO_2 emissions.

Data

As previously reported, the carbon intensity of Austin Energy's electrical grid was found to be 0.974792 lbs of CO_2 equivalent/kWh over fiscal year 2013. For the purpose of this study, 67 homes were chosen from the Pecan Street database that have disaggregated energy use data for this entire period. Since Pecan Street obtained many of its initial participants through its photovoltaics (PV) rebate program, all of these homes are equipped with PV. To simplify the calculations for this analysis, only the total whole home energy use data was used, isolating the emissions impact of a residential energy storage system from that of a distributed energy system.

According to the 2013 Electric Reliability Council of Texas (ERCOT) wind generation data summarized in Figure 63, wind power production on the ERCOT grid is highest between 10 PM and 5 AM. While Figure 63 shows the data averaged over the entire year, this profile is consistent regardless of the time of year.

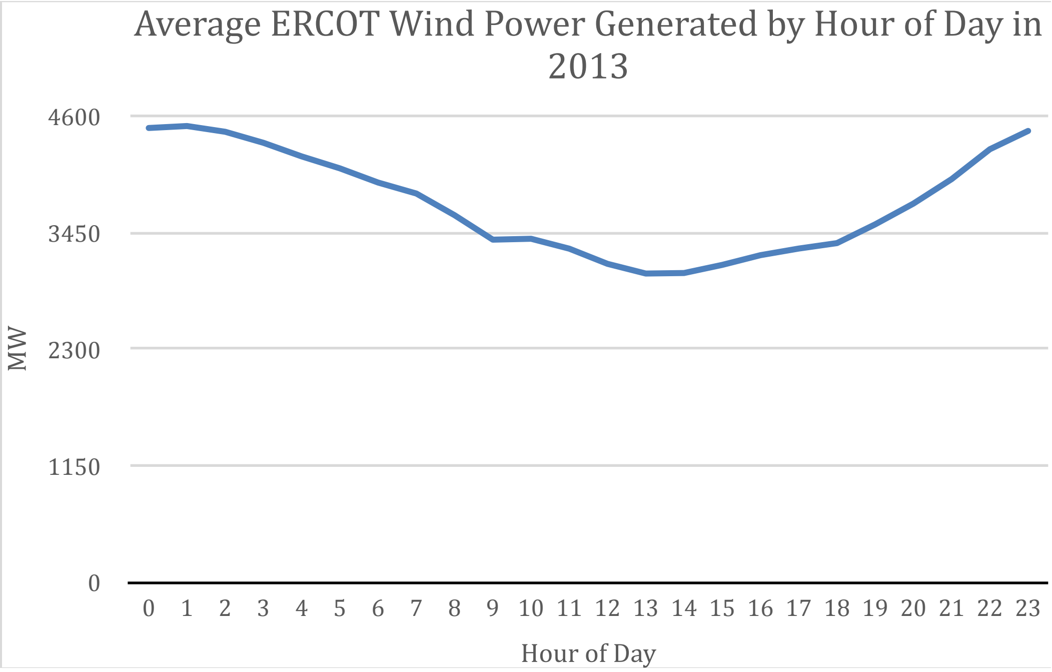

Figure 63: Average ERCOT wind generation by hour of day in 2013.[12]

Additionally, as illustrated in Figure 64, wind energy production over the course of 2013 was highest from February through June as well as October and November. Total wind energy production on the ERCOT grid was above 2,500,000 MWh in February through June, October, and November 2013.

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[12] While the total wind capacity of the ERCOT grid was recorded to be 11064.4 MW for almost the entire year, an additional 141.1 MW of capacity were added on December 13, 2013. This additional capacity may have slightly skewed the numbers in this graph.

