Human Decisions for the Wise Use of Energy

Precourt Energy Efficiency Center
Going Forward

May 24, 2016

Executive Summary

The Precourt Energy Efficiency Center (PEEC) was founded at Stanford University in October 2006 through a generous gift from Stanford alumnus Jay Precourt. PEEC is a research center dedicated to energy efficiency – economically efficient reductions of energy use.

> Learning to more effectively manage energy consumption at the individual, corporate, and government level is critical to our national security, to our environment, and to our economy. – JAY PRECOURT

MISSION

The mission of PEEC is to understand, analyze, and develop cost-effective and feasible policies, programs, technologies, and market structures that could enhance energy efficiency both within the United States and around the world.

The mission of PEEC differentiates it from other energy efficiency centers in that our primary emphasis is on the human forces at work in encouraging or inhibiting adoption of energy efficient technologies and practices, and only secondarily on technologies themselves. We emphasize those changes in human institutions, markets, regulations, incentives, communications, and other areas that can result in systematic changes in the ultimate choices that individuals, companies, or entire economies make, including choices to develop, adopt, or to utilize particular technologies.

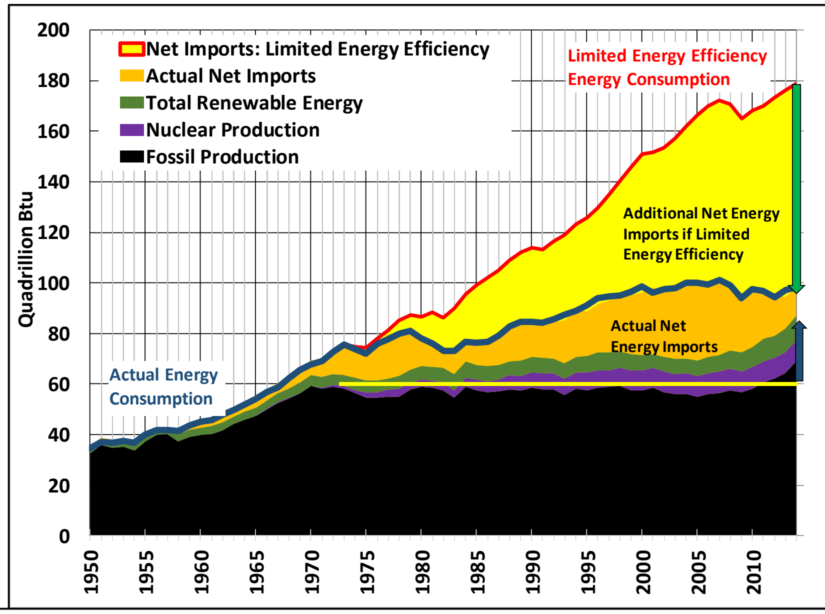
In short, PEEC focuses on human decisions for the wise use of energy.

WHY ENERGY EFFICIENCY?

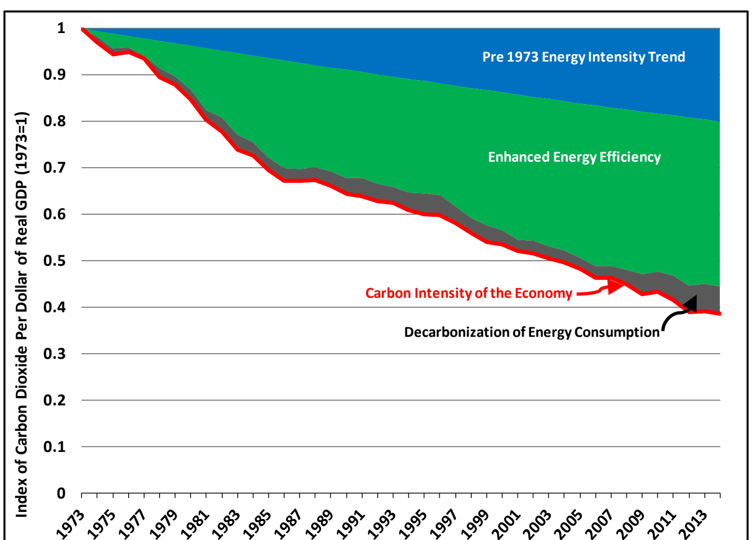
Energy efficiency benefits the environment by reducing air and water pollution and carbon emissions, benefits the nation's security by reducing dependence on foreign sources of fossil fuels, and benefits the U.S. economy by reducing cost of consuming energy.

Beginning with the 1973 oil embargo, there has been a cumulative process of energy efficiency improvements, reducing U.S. economy-wide energy intensity by 57% from 14,000 BTUs per dollar of GDP in 1973 to 6,000 BTUs per dollar of GDP in 2014 (2009 dollars).

As a result, net energy imports have declined to below their 1973 level. Although domestic energy production has increased, energy efficiency has reduced energy consumption by well over three times as much as has the increase in all forms of domestic energy production combined. Energy efficiency has put the United States on the road to net energy sufficiency, greatly enhancing security, as shown in the graph on the right.



U.S. Net Energy Imports: Actual vs. Limited Energy Efficiency
Green arrow: Enhanced Energy Efficiency; Blue: Domestic Supply



Factors Leading to Reduced Carbon Intensity of U.S.

Energy efficiency has also been dominant in reducing carbon dioxide emissions. The US data on carbon intensity is graphed from 1973 through 2014 in the chart below, in which data are normalized relative to 1973 levels. Here the pre-1973 energy intensity trend is shown as a blue area; impact of enhanced energy efficiency since 1973 is shown as a green area; and the impact of de-carbonization of energy consumption is shown as a gray area. The carbon intensity of the U.S. economy – carbon dioxide emissions per constant dollar of GDP – is shown by the red line.

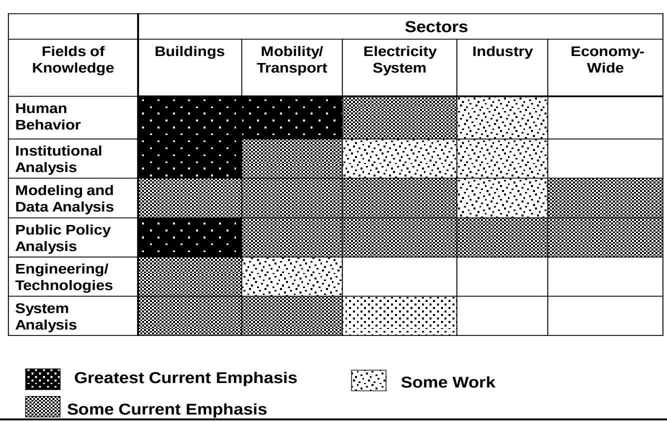
The carbon intensity of the economy has decreased 61%, to 39% of the 1973 intensity, driven primarily by the 57% reduction in U.S. economy-wide energy intensity (the green plus the blue areas). U.S. energy intensity reductions have been about nine times as important as all clean energy supply technologies put together in this de-carbonization of the U.S. economy.

The remarkable success of energy efficiency in bringing numerous economic, environmental, and security benefits to the United States has been in spite of the many barriers that inhibit full implementation of energy efficient actions. Barriers – all related to human choices – include market failures, institutional barriers, and behavioral issues. Overcoming these barriers has not proven easy, although there are important opportunities to enhance energy efficiency by overcoming these barriers.

The existence of these barriers, coupled with the remarkable history of energy efficiency, underlie the mission and approach of PEEC. We work to understand and overcome barriers in order to understand and develop cost-effective and feasible policies, programs, technologies, and market structures that could further enhance energy efficiency both within the United States and around the world.

PEEC RESEARCH

PEEC concentrates on six different areas: human behavior; institutional analysis; modeling and data analysis; public policy analysis; engineering/technologies; and systems analysis. PEEC works on the fundamental problem of overcoming the policy, behavior, technology, and market barriers to energy efficiency. The scope of past work at PEEC is illustrated by this matrix of the various fields of knowledge applied within the major energy-consuming sectors.