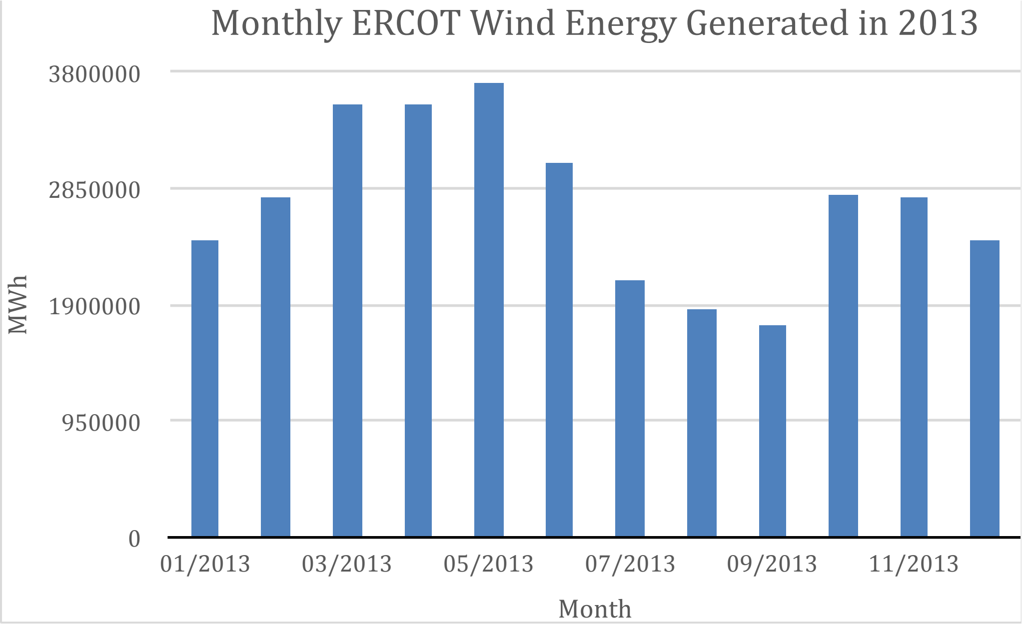

Figure 64: Monthly ERCOT wind generation in 2013[13]

Because more wind power is generated at night, when homes typically use the least power, the grid would benefit from the use of energy storage technologies to redistribute wind power. As illustrated by Figure 65, Mueller homes from the sample described in the Data section above generally use the most power in the evening. Wind power could thus be redistributed from10 PM to 5 AM to these peak demand hours. This would be particularly helpful during the summer months (June through August), when Austin residents typically use the most power due to high air conditioning use. While Austin Energy defines its peak hours as 4 – 7 PM, residents in the sample shown in Figure 65, below, from the Mueller neighborhood consumed the most power between 6 and 9 PM during fiscal year 2013.

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[13] See footnote 6.

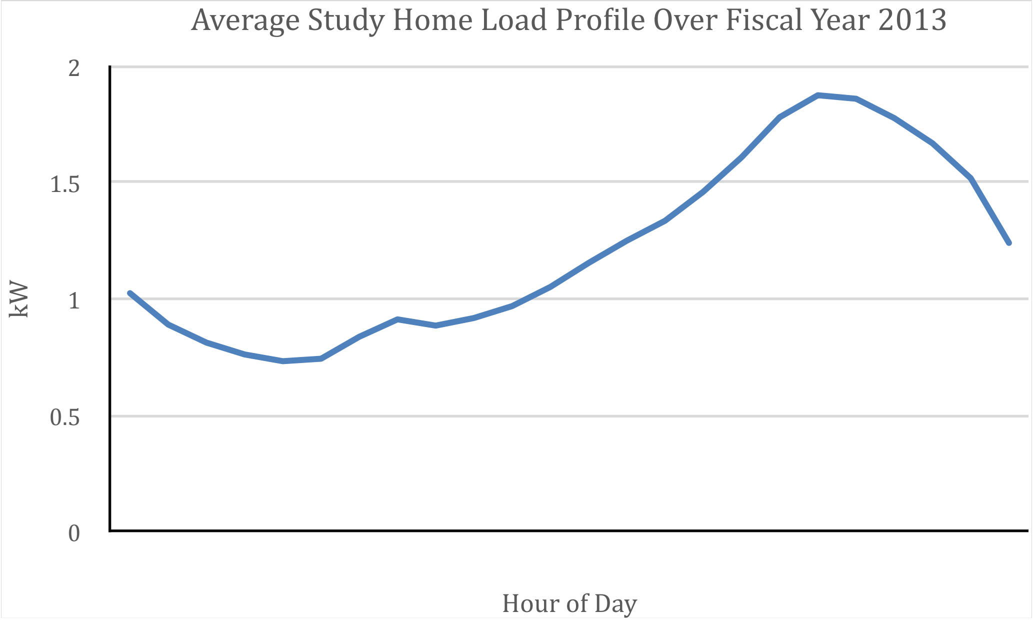

Figure 65: Peak consumption profile during fiscal year 2013

Methodology

In the modeled simulation, homes are each equipped with a 20 kWh battery, which is activated at midnight on October 1, 2012 and allowed to function through September 30, 2013. A 10% loss of energy drawn from the grid as it is transferred into and out of the battery is assumed, so only 81% of the energy stored in the battery will be available for use in the home after it has been transferred into and then back out of the battery.

For simplicity, hard charging and discharging times were assumed for the batteries in this simulation. During wind production hours every night (from 10 PM to 5 AM), each home's battery will fully recharge, thus storing power for later in the day. The battery will then discharge during peak consumption hours, defined here as 4 PM to 10 PM, to meet the home's electricity demand. Under these conditions, each home's energy use will be composed of a larger percentage of wind power, since it is now available from the battery at times other than while it is being generated.

Austin Energy does not have hourly wind generation data, therefore the simulation uses ERCOT data for this time period to determine variations in the carbon intensity of the grid over the course of the day. It is assumed that the ERCOT grid's carbon intensity is the same as Austin Energy's carbon intensity. This is unlikely to be true in reality because Austin Energy is only responsible for a small portion of the energy on the ERCOT grid, so it may draw on a different mix of power sources from that of ERCOT as a whole.

While in reality the proportion of the power on the grid that is wind power varies fluidly throughout the day, this analysis utilized the average percentage of wind power for each of the two periods covered in FY13. During battery charging hours (10 PM to 5 AM), the ERCOT grid utilized 14.24% wind energy on average over FY2013. During battery discharging hours (4 PM to 10 PM), the ERCOT grid utilized 8.79% wind energy on average over FY2013.

Over all of fiscal year 2013, the average percentage of power on the ERCOT grid supplied by wind was 10.91%. Since renewables and nuclear energy were responsible for 43.49% of the power on the Austin Energy grid over fiscal year 2013, it was assumed that only the remaining percentage of power produced was responsible for Austin Energy's CO_2 emissions. Excluding wind power, it can thus be estimated that 32.58% of Austin Energy's power does not produce CO_2 emissions. It was assumed that if wind power was not available to meet consumption demands at any given time, the power would be supplied by sources with the same average carbon intensity as the total CO_2-emitting sources on the Austin Energy grid. The percentage of power that produces CO_2 emissions thus varied between 53.18% during battery charging hours and 58.63% during battery discharging hours.

The carbon intensity of the grid during each of the time periods in the simulation will be proportional to the carbon intensity of the grid on average. Using this methodology, the project team arrived at the following carbon intensities for battery charging and discharging:

Table 35. Battery Charging and Discharging Carbon Intensities

Event	**Time**	**% Non-CO_2 Emitting Power Sources, Excluding Wind**	**% Wind Power**	**Total % Non-CO_2 Emitting Power Sources**	**% CO_2 Emitting Power Sources**	**Carbon Intensity of Austin Energy Grid (lbs CO_2 equivalent/ kWh)**
Battery Charging	10 PM – 5 AM	32.58	14.24	46.82	53.18	0.917350
Battery Discharging	4 PM – 10 PM	32.58	8.79	41.37	58.63	1.011362

It was assumed that all batteries charged at a rate of 3.175 kW for the entire period from 10 PM to 5 AM every night, or until they were filled if their excess power remained in the battery from the previous day. At this rate, the batteries would fully charge from an empty state during the allotted charging time. Batteries would be discharged beginning at 4 PM and continue to do so until depleted. Consumption demand was based on actual consumption over the course of fiscal year 13 from the 67 homes included in the simulation. Each home was modeled separately to result in 67 home simulations.

To determine the amount of CO_2 emissions averted, the amount of CO_2 emitted in the absence of the battery was compared to the amount of CO_2 emitted in the presence of the battery.

Results

The average daily reduction in CO_2 emissions from an individual home in the simulation was 0.015 lbs of CO_2 equivalent. This amounted to an average emissions reduction of 5.556 lbs of CO_2 equivalent per home over the year the simulation was done, for a total of 372.247 lbs of CO_2 equivalent for all 67 homes together.

The average home on the average day in this study reduced the amount of energy in its battery to 9.139 kWh, which means that the remaining 9.139 kWh was not used over the course of the day. The daily battery energy consumed varied between 3.157 kWh for the home that made the most of its battery capacity to 15.268 kWh for the home that made the least use of its battery capacity. This suggests that there are a number of adjustments that can be made to optimize this situation to achieve a larger emissions reduction at a lower cost.

Stakeholder Feedback

Residential participants in the Pecan Street Smart Grid Demonstration Program were enthusiastic about being a part of this project for varying reasons, from reducing carbon footprints to saving money on energy bills. Many of the participants expressed that they appreciated an opportunity to 'do their part to address climate change,' and participating in the program has helped them reach this feeling of achievement. As one homeowner put it, "adding energy monitoring to my solar panels and electric car has really put me in a place where I can truly feel like I'm helping to save the planet." Many of the participants already consider themselves green, but as one volunteer states, "by being able to monitor my energy use down to the circuit and plug, I can do my part to reduce waste and reduce my overall energy consumption, helping me be more efficient in my electricity use and save even more money."

Most homeowners expressed surprised by the data they receive about their energy use. One homeowner said "It's been very eye-opening to have access to the small details of our energy use – to be able to put a number on how much energy we save by opening the blinds instead of flipping on a switch, or to understand the cost of one degree of air conditioning, or even just to play around with trying to get our energy use to net zero."

Technology partners agree that Pecan Street is conducting ground-breaking research to shape energy systems. One member says, "Information technology and data management will be crucial to these smarter grids, and we are proud to put technology and expertise toward the goal of ensuring our energy future is efficient and sustainable."

A major automaker, GM, said that partnering on this research "provides us with a unique opportunity to observe charging details with many real customers in a concentrated setting. We are moving our lab demonstrations into the real world. This project will help us develop future capabilities of plug-in vehicles."

A significant area of stakeholder feedback from research partners is that the data Pecan Street had collected throughout the study period is extremely valuable to researchers working in areas of public interest research, and that this data should be made more readily available. Pecan Street responded to this feedback by creating Dataport, a suite of online research tools that includes Pecan Street's research database of customer energy, gas, and water use.