PEEC Research Emphasis Areas

Through collaborative approaches across disciplines, PEEC has made significant strides during the last ten years.

- 240+ Research publications
- A forthcoming book – *Energy Efficiency: Building a Clean, Secure Economy*
- 64 Funded projects
- 59 Graduate students
- 43 Affiliated Stanford faculty members

Several examples of this research are outlined below. More discussion of this research is available at http://PEEC.stanford.edu

RESEARCH EXAMPLES

Human Behavior: the choices people make and the motivations for those choices.	
Experiments with Appliance Choice - Knutson, Sawe, Sahoo	This work uses a combination of national econometric and psychometric surveys and neuroimaging behavioral experiments to study consumer purchases of energy-efficient products and the effect of the Energy Star label. The ongoing neuroimaging work has found that the Energy Star label activates the brain's "reward pathway", associated with positive emotions, in a similar (and additive) way to low prices.
Institutional Analysis: institutional, organizational, transaction cost, and behavioral economics, particularly as they relate to invention, commercial design, and adoption of energy efficient technologies.	
Supply Chain Design under Uncertain Production and Transportation Costs - Plambeck, Islegen	This research employs mathematical theories of stochastic dominance, monotone comparative statics, and optimization under uncertainty to derive insights on optimal facility location and design and address uncertainty in production and transportation costs, as well as investment in energy efficiency and renewable energy for managers and policymakers.
Modeling and Data Analysis: the development, assessment, and application of mathematical models for projecting the energy use under various conditions.	
Incentives and Politics of Utility-Based Energy Efficiency Programs in California - Sweeney, Eom	This research explores the implementation of utility-based energy efficiency programs that employ a shared-savings incentive mechanism and the interest-group politics of shaping the incentive mechanism. Analyses of the economic models offer two major policy implications for California energy efficiency programs: a higher-than-adopted incentive rate would achieve not only a greater net social benefit but also greater bill savings for customers; and social efficiency would be better achieved by customizing incentive mechanisms for individual utilities and updating them on a regular basis.
Public Policy Analysis: examination of policies that have been established in the public domain or those that could be established.	
Contributing to CARB's AB 32 Cost-Effectiveness Determination - Sweeney, Weyant, Chowdhary, Palavadi Naga, Chan, Sathe, Westersund, Gillingham, Guy, Lambie, Sudarshan	Researchers developed a marginal abatement cost curve for AB 32 interventions and successfully pushed the California Air Resources Board to do incremental analysis of the various policy options.
Engineering/Technologies: developing, testing, and deploying devices or other technologies that may lead to more efficient use of energy.	
Advanced Learning Automation - Aghajan, Khalili, Chen	This research looks at how automation can improve efficiency with minimal user input. The project built an automated light and TV control implementation using a network of wireless switches based on detecting the location of a user and their pose with a number of cameras. Investigators also developed a web-based user interface to capture the user's input about the automation setting and build a context-aware user profile, which was used to adapt the setting according to the user's preferences.
Systems Analysis: understanding and influencing the operation of a complex set of interacting parts.	
An Integrated Conceptual Design Process for Energy, Thermal Comfort, and Daylighting - Fischer, Haymaker, Welle	This research sought to reduce the time required to complete performance-based analysis methods supported by product models during the conceptual design phase. The research demonstrated that multidisciplinary analysis (MDO), a process which has been used heavily in the automotive and aerospace industries, can be applied to the architecture, engineering, and construction industry for CAD-centric energy and daylighting simulation on a large scale and within the time constraints typical of building conceptual design.

PEEC Core Activities

Six PEEC core activities support the basic mission and enable PEEC scholars to develop and transfer insights and solutions to industry, government, and academic communities in a way that would not be possible without the center.

1. **Research within PEEC.** PEEC includes a small long-term research staff, shorter-term visiting researchers, post-doctoral scholars, and graduate students that advance its research mission.

2. **Research within Stanford.** PEEC both draws from and contributes to the research activities of all seven schools of Stanford University as well those of our umbrella institution, the Precourt Institute for Energy.

3. **Education.** PEEC staff work with and advise post-doctoral, graduate, and undergraduate students in shared and separate research activities, while most PEEC-funded Stanford research teams also provide similar educational opportunities to the university community.

4. **Conferences**. PEEC fosters influential discussions of energy efficiency research and promotes potential and existing policy, behavioral, and technological solutions through strategic outreach activities, which include the Behavior Energy and Climate Change Conference, the Silicon Valley Energy Summit, and the Vail Global Energy Forum.

5. **International Collaborations.** PEEC promotes energy efficiency around the world. Activities include hosting visiting researchers, briefing international experts, and collaborating with researchers in many different countries.

6. **Energy Policy Analysis/Support.** PEEC works to analyze energy policy options and to support positive changes to policies at the international, U.S., state, and local level.

PEEC Future Goals

PEEC plans to strengthen and expand Stanford University's role as a global-leader in energy efficiency research by further developing and promoting its multi-disciplinary approach to understanding and addressing behavioral and economic barriers to implementing energy efficient policies, practices, and technologies at the local, national, and international scale. To achieve this vision, PEEC is committed to:

- **Expand research** into technology adoption, the future of transportation, demand-side management, energy use in various industries, and influencing of public policy to more fully embrace energy efficiency policies and practices.
- **Continue leadership** in the developing field of energy behavior.
- **Establish further ties with partners**, such as industry and government, to ensure a strong solutions-oriented focus and channels for impact. This would in part include continuing to collaborate on research and inviting speakers from outside academia, continuing to provide briefings to industry and policy makers, and increasing work with campus corporate affiliates programs.
- **Increase opportunities** for students, industry, and government to learn from, collaborate on, and apply PEEC research.
- **Increase global impact** through strategic international partnerships and a thriving visiting scholar program. The emphasis can be expected to be China and India, the two countries likely to have the biggest impact on global climate.
- **Provide intellectual and financial support** for graduate students and intellectual support for undergraduate students interested in the efficient use of energy from across the University.
- **Increase the impact on industry** through conferences such as the Silicon Valley Energy Summit and cutting edge focused workshops on specific topic areas.
- **Increase the impact on world-wide research and application of behavioral intervention** through the Behavior, Energy, and Climate Change (BECC) Conference. Expand the scope of BECC to include more energy efficiency behavioral interventions in corporations and other organizations.

By building on a decade of field-shaping research and a multi-disciplinary approach specifically developed to understand and address the most complex barriers to energy efficiency, Stanford will continue its leadership in energy efficiency research, in informing policy, in communicating with commercial and industrial businesses, and in education.

For more information on the Precourt Energy Efficiency Center, see:

http://peec.stanford.edu

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Precourt Energy Efficiency Center at Age 10

Established in October 2006, the Precourt Energy Efficiency Center (PEEC) (originally named the Precourt Institute for Energy Efficiency) was founded at Stanford University through a generous gift from Stanford alumnus Jay Precourt. PEEC is a research lab dedicated to energy efficiency – economically efficient reductions of energy use.

PEEC Mission

The mission of PEEC is to understand, analyze, and develop cost-effective and feasible policies, programs, technologies, and market structures that could enhance energy efficiency both within the United States and around the world. [1]

In pursuing this mission, PEEC works on the fundamental problem of overcoming the policy, behavior, technology, and market barriers to energy efficiency.

The mission of PEEC differentiates it from other energy efficiency centers in that our primary emphasis is on the human forces at work in encouraging or inhibiting adoption of energy efficient technologies and practices, and only secondarily on technologies themselves[2]. We emphasize those changes in human institutions, markets, regulations, incentives, communications, etc. that can result in systematic changes in the ultimate choices that individuals, companies, or entire economies make, including choices to develop, adopt, or to utilize particular technologies.

In short, PEEC focuses on human decisions for the wise use of energy.

PEEC Core Activities

Six PEEC core activities support the basic mission: research within PEEC, research within Stanford, education, conferences, international collaborations, and energy policy analysis/support. These activities enable PEEC scholars to develop and transfer insights and solutions to industry, government, and academic communities in a way that would not be possible without the center. We provide brief summaries of these activities below and more detail in a subsequent section of this document.