Dataport (dataport.pecanstreet.org) access is available for free to university researchers and to teachers for STEM curriculum development. Dataport's mission is to advance global university-based research and training on data science, energy, engineering, the environment and human behavior. The service will also provide a free set of tools for high school and post-secondary instructors for curriculum development in science, technology, engineering and math (STEM) fields.

Dataport members help validate data which is then quality checked and certified for inclusion by Pecan Street's trained staff in a validated data table that other members are able to access. Member researchers also identify and prioritize needed survey, energy audit and other types of static data, provide guidance on database formatting upgrades, and recommend solutions for any persistent data quality issues.

Dataport is operated by Pecan Street, with oversight and guidance from a board of advisors made up of five university faculty from four-year postsecondary educational institutions: MIT, Stanford, Carnegie Mellon University and UT. Pecan Street staff are responsible for operating computing systems, database systems, data protection, research participant recruitment, and identity anonymizing protocols.

Dataport launched on March 6, 2014, originally under the title of WikiEnergy. To date, Dataport has over 150 active members from around the world, with particular concentrations from MIT, Carnegie Mellon University, University of Texas at Austin, The University of California Berkeley, and Stanford University.

VI. Conclusions

Through implementation of the Energy Internet Demonstration, Pecan Street discovered opportunities for an open-platform Energy Internet to more rapidly advance the transition toward a smart grid that readily integrates distributed energy resources and accommodates customer-owned disruptive technologies, such as electric vehicles.

For customer systems, Pecan Street found that when engaging customers in behavioral change programs, such as demand response and energy conservation, it is critical that information on energy consumption be presented in an actionable manner. Recommendations should move beyond "how to save money on your electric bill," which has limited enduring interest for customers. Rather, recommendations should focus on using home energy use to make home highly tailored home maintenance, appliance maintenance and home retrofit recommendations. The project team also found that significant opportunity to reduce electricity consumption during peak hours can be realized by encouraging customers to purchase natural gas-powered appliances rather than electric-powered, when natural gas power is an option.

Finally, until reliable and accurate disaggregation algorithms can be developed that utilize meter data, customer-oriented programs and services will rely on detailed data provided by a HEMS on how the customer uses energy. It is therefore critical that any system that acquires data to provide customer services needs to have on-board data caching. This is due to inevitable intermittencies in even the most robust Internet and cellular networks.

To demonstrate the impacts of the Energy Internet on utility infrastructure, the project team seeded its testbed with dense distributions of distributed energy, electric vehicles and HEMS that collected data on the consumption patterns within participant premises and how those patterns change in response to new technologies and/or behavioral interventions. By selecting the Mueller community in Austin to serve as the primary testbed, Pecan Street ensured the project would also be seeded with highly efficient and smart appliances. The project team combined its observation of near real-time consumption and generation data from participating premises with data collected on transformer performance. The combination of data from the premises and data from the transformers serving participating homes enabled the project team to draw useful conclusions about impacts on utility infrastructure.

The project team analyzed opportunities to optimize the benefits of customer-sited distributed generation for both the utility and the customer. West-facing rooftop solar PV was found to be more load-aligned than south-facing, and therefore may provide greater system benefit and overall higher utility for demand reduction purposes.The lack of load alignment of generation from south-facing solar PV results in higher operational loads and operating temperatures for utility transformers during shoulder months, when PV generation increases but midday residential electricity use is typically low. However, areas without significant cooling loads, such as coastal California, could experience challenges at lower penetrations of residential PV than what was witnessed in this demonstration program during late spring when electricity use did not increase in step with solar panel generation.

Utilities serving customers in the Sunbelt region that provide solar rebates to customers may want to consider providing a higher rebate for west-facing systems, similarly to the California

Energy Commission ruling on September 3, 2014 that approved new incentives for west-facing PV systems, because these systems should provide greater benefit the utility. Utilities in other regions may want to undertake similar research projects to discover optimal rooftop PV alignment that will maximize any utility incentives or rebates offered for installation of distributed generation assets. Pecan Street offers consulting services to help regions throughout the world undertake studies that collect granular data on customer behavior and utilize field trials to explore opportunities to optimize the relationship between customers and their electric utility.

The Energy Internet presents new opportunities to utilities to utilize customer-owned resources for more effective demand response and market arbitration. The project team's behavioral trials demonstrated that actionable recommendations to consumers can have a measurable impact on energy usage even without monetary incentive. Home energy storage systems with individual circuit load control and independent energy source capability have the ability to turn demand response into a customer financial benefit instead of the typical unwanted change to an air conditioning/heating setting change. Behavioral modification that relies on manual actions by customers (as opposed to automated, "set and forget" structures) will face significant headwinds in producing predictable customer response, which has implications for the structures of pricing and demand response programs.