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[1] The PEEC mission statement has been sharpened since PEEC was first established. The mission statement has been: "… to advance the understanding of energy efficient behaviors, technologies, and markets in order to develop and identify cost-effective and economically deployable policies and technologies to improve energy efficiency both within the United States and around the world."

[2] An exception is the recently-organized E2e project, a joint initiative of University of California – Berkeley, the Massachusetts Institute of Technology, and the University of Chicago. The E2e project focuses on understanding the energy efficiency gap, and uses various evaluation strategies to measure and enhance the impact of energy efficiency initiatives.

Research within PEEC. PEEC includes a small long-term research staff, shorter-term visiting researchers, post-doctoral scholars, and graduate students that advance its research mission. They give PEEC the ability to understand the changing energy efficiency landscape, to identify where fundamental contributions are needed, and to determine what education and outreach activities could be most fruitful.

Research within Stanford. PEEC both draws from and contributes to the research activities of all seven schools of Stanford University as well those of our umbrella institution, the Precourt Institute for Energy. The complexity of energy use and energy efficiency makes such University-wide research particularly valuable. In particular, PEEC provides seed grants for faculty/student teams beginning new areas of energy research. PEEC has also been instrumental in obtaining external research grants to fund cross-Stanford research teams.

Education. PEEC contributes to the educational fabric of Stanford University in several ways. PEEC staff work with and advise post-doctoral, graduate, and undergraduate students in shared and separate research activities, while most PEEC-funded Stanford research teams also provide similar educational opportunities to the university community. PEEC encourages students to participate in the conferences it supports, to engage with its international collaborators, and to gain knowledge of the energy policy process through internships and outside events. In addition, PEEC hosts the Sustainable Mobility Seminar series where Stanford students can learn from academic and industry experts, as well as present original research.

Conferences. PEEC fosters influential discussions of energy efficiency research and promotes potential and existing policy, behavioral, and technological solutions through strategic outreach activities, which include the Behavior Energy and Climate Change conference, the Silicon Valley Energy Summit, and the Vail Global Energy Forum. Other venues for broad dissemination of PEEC research include major conferences, specialized workshops, and university presentations.

International Collaborations. PEEC invests in energy efficiency efforts around the world. Activities include hosting visiting researchers, providing briefings to international experts, and collaborating with researchers in many different countries.

Energy Policy Analysis/Support. PEEC works to analyze energy policy options and to support positive changes to policies at the international, U.S., state, and local level. PEEC has an important focus on California policy activities, and in particular on state regulatory policy governance.

Why Energy Efficiency?

Energy policy strives for improvement in the health and growth of the economy, protection of the domestic and international environment, and enhancement of domestic and international security. These three policy goals are summarized by the energy policy triangle. Energy efficiency – defined here as economically-efficient reductions in energy use – reduces the energy intensity of the economy – defined here as energy consumption per constant dollar of gross domestic product (GDP). Energy efficiency has beneficial impacts on all three vertices of the energy policy triangle.

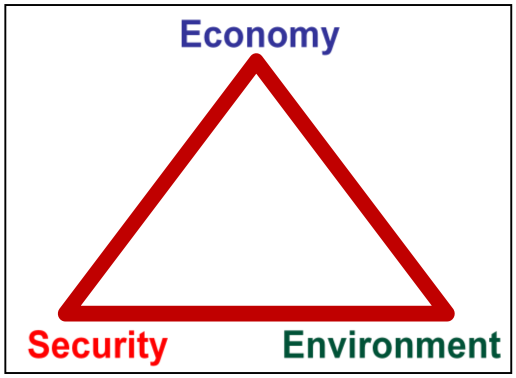

Figure 1 Energy Policy Triangle

Energy efficiency is beneficial for the environment: Reductions in energy use mean that less energy has to be produced, transported, or transmitted to meet human needs, thereby avoiding associated environmental damages. While scientists work to develop the low-carbon energy production technologies of the future to respond to concerns about global climate change, the largest reductions in greenhouse gases in the past and over the next few decades will come from more efficient use of electricity, oil, and natural gas.

Energy efficiency is valuable to national security. Energy use impacts several issues of U.S. security, including vulnerability to deliberate or accidental restrictions on oil imports, vulnerability to rapid fluctuations in energy prices, and limitations on foreign-policy options as a result of U.S. dependence on foreign energy sources. Advances in efficiency – more than domestic energy supply increases – have allowed the U.S. to reduce energy imports so that the nation may soon become self-sufficient in energy.

Energy efficiency is advantageous for the aggregate economy. Reductions in the government's use of energy can provide savings for the federal government, reduce the federal deficit, and reduce the trade deficit. Cost-effective reductions in the use of energy by businesses can make them more profitable and thus increase GDP. Cost-effective reductions in the use of energy by households can leave them with more disposable income available for other purposes.

In sum, energy efficiency – economically-efficient reduction in energy use – benefits the environment by reducing air and water pollution and carbon emissions, the nation's security by reducing dependence on foreign sources of fossil fuels, and the U.S. economy by reducing energy consumption per constant dollar of GDP. Quoting from Secretary George Shultz: "What is the cleanest energy around? The energy that is not used. What is the least expensive energy around? The energy that is not used. What is the most secure energy around? The energy that is not used. So energy efficiency is a triple play."

What Has Energy Efficiency Accomplished in the United States?

Since the oil embargo in 1973, individuals, corporations, and other organizations have found ways of economically reducing energy use, so that energy efficiency is now all around us. For example, a high-quality LED light bulb uses only 11 watts to provide the same amount of light as a 60-watt incandescent lamp. A refrigerator purchased today uses less than a third of the energy used by a 1973 refrigerator. New cars get about twice the mileage of cars on-the-road in 1973. Air travel uses about one quarter as much fuel per passenger mile as in 1970. Companies have adopted data-driven methods for finding energy inefficiency and for reducing energy use. These are but a few examples of energy efficiency changes all around us.

These changes together have been part of a slow cumulative process of energy efficiency improvements since the 1973 energy crisis. Starting then, annual changes in energy intensity of 2.7% or 1.7% per year accumulated over four decades, reducing U.S. economy-wide energy intensity by 57% from 14,000 BTUs per dollar of GDP in 1973 to 6,000 BTUs per dollar of GDP in 2014 (both figures in 2009 dollars).

Impacts of energy efficiency and of domestic energy production changes are quantified in Figure 2 which plots U.S. energy consumption, domestic supply, and net imports of primary[3] energy from 1973 through 2014. The red curve shows what energy use would have been under the pre-1973 trends; the blue line shows the actual energy use.

The difference between total energy used (the blue line) and total domestic supply of energy (the black, purple, and green areas) gives net energy imports. Actual net energy imports are shown as an orange area and the net energy imports under the under the pre-1973 trends are shown as the yellow area plus the orange area, given the actual levels of domestic primary energy production.

Net energy imports have declined to just below the 1973 level. While domestic energy production from all U.S. sources combined has increased, increases in efficiency have reduced consumption of energy from what it would have been by well over three times the increase in all forms of domestic energy production. Energy efficiency has put the United States on the road to net energy sufficiency, greatly enhancing security.

[3] Much more detail is in the forthcoming book, *Energy Efficiency: Building a Clean Secure Economy*, by James Sweeney, to be published by the Hoover Institution Press, summer 2016.