Energy storage installed at the point of use and where electricity is generated through customer-owned distributed generation resource has the potential to significantly alter the relationship between homes and the utility. Pecan Street's research found that homes with energy efficient technologies such as compact fluorescent lighting, variable speed drives and switching mode power supplies have unintended power quality consequences when paired with high density of residential solar. Transformers and neighborhoods operating at a power factor of 0.2 are possible and may present challenges to traditional operations and grid stability. When distributed solar is not present, grid-scale solutions installed at the substation or generation station still expose the grid assets nearest the residential customer to the variability of distributed generation. Storage installed at the point of generation can mediate power quality of the home, reducing the burden on the utility to supply reactive power.

Though home energy storage systems provide potential to reduce variability and intermittency in residential load and residential solar generation, Pecan Street's efforts with utilities show resistance to accommodating these systems within the utility generation and interconnection rules. These systems, with an appropriate communication interface and functionality, and appropriate market regulations can turn intermittent distributed resources into a utility and customer asset. Utilities may want to undertake additional research to evaluate the opportunities for residential energy storage to provide grid services and to develop model interconnection guidelines that simplify the permitting and connection process. Customer-owned systems that do not require utility investment could prove to be critical resources that add intelligence to the grid and enabled distributed energy management without expensive upgrades to centralized utility infrastructure.

Evaluation of electric vehicle integration into the Energy Internet platform revealed that though there is some coincidence of electric vehicle charging with peak power demand, charging time is more distributed across the day and night than was anticipated. The project team's behavioral trials revealed that EV owners have more dynamic charging behavior than anticipated and are willing to modify their charging times to occur outside of peak hours if incentivized through variable pricing models, such as the Time of Use pricing method that was tested in this study.

Though there is opportunity for electric vehicles, which contain on average a 20 kW battery, to provide energy storage services to the grid, there is a lack of commercially available cost-effective residential hardware products that would integrate the EV into the existing home residential electric infrastructure in a useful way.

To further evaluate integration of EVs into the home, the project team developed software programs and tested third-party systems that intelligently manage EV charging to avoid coincident power use between the EVSE and other major loads in the home, such as the HVAC system. While prototype systems are relatively easy to build, there is not yet an effective method for utilities to compensate the consumer for the purchase and use of these products.

Overall, the Energy Internet Demonstration found that an open-platform approach to leveraging customer systems for grid management services has the potential to rapidly accelerate adding intelligence to the grid, resulting in a more efficient and reliable energy system. By moving towards decentralized energy production and management, utilities can build greater resilience into the grid, reduce the need for costly upgrades to centralized grid infrastructure and offer more services to residents that increase the value they receive from their utility while creating opportunities for new product markets that will generate economic development and local innovation. Utilities and communities in other areas of the country can build upon the framework created by Pecan Street Inc. to establish their own research and development testbeds that will reveal the locally appropriate solutions for energy management. These field trials have the added benefit of creating significant datasets that, when provided at no cost to academic researchers as Pecan Street has done, enable significant new research into areas of public and industry interest, such as climate change mitigation and adaptation, grid reliability and community resilience.

VII. Contacts

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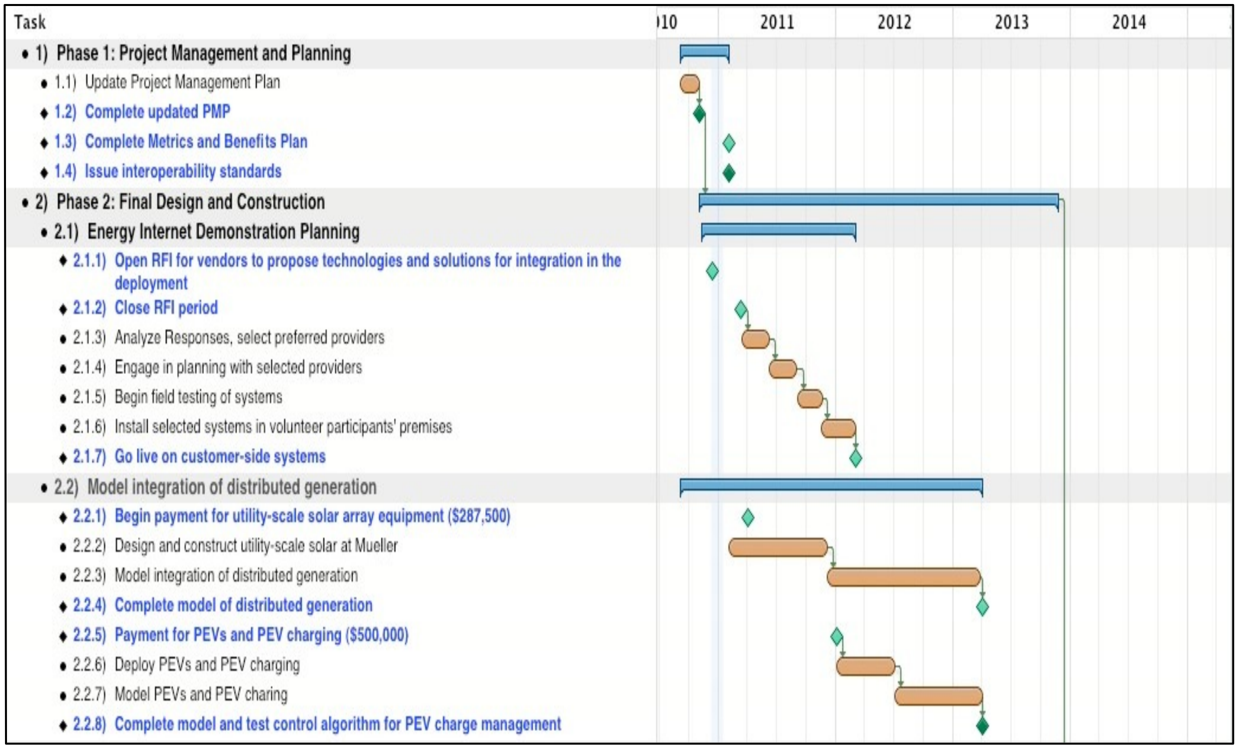
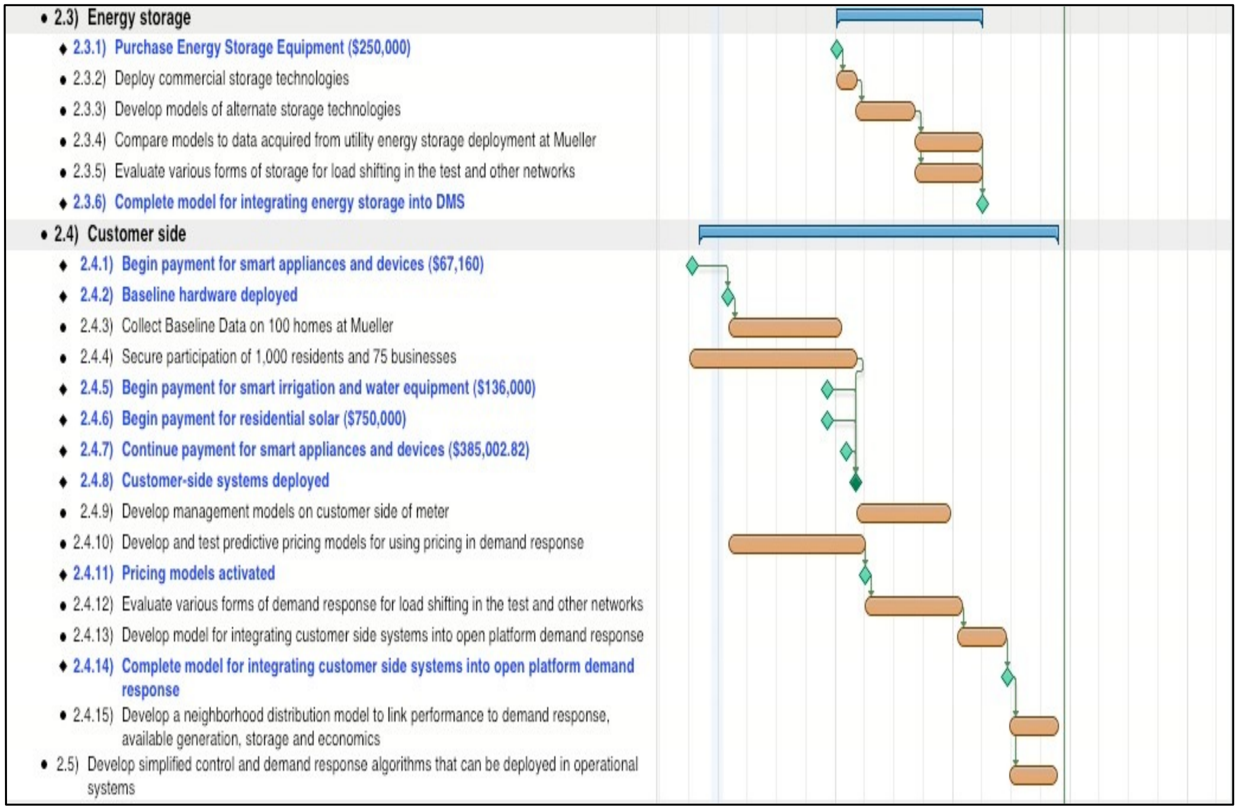
Appendix A: Pecan Street Integrated Schedule