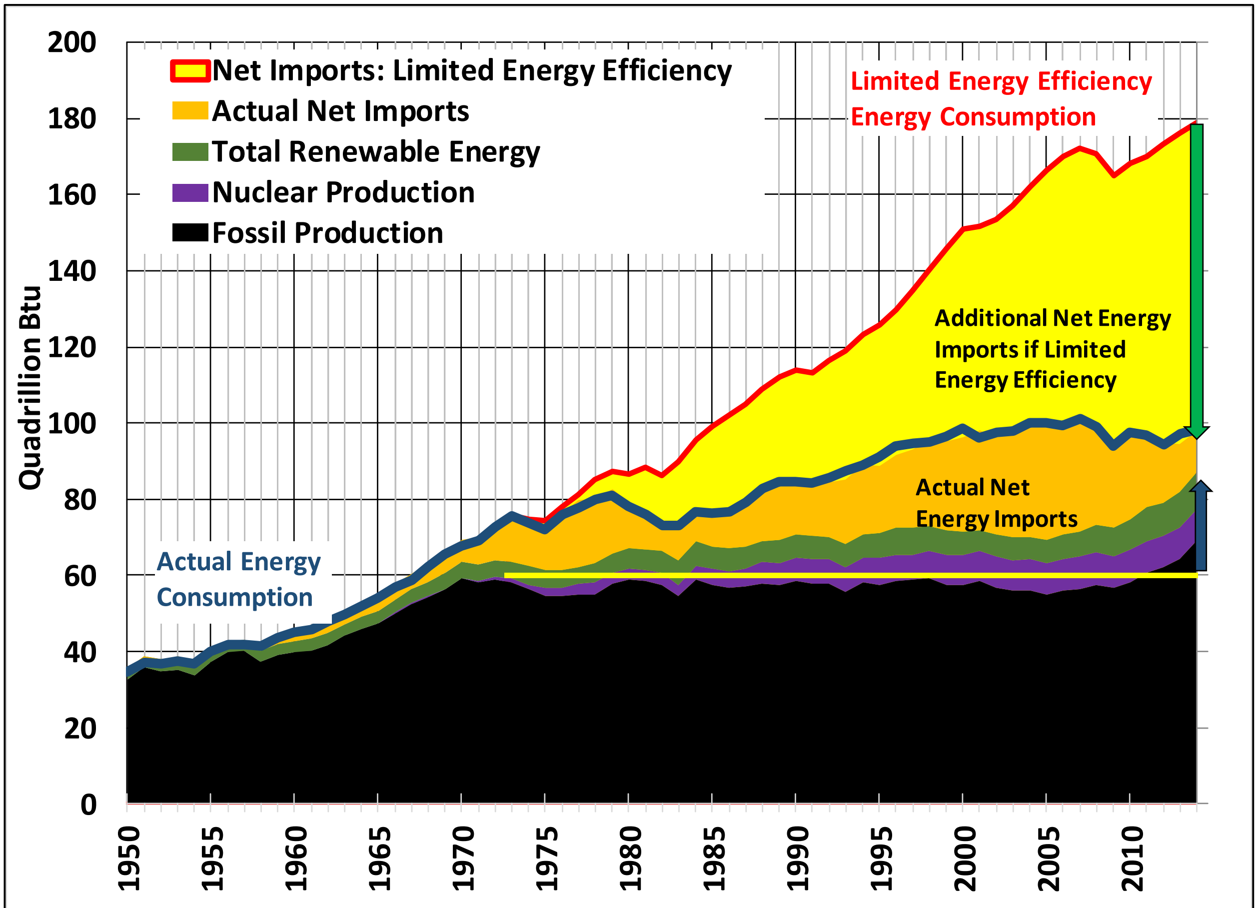

Figure 2. U.S. Net Energy Imports: Actual vs. Limited Energy Efficiency
Green arrow: Enhanced Energy Efficiency; Blue: Domestic Supply Increase

Energy efficiency has also been dominant in reducing carbon dioxide emissions. The carbon intensity of the economy—carbon dioxide emissions per constant dollar of GDP—is the product of two factors: the carbon intensity of energy consumption and the energy intensity of the economy.

Normalized relative to 1973 levels, U.S. data are graphed from 1950 through 2014 in Figure 3. This graph shows the percentage change in carbon intensity of the economy from 1973 decomposed into the three components: the pre-1973 energy intensity trend, shown as a blue area, impacts of enhanced energy efficiency since 1973, shown as a green area, and impacts of de-carbonization of energy consumption, shown as a gray area. These three factors taken together have reduced carbon intensity of the U.S. economy to 39% of its 1973 intensity, as shown by the red line, labeled “Carbon Intensity of the Economy.”

Since 1973, U.S. energy intensity reductions (the green plus the blue areas) have been about nine times as important as have reductions in carbon intensity of energy consumption for reducing the carbon intensity of the economy. Enhancements in energy efficiency have been about six times as important as reductions in carbon intensity of energy consumption for decarbonizing the U.S. economy.

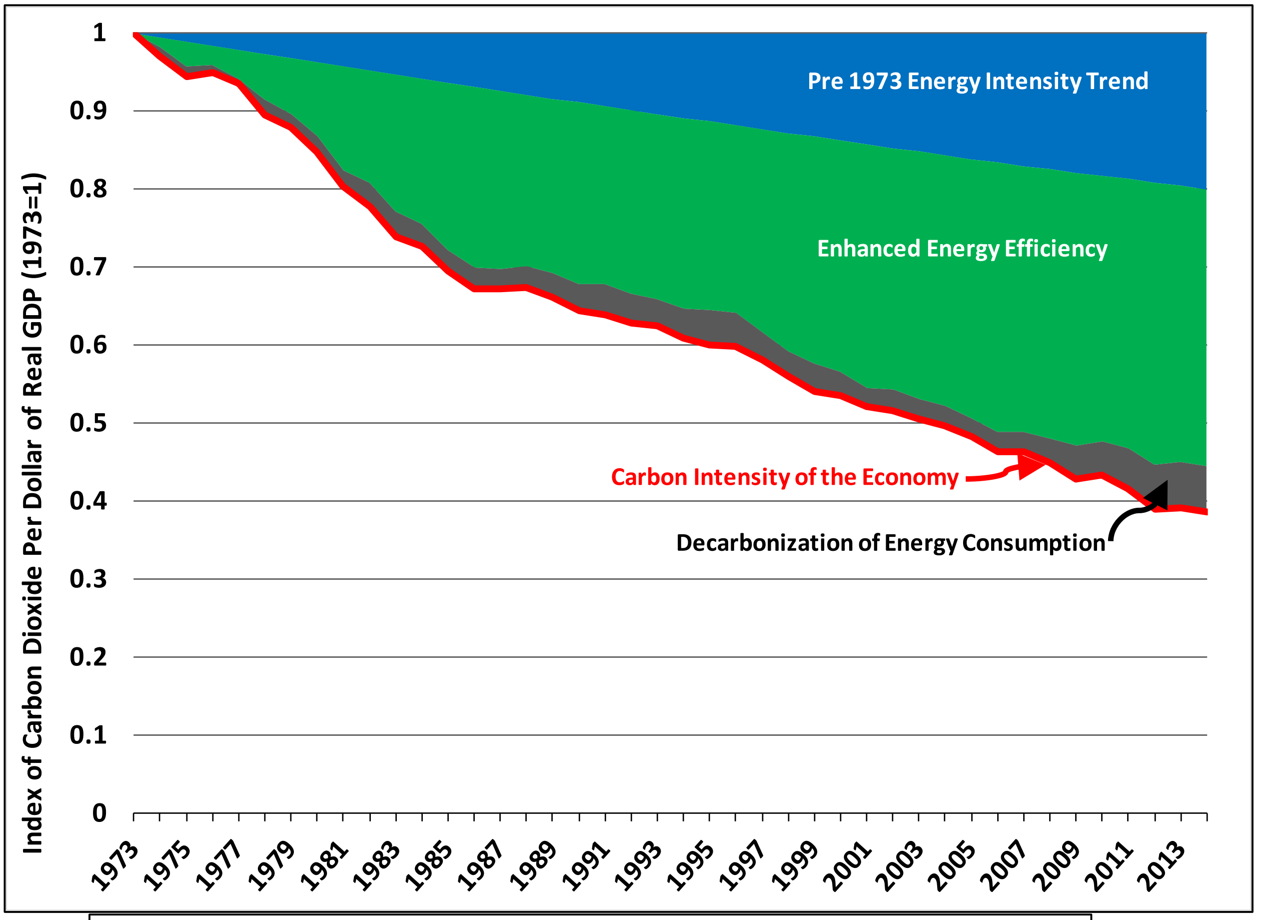

Figure 3. Factors Leading to Reduced Carbon Intensity of U.S. Economy

Barriers to Energy Efficiency

Even with its many economic, environmental, and security benefits, numerous barriers, inhibit full implementation of energy efficient actions. Many energy options are not chosen even though they appear to be desirable to the individual or organization making the decision. These are often discussed informally as “unpicked fruit” or “fruit rotting on the tree.” More formally, the failure to choose such optimal energy options is referred to as the “energy efficiency gap.” The barriers to uptake of energy efficient options – all part of human choices – can be summarized in terms of market failures, institutional barriers, and behavioral issues. Some of these barriers are listed in Table 1 below.