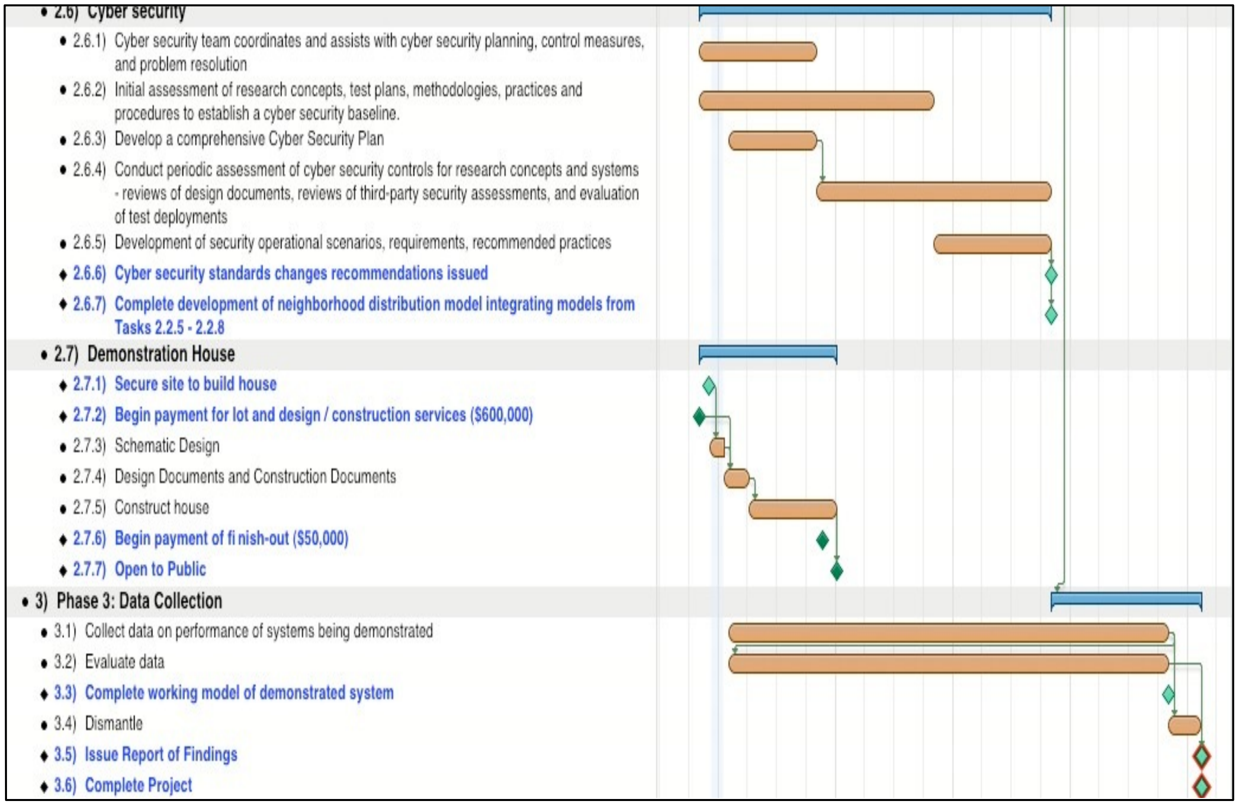


Task

- 1) Phase 1: Project Management and Planning
  - 1.1) Update Project Management Plan
  - ♦ 1.2) Complete updated PMP
  - ♦ 1.3) Complete Metrics and Benefits Plan
  - ♦ 1.4) Issue interoperability standards
- 2) Phase 2: Final Design and Construction
  - 2.1) Energy Internet Demonstration Planning
    - ♦ 2.1.1) Open RFI for vendors to propose technologies and solutions for integration in the deployment
    - ♦ 2.1.2) Close RFI period
    - 2.1.3) Analyze Responses, select preferred providers
    - 2.1.4) Engage in planning with selected providers
    - 2.1.5) Begin field testing of systems
    - 2.1.6) Install selected systems in volunteer participants' premises
    - ♦ 2.1.7) Go live on customer-side systems
  - 2.2) Model integration of distributed generation
    - ♦ 2.2.1) Begin payment for utility-scale solar array equipment ($287,500)
    - 2.2.2) Design and construct utility-scale solar at Mueller
    - 2.2.3) Model integration of distributed generation
    - ♦ 2.2.4) Complete model of distributed generation
    - ♦ 2.2.5) Payment for PEVs and PEV charging ($500,000)
    - 2.2.6) Deploy PEVs and PEV charging
    - 2.2.7) Model PEVs and PEV charing
    - ♦ 2.2.8) Complete model and test control algorithm for PEV charge management



- 2.3) Energy storage
  - ♦ 2.3.1) Purchase Energy Storage Equipment ($250,000)
  - 2.3.2) Deploy commercial storage technologies
  - 2.3.3) Develop models of alternate storage technologies
  - 2.3.4) Compare models to data acquired from utility energy storage deployment at Mueller
  - 2.3.5) Evaluate various forms of storage for load shifting in the test and other networks
  - ♦ 2.3.6) Complete model for integrating energy storage into DMS
- 2.4) Customer side
  - ♦ 2.4.1) Begin payment for smart appliances and devices ($67,160)
  - ♦ 2.4.2) Baseline hardware deployed
  - 2.4.3) Collect Baseline Data on 100 homes at Mueller
  - 2.4.4) Secure participation of 1,000 residents and 75 businesses
  - ♦ 2.4.5) Begin payment for smart irrigation and water equipment ($136,000)
  - ♦ 2.4.6) Begin payment for residential solar ($750,000)
  - ♦ 2.4.7) Continue payment for smart appliances and devices ($385,002.82)
  - ♦ 2.4.8) Customer-side systems deployed
  - 2.4.9) Develop management models on customer side of meter
  - 2.4.10) Develop and test predictive pricing models for using pricing in demand response
  - ♦ 2.4.11) Pricing models activated
  - 2.4.12) Evaluate various forms of demand response for load shifting in the test and other networks
  - 2.4.13) Develop model for integrating customer side systems into open platform demand response
  - ♦ 2.4.14) Complete model for integrating customer side systems into open platform demand response
  - 2.4.15) Develop a neighborhood distribution model to link performance to demand response, available generation, storage and economics
- 2.5) Develop simplified control and demand response algorithms that can be deployed in operational systems