There is both good news and bad news regarding the barriers to energy efficiency. The bad news is that fixing these issues has not proven easy. The good news is that there are opportunities to enhance energy efficiency by overcoming these barriers. Some opportunities depend on the human choices of technological developments by the private sector, by universities, and by governmental labs. Other opportunities depend on better government policies. And still others depend on changes in human choices motivated by changing information, beliefs, incentives, and institutional structures and policies.

Market Failures
Market power of makers of existing technologies
Externalities: in Use
Spillovers: R&D and Learning-by-doing
Principal/Agent Problems (Split Incentive Problems)
Transaction Costs in Efficiency Markets
Network externality: Complementary Products Requiring Large Non-Recoverable Investments
Institutional Barriers
Fragmented Structure of Construction industry
Limited Modeling Tools for Building Design
Corporation Organization (energy as overhead)
Limited Energy Information & Control Systems
Distortionary Regulatory & Fiscal Policies (e.g. obsolete building codes)
Local Governmental Land Use Institutions (e.g. zoning or transport decisions)
Behavioral Issues
Low Salience of Energy Issues.
Transaction Costs: Efficiency Upgrades, Determining Optimal Purchases
Limited Cognitive Skills
Poor Information about Electricity Prices
Poor Information about Equipment/Appliances Energy Use
Incentives and Priorities for Managers
Limited Feedback: Energy Choices to Outcomes

Table 1. Some Barriers to Optimal Energy Use

The existence of these barriers underlies the mission and approach of PEEC: We work to understand and overcome these barriers in order to understand and develop cost-effective and feasible policies, programs, technologies, and market structures that could further enhance energy efficiency both within the United States and around the world. Understanding these barriers has been fundamental to determining the PEEC areas of emphasis.

PEEC Emphasis Areas

Out of the large area of inquiry encompassed by PEEC's mission, the center emphasizes particular research areas based on several criteria, including: (1) an understanding of the significance to energy use of overcoming specific barriers to optimal energy use; (2) an assessment of the limitations of activities conducted elsewhere; and (3) knowledge of what can be done successfully at Stanford. The resulting areas of emphasis can be best described in terms of the fields of knowledge employed at PEEC and of the energy consuming sectors to which these fields of knowledge are being applied.

Emphasis Areas: An Overview

The scope of past work at PEEC can be illustrated by a matrix, Figure 4, of important fields of knowledge as applied to energy-consuming sectors. These fields of knowledge and consuming sectors are each discussed more fully below, with more specific contributions and impacts detailed in Appendices A and B.

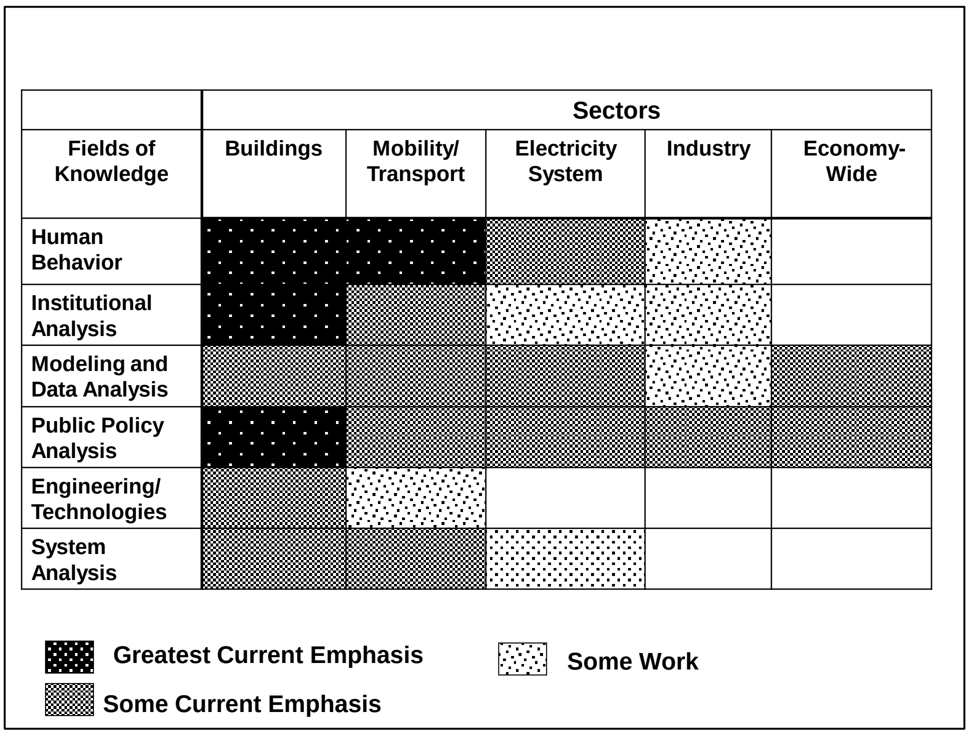

Figure 4. PEEC Research Emphasis Areas

Figure 4 uses shading to show the emphasis, to date, in PEEC. The darkest shading is for areas of the greatest current emphasis – human behavior applied to buildings and to mobility/transport, and institutional and public policy analysis as they relate to buildings. The medium shading is for areas of moderate emphasis, including public policy analysis and modeling and data analysis as applied to most sectors. The lightest shading is for areas in which PEEC has sponsored or conducted some work, while areas with no shading are ones that we have yet to place substantial emphasis. Going forward, the shaded areas are those that we expect to continue to emphasize.

Fields of Knowledge

We can think of the many requisite fields of knowledge for "to understand, analyze, and develop cost-effective and feasible policies, programs, technologies, and market structures that could enhance energy efficiency" as grouped into six different areas related to the PEEC mission:

- Human Behavior
- Institutional Analysis
- Modeling and Data Analysis
- Public Policy Analysis
- Engineering/Technologies
- Systems Analysis

Human behavior includes the choices people make and the motivations for those choices. According to PEEC, behavior, contrary to narrow definitions formalized by utilities related to habits such as turning off lights, includes any actions or decisions requiring humans. Examples include purchasing, installing, and correctly using technologies; implementing settings on timers or control devices (e.g., thermostats), performing maintenance, among others. Human choices can be influenced by economic incentives, markets, institutional structures, available technologies, attitudes, information, values, habits, nudges, or other behavioral interventions. Furthermore, human behavior includes choices people make as they decide what products to buy, what tradeoffs they are willing to make in the products, how much to utilize those products, and how much information to gather in making those choices.

One critical component in understanding why energy is used inefficiently is insight into human behaviors that control its use. Behavioral sciences can contribute a wealth of information. By investigating why certain populations make decisions, what barriers and incentives exist to persuade people to be more or less efficient users of energy, and what historically has made a significant difference in successfully modifying those human choices, PEEC researchers are enabling the creation and adoption of energy saving practices and technologies.

Human behavior focuses most sharply on people. This field of knowledge draws on neoclassical economics, behavioral economics, neural economics, social and cognitive psychology, anthropology, sociology, marketing, and medical practice. Broadly defined, human behavior related to energy use has been the area of greatest emphasis in PEEC and will continue to command such attention. This is because: 1) It is a field of knowledge that is important for understanding and encouraging energy efficiency, 2) it has not commanded sufficient research attention elsewhere, and 3) it can be done successfully at

Stanford because of the broad range of resources available and the interdisciplinary attitudes among many faculty, staff, and students.

Institutional analysis is an umbrella term we use to refer to such (related) interdisciplinary areas as institutional, organizational, transaction cost, and behavioral economics, particularly as they relate to the invention, commercial design, and adoption of energy efficient technologies. Drawing from definitions established by the Society for Institutional and Organizational Economics, we see institutional analysis as comprising "studies of governance mechanisms both at the organizational and at the institutional level" and "rooted in economics but open regarding research methodology, as long as the methodology is based on logic and thereby produces falsifiable results."

Institutional analysis is a newer area of emphasis in PEEC and one that will be expanded in the future. Like human behavior, 1) it is a field of knowledge that is important for understanding and encouraging energy efficiency, 2) it has not commanded sufficient research attention elsewhere, and 3) it can be done successfully at Stanford because of the broad range of resources available and the interdisciplinary attitudes among many faculty, staff, and students.

Modeling and Data Analysis includes the development, assessment, and application of mathematical models for projecting the energy use under various conditions. It includes statistical studies of electricity use load patterns over time by various classes of customers and econometric studies of how changing conditions influence use of energy. At a national level it includes study of the time changes in energy intensity of the entire economy.

Developing meaningful solutions to pressing energy efficiency issues often involves forecasting future demand for electricity, natural gas and oil in order to understand the potential impact of technological and policy innovations. One of the challenges in designing policies, as opposed to other types of design and engineering is that it is difficult to run relevant experiments at the state, national, and international scales necessary for useful simulations. Therefore, evaluations of the effectiveness of policy designs have been limited to assessing the effectiveness of policies implemented in the past. However, in a rapidly changing sector including new technologies and policy instruments, its critical to be able to test policies and run these experiments without having to wait years or decades to assess outcomes. Energy policy modeling gives us the ability to do just that. With accurate energy policy models, we can design, evaluate, and understand novel energy policy approaches and the impact of energy technologies currently under development through simulations and studies.

At Stanford, the Energy Modeling Forum (EMF) provides a nexus for examining many of these models and using them to analyze energy policy and planning issues. Professor John Weyant, Deputy Director of PEEC, and Hillard Huntington of the EMF bring a wealth of knowledge about existing energy policy models, including those developed in the U.S. and throughout the world. Professor Weyant is the deputy director of PEEC and links the center to the larger energy modeling community.

Modeling and data analysis will continue as an area of significant emphasis. This is because 1) it is a field of knowledge that is important for quantifying energy efficiency, 2) it is an area of research that is being done elsewhere, but there is still much to be done 3) it can be done successfully at Stanford because of the strong capabilities in economics, statistics, and other mathematical sciences and because of the long-term presence of the Energy Modeling Forum and its associated community.

Public Policy Analysis includes examination of policies that have been established in the public domain or those that could be established – with the goal of improving policies and facilitating the dissemination of those determined to be effective. This broad category includes federal governmental policies such as fuel efficiency standards for automobiles, refrigerators, or other appliances, and federal procurement policy. It includes taxes, cap-and-trade programs, and subsidies that may influence energy use. Public policy can be set at the national level (e.g. CAFE standards for automobiles), at the state level (e.g. building codes, California carbon standards for automobiles, or utility incentives), at the local level (e.g. local efforts to encourage energy efficiency or local choices on enforcing building codes as it issues building permit), or even at the international level (e.g. international trade policy.)

Public policy analysis draws heavily from each of the fields described above. Principled public policy analysis depends on a strong analytical underpinning, requiring deep understanding of human behavior, as influenced by economic and other motivations, of the institutions shaping human choices, and of the systems being influenced.

Quantitative understanding of the implications of public policy requires modeling and data analysis. Public policy analysis has been a large area of emphasis and continues to command attention from many of the PEEC faculty, staff, and students. This is because: 1) public policy is a field of knowledge that is important for encouraging or discouraging energy efficiency, 2) public policy implementation is often not based on a strong analytical underpinning, and 3) policy analysis can be done successfully at Stanford because of the broad range of resources available and the interdisciplinary attitudes among many faculty, staff, and students.

Engineering/Technologies involves developing, testing, and deploying devices or other technologies that may lead to more efficient use of energy. They could include optimization algorithms to determine when electricity is used and when gasoline is used for a plug-in electric vehicle, or sensor networks that determine room occupancy and optimally adjust the heating and lighting system to account for changing conditions. They also include the development of web applications and supporting platforms; collection of sensor data which enables our group and others beyond the Stanford community to develop algorithms, insights into behavior patterns that inform program and policy development, and novel user feedback and program evaluation approaches;

interdisciplinary work to assess the impact, feasibility, and critical next steps of novel technologies such as electricity disaggregation (this work resulted in 30,000 paper downloads the first year and spawned biannual workshops and significant research and development); funding for engineering technologies such as heat scavenging devices that capture waste heat from automobile engines; and the generation of outside-the-box energy saving alternatives to everyday practices and technologies as informed by anthropology and design work.

PEEC will continue work that interfaces engineering and technology with analytics, policy, behavior, and other areas of PEEC expertise, and aims to augment its work on technology adoption. Basic engineering and technology advances are important for increasing energy efficiency, but this will remain a relatively small area of research at PEEC given much work is already being conducted elsewhere at Stanford (e.g., GCEP, TomKat Center, SIMES), in other energy efficiency centers (e.g. UC Davis, UC Santa Barbara), and in companies that are highly concentrated in the Bay Area due to the ground breaking technology, policy, and investment climates here (e.g., start-ups, corporate research centers, and also manufacturing facilities like Tesla). However, being in the heart of this energy engineering and technology hub provides PEEC unparalleled opportunities for leveraging future trends, collaboration, and impact.

Systems Analysis includes understanding and influencing the operation of a complex set of interacting parts. For example, mobility choices are influenced by the entire transportation system, including the existence of public transport, the coordination between buses, trains, subways, and airports. In buildings, the operations of an HVAC system depend on the human responses to the system and the subsequent building adjustments. Our work under the ARPA-E grant focused on the interaction between technology (sensors, data, feedback, etc.) and behavior, examining the possible consequences of these interacting elements. Systems analysis often becomes a process of pulling together the “big picture” of the consequences of human behavior, institutions, policy, and technologies, often involving quantitative modeling and data analysis.

This area overlaps greatly with each of the other fields of knowledge and is relies heavily on research from all of the other fields. Thus in many cases the efforts in this field are derivative of the other fields of knowledge. Therefore, the relative emphasis on this area will depend on the specific research conducted by the PEEC community and by the external organizations with which we interact.

Energy Consuming Sectors

A second dimension of our focus is in terms of the sectors in which energy is used. These data are shown in the following figure. The four consuming sectors – residential, commercial, industrial, and transport – are shown in different colors. Within a sector, solid colors denote the amount of primary energy used directly; the lighter color within a sector denotes the amount of primary energy used to generate the electricity used by that sector.