- 2.6) Cyber security
  - 2.6.1) Cyber security team coordinates and assists with cyber security planning, control measures, and problem resolution
  - 2.6.2) Initial assessment of research concepts, test plans, methodologies, practices and procedures to establish a cyber security baseline.
  - 2.6.3) Develop a comprehensive Cyber Security Plan
  - 2.6.4) Conduct periodic assessment of cyber security controls for research concepts and systems - reviews of design documents, reviews of third-party security assessments, and evaluation of test deployments
  - 2.6.5) Development of security operational scenarios, requirements, recommended practices
  - ♦ **2.6.6) Cyber security standards changes recommendations issued**
  - ♦ **2.6.7) Complete development of neighborhood distribution model integrating models from Tasks 2.2.5 - 2.2.8**
- 2.7) Demonstration House
  - ♦ **2.7.1) Secure site to build house**
  - ♦ **2.7.2) Begin payment for lot and design / construction services ($600,000)**
  - 2.7.3) Schematic Design
  - 2.7.4) Design Documents and Construction Documents
  - 2.7.5) Construct house
  - ♦ **2.7.6) Begin payment of finish-out ($50,000)**
  - ♦ **2.7.7) Open to Public**
- 3) Phase 3: Data Collection
  - 3.1) Collect data on performance of systems being demonstrated
  - 3.2) Evaluate data
  - ♦ **3.3) Complete working model of demonstrated system**
  - 3.4) Dismantle
  - ♦ **3.5) Issue Report of Findings**
  - ♦ **3.6) Complete Project**

Appendix B: Derivation of Austin Energy's Grid Emissions Rate

This analysis estimates Austin Energy's grid electricity emissions rate to be 0.974792 lbs. CO2e/KWh, which equals 0.000487 short tons of CO2e/KWh and 0.000442 metric tons of CO2e/KWh.

The derivation of the numbers above stems from the *Austin Energy 2013 Annual Performance Report*. Austin Energy's average system carbon intensity is calculated as total greenhouse gas emissions at the point of combustion in pounds of CO_2-equivalents divided by the net generation in KWh from Austin Energy resources. Austin Energy generation resources include,

> "Natural gas, coal, and nuclear-powered units; renewable resources owned by Austin Energy; and purchased power from renewable and non-renewable resources. GreenChoice® energy sales are subtracted from the net generation total since GreenChoice® customers can claim their carbon intensity to be 0 lbs of CO2-equivalents/kWh."

The difference between the emissions rate reported here and the emissions rate reported by Austin Energy in its 2013 Annual Performance Report is that this calculation includes the GreenChoice electricity consumption, so that the grid emissions rate captures emissions for all energy consumed generated by Austin Energy.

For converting the CY 2013 and CY 2012 emissions rate to fiscal year (FY) 2013 emissions rates, the following formula was used, which proxies 3 months of 2012 and 9 months of 2013:

*(CY 2013 Emissions Rate)*0.75 + (CY2012 Emissions Rate)*0.25 = FY2013 Emissions Rate*

OR

*1.05*0.75 + 1.03*0.25 = 1.045 lbs. CO2e/KWh*

The calculation utilizes the above information as well as information, provided below, from from the *Austin Energy 2013 Annual Performance Report*:

- Total renewable energy (RE) purchased by AE in FY2013 was 2,656,952,000 kWh
- GreenChoice sales for FY2013 was 861,972,633 kWh
- The combined generation percentage of RE, nuclear, coal, and gas is 85.06%
- Total nuclear, coal, and gas generation for FY2013 was 8,256,118,000 kWh

To determine **total KWh of AE generation**, the following equation was used:

(100/85.06)((8,256,118,000 KWh from Nuclear, Gas, and Coal + 2,656,656,952,000 KWh from RE)) = **12,829,849,517.987 KWh**

To determine **total lbs. CO_2e from Austin Energy generation**, the following equation was used:

*1.045 lbs CO2e *(12,829,849.517987 MWh total generation – 861,972,633 MWh from GreenChoice) =* ***12,506,431,344.811 lbs. CO_2e***

Lastly, to solve for the **emissions rate**, the following equation was used:

(12,506,431,344.811 lbs. CO_2e from AE generation)/(12,829,849,517.987 kWh of total AE grid generation) = 0.974792 lbs. CO_2e/kWh, which equals 0.000487396 short tons of CO_2e and 0.0004421582135 metric tons of CO_2e