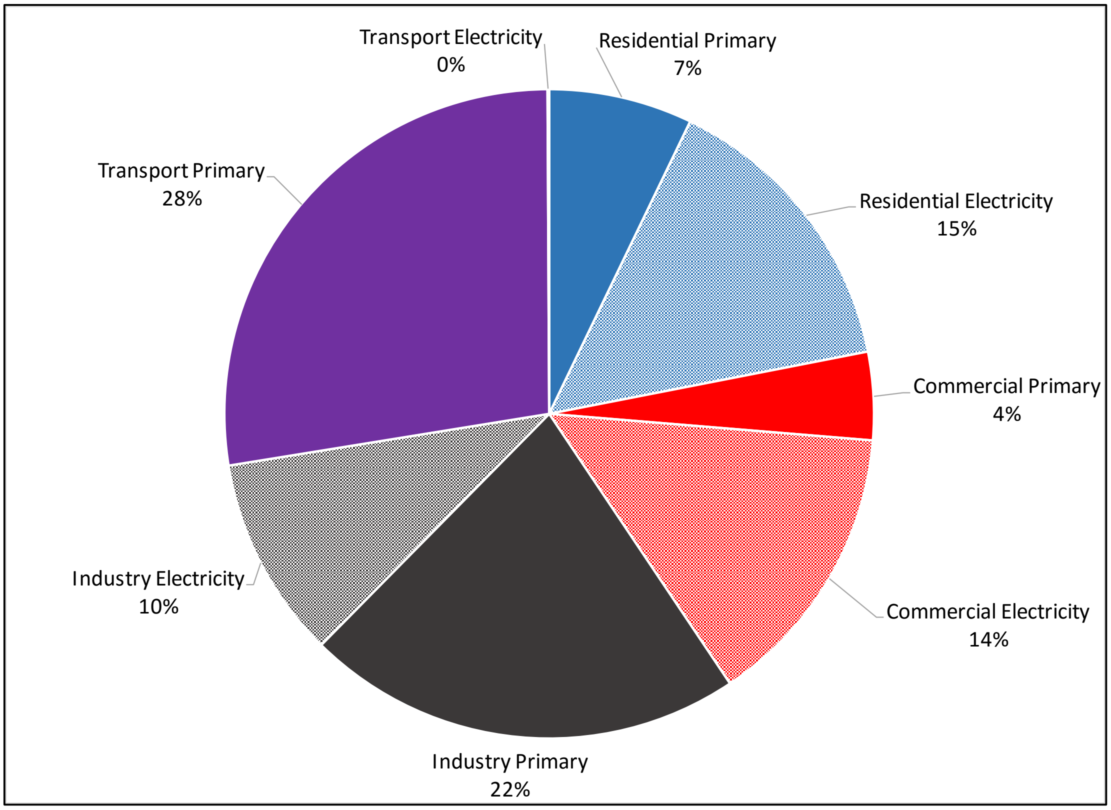

Figure 5 Consumption of Energy in the United States: 2014

This graph shows that energy used by the residential sector and the commercial sector. That is, energy used within buildings accounts for 40% of the total energy consumption in the United States. Within buildings, electricity is used dominantly through electricity (29%) and only a small amount of primary energy is used directly (11%).

Given the important role of energy used within buildings (including the appliances and electronics within the buildings), PEEC has placed a primary research emphasis on energy use in buildings, for both the residential and commercial sectors. This work has included, or will include, research on commercial and residential building design, construction, operations, embedded technologies, appliances, and connectivity among equipment (e.g., the internet of things), and connectivity among sectors (e.g. rooftop photovoltaics, behind-the-meter batteries, and electric vehicles.)

This graph shows that energy used by the transport sector – dominantly highway transportation and secondarily air transportation – accounts for 28% of the energy in the United States. This is almost entirely used directly as primary energy; only a miniscule amount is used as electricity.

Given the important role of energy used in transportation, PEEC has placed a significant emphasis on this sector, primarily on personal mobility and only minimally on freight transport. This work has included research on electrification of passenger cars and light duty trucks; new business models in the transportation system; efficiency through connectivity/automation; role of fuel efficiency standards in light duty vehicles. This area deserves more emphasis in the future. The graph also shows that almost one third of U.S. energy is used in the industrial sector, with the greatest amount (22%) used directly as primary energy and a smaller amount used through electricity (10%).

However, PEEC has put far less attention on the industrial sector. The industrial uses of energy are extremely heterogeneous. PEEC has been able to include some work on particular functions, e.g. supply chain management, but it is difficult to cover the industrial sector with only a limited number of researchers. In the future, PEEC plans to expand its emphasis in this sector for select high-impact areas.

Within the various sectors, about 39% of the energy is used through electricity. PEEC research directly relates to building and transportation use of electricity. PEEC has done work on system reliability and systems-level linkages and tradeoffs, primarily on real time metering and feedback as well as the electrification of vehicles. Other work on grid optimization and control is being conducted through other organizations at Stanford (e.g. the TomKat Center and the Bits and Watts initiative), which also involve collaborations with PEEC researchers. PEEC has not focused a large fraction of attention on the efficiency of the electric distribution system, though significant advances in efficiency may be possible at this stage as well. In the future, PEEC will continue to focus on the end-use of electricity rather than the electricity generation and distribution sector.[4]

PEEC Accomplishments

Through collaborative approaches across disciplines, PEEC has made significant strides during the last ten years. In summary, PEEC research has led to:

- 240+ Research publications
- A book forthcoming in August 2016 – *Energy Efficiency: Building a Clean, Secure Economy*

[4] However, Dian Grueneich is participating in the Bits and Watts initiative.

- 64 Funded projects
- 59 Graduate students
- 43 Affiliated Stanford faculty members

These accomplishments are discussed in more depth in subsequent sections of this document. The section “PEEC in More Depth” describes Research within PEEC, Research within Stanford, Education, Conferences and Workshops, International Connections, and Policy Analysis and Advocacy.

Appendix A provides a multiple-page table of the various seed grants and funded projects from PEEC, which details the research area, research description, year of funding, and the investigators and partners of each project.

Appendix B gives seventeen examples of past PEEC projects, describing these projects in much more depth than would be possible in the tabular form of Appendix A.

Appendix C lists 240 of the publications that we have been able to identify to date from the various PEEC projects.

We turn now to the vision of PEEC going forward for the next five years.

Precourt Energy Efficiency Center: The Next Five Years

In the coming five years, PEEC is committed to strengthening and expanding Stanford University’s role as a global-leader in energy efficiency research by further developing and promoting its multi-disciplinary approach to understanding and addressing behavioral and economic barriers to implementing energy efficient policies, practices, and technologies at the local, national, and international scale.

Strategic Goals for 2016-2021

To achieve this vision, PEEC is committed to achieving the following strategic goals:

- Our analysis has identified what we see as the highest impact areas of future work in energy efficiency and we have used this to guide the center’s research portfolio. Some of these high impact areas will include technology adoption, the future of transportation, demand-side management, energy use in various industries, artificial intelligence, and influencing of public policy to more fully embrace energy efficiency policies and practices.
- Continue the center’s leadership in the developing field of energy behavior.
- Establish further ties with real world partners, such as industry and government, to ensure a strong solutions-oriented focus and channels for impact. This would in

part include continuing to collaborate on research and inviting speakers from outside of academia, continuing to provide briefings to industry and policy makers, and increasing work with campus corporate affiliates programs and the Office of Technology Licensing.

- Increase the opportunities for students, industry, and government to learn from, collaborate on, and apply PEEC research.
- Increase global impact through strategic international partnerships and a thriving visiting scholar program. The emphasis can be expected to be China and India, the two countries likely to have the biggest impact on global climate.
- Provide intellectual and financial support for graduate students and intellectual support for undergraduate students interested in the efficient use of energy from across the University.
- Increase the impact on industry through conferences such as the Silicon Valley Energy Summit and cutting edge focused workshops on specific topic areas, such as we have done with energy feedback devices, and energy disaggregation.
- Increase the impact on world-wide research and application of behavioral intervention through the Behavior, Energy, and Climate Change (BECC) conference. Expand the scope of BECC to include more energy efficiency behavioral interventions in corporations and other organizations.

By building on a decade of field-shaping research and a multi-disciplinary approach specifically developed to understand and address the most complex barriers to energy efficiency, Stanford can continue its leadership in energy efficiency research, in informing policy, in communicating with commercial and industrial businesses, and in education.

Key Areas for Expanded Research

In addition to continuing the research areas that have been described above, there are several areas that we intend to expand during the next five years. These are described in what follows.

Energy Efficiency and Behavior

PEEC is about human decisions for the wise use of energy. The Center is an established world leader for the study of energy efficiency and behavior. In the near future we will expand our work in this area, collaborating more with the economic and psychology department faculty and heightening the scope and profile of the BECC conference to further influence the conversation about why decisions are made and what can lead us to a more efficient and effective energy future.

We expect to pursue several specific focus areas described below. If successful, these could serve as capstone projects for residential behaviorally oriented energy efficiency work. The first area aims to develop maximally effective diffusion and adoption channels, the second aims to develop new more energy efficient products and practices that could be spread through those channels (in addition to standard energy efficiency products and practices), and the third aims to package and disseminate learnings across these and the full span of behavior work performed over the past decade at PEEC.

We plan to leverage the ARPA-E Integrative Project for widespread energy savings as well as running experiments at scale, in order to accumulate and disseminate energy behavior and evaluation learnings and best practices. Through the ARPA-E Integrative Project, we have developed a web application that currently has about 1,000 national users per month and an equal number of international users; we aim to increase users in the coming months through product revisions, additional diffusion approaches, and advertising and website optimization. The application cuts to the chase of getting energy savings, by identifying the biggest bang for the buck actions, triaging users, articulating steps, and overcoming barriers (e.g., prepopulating order forms). Further, we incorporate behavioral economic nudges, and narrative, which have both been shown to have large impacts on behavior change in the real world. The goal of future work is to (a) Achieve widespread use of the app and meaningful energy savings, (b) Use it to run behavioral experiments at a scale not yet performed, and share findings and best practices with industry, utilities, and others, (c) Develop and test innovative diffusion approaches (we have culled a list of about ten approaches across advertising firms and industries), (d) Develop innovative evaluation approaches (e.g., matching application click data with smart meter data to ascertain the energy saving impact of specific actions), and (e) Explore extending the platform beyond the residential into the commercial sector.

Second, we plan to pursue work in design and behavior, to help facilitate the development of energy saving products. This work will potentially include three projects: (a) The first includes the completion of a paper that surveys innovations across cultures and throughout history to achieve everyday needs (such as thermoregulation, cooking, and food preservation), as these needs are consistent with ours today but historically have used much less energy. An example from ancient Korea is the underfloor radiant heating system that utilized heat secondary to cooking and retained it through the thermal mass of floor stones. We categorize the innovations based on energy saving principle, then have building scientists quantify energy savings potential if the principle were adapted to our culture. This guides the selection of which innovations are highest impact, and these can be used to facilitate design sessions with professional designers e.g., IDEO and Other Labs) or Stanford students (e.g., in a maker space in Roble dorm), and if designs prove promising we could then explore commercial partnerships. (b) The second project would be implemented as an experiment embedded within the design sessions in the first project - it would investigate how to best 'set up' the design sessions to increase innovative outcomes. (c) The third project relates to improving the energy efficiency of housing stock by making smaller living spaces more feasible thereby enabling wider adoption.

Third, we will perform additional work in education and dissemination of learnings. BECC is a marketplace of ideas and work in the behavior and energy space, but there is great value and it is an apt time to consolidate and organize findings from our learnings over the past decade. The intent is to develop a year-long course to train students and also professionals (e.g., at utilities and in industry) to apply behavior change techniques and methodologies to program development. Academically oriented findings would only be a part of the coursework; other work would include procedures for scoping and developing high impact programs, pragmatic learnings related to implementation and logistics, incorporating and working with creatives (e.g., advertising and video developers), and learning and leveraging modern diffusion channels (e.g., Google Adwords). This work would be implemented in both a regular classroom, as well as through a Google Hangout or Massive Open Online Course (MOOC) to enable it to reach audiences at scale and persist in the future (through recordings). To complement this work, we will also complete the behavior and energy review paper, and convert our California Energy Commission ARPA-E close out summary document to a journal article to achieve wider dissemination.

Demand Side Management

Demand side management includes both achieving greater efficiency and in shifting the time pattern of electricity loads without necessarily reducing the total use of electricity over time. PEEC has traditionally addressed the former – achieving greater efficiency – but has put less attention in the latter – shifting the time pattern of electricity loads. This demand-side-management of the time pattern of electricity loads will be an area of growing importance as more intermittent wind and solar electricity generation is incorporated into the grid. Such demand side management can be expected to allow a larger penetration of intermittent renewables than would be economically possible otherwise.

PEEC plans to expand on the work of Professor Ram Rajagopal to better understand smart grid data, why and how market demand-response and energy-efficiency programs work, and the demand-response potential in particular circumstances. This will help inform electric utilities which programs are reducing consumption during periods of very high demand or, in the case of efficiency, eliminating waste – in order to emphasize those programs compared to others, resulting in improved cost-effectiveness and energy savings.

This will require several fields of knowledge – human behavior, public policy, and modeling and data analysis. In addition, additional systems analysis and engineering /technologies will be required because people are likely to want to automate responses to demand-side-management interventions. Artificial intelligence may also be important for this automation.

Tech/Artificial Intelligence

In addition to increasing our emphasis in technology adoption, we plan to explore one new technology area: Artificial Intelligence (AI), in part as it interfaces with behavior and energy. AI is intelligence exhibited by machines or software, and has significant potential for transformational impact. Though AI has been around for a couple of decades, the increasing maturity of machine learning algorithms, the greatly improved cloud computing power in the last year which allows many more developers to run these algorithms, and the emerging emphasis AI is receiving in the tech industry are all greatly accelerating the pace of advances. Areas where it is soon to or already having prominent impact in energy include autonomous vehicles, drone agriculture, home automation, and manufacturing and shipping optimization. We aim to hold 1-2 workshops (one with a tie in to behavior and neuroscience, the other without) to explore the breadth of AI approaches across domains, and their potential applications to saving energy. A survey paper of AI and energy current applications and new ideas, potentially with quantifications of their potential energy saving impact, is an anticipated deliverable (in a vein similar to the disaggregation review paper published by PEEC, which received 30,000 downloads in its first year and spawned bi-annual workshops and research and development work). Depending on the outcome of this work, we may search for a post-doc or research associate to focus on this area.

Transportation/Mobility

The potential for energy savings in the transportation sector is large and public policy will continue to focus in this area. In particular, fuel efficiency regulations for light duty vehicles will continue as an important public policy issue. However, PEEC work in mobility/transport has been smaller than appropriate, given the large potential.

PEEC seeks to expand its research on the technological and behavioral barriers to improved energy efficiency in mobility choices and opportunities both for the residential and commercial markets.

The advent of ridesharing, autonomous vehicles, and electric vehicles has the potential for significant market disruption. This has implications in terms of vehicle purchases, transit usage, and a number of other issues that will ultimately effect greenhouse gas emissions, energy security, and the economic landscape of transportation globally.

Currently there is great uncertainty about the impacts of these changes. For example, the development of autonomous vehicles could either decrease or increase the use of energy by light-duty vehicles. On one hand, autonomous vehicles could more efficiently use fuel for a given trip. On the other hand, the lengths of commutes could be substantially expanded if the vehicle operator – no longer really a driver –could be working productively during the commute, thereby increasing energy demand. Similarly, rather than parking the vehicle in an expensive urban parking garage, operators might instruct cars to keep driving or to find distant, inexpensive parking until the next drive, also increasing energy use. In addition, fully autonomous vehicles could provide significant opportunities for access to personalized transport from population segments currently denied that access (e.g., the handicapped, the underage, etc.) that would also increase energy demand.

In the next five years, PEEC expects to expand and broaden its focus in the area of transportation behavior and economics, including institutional analysis in mobility, and in modeling and data analysis regarding new mobility trends.

Institutional Analysis

Our research in institutional analysis is driven by indications that the current understanding of the dynamics of energy technology change is inadequate. In particular, the government's role in influencing change needs additional study. Retrospective reviews of government cost-benefit analyses do show a systematic bias toward overestimating the costs of most regulations over the last forty years, including energy and environmental regulations, at a rate of more than 25%; this is often attributed to inadequate modeling of innovation. Meanwhile, an active debate exists about the nature of a documented "gap" between societal uptake of energy efficient technologies and higher expected adoption rates, if assessments of the cost-minimizing nature of these technologies are accurate.

In the coming years, we will continue to research problems that advance the underlying science of institutional analysis as it relates to energy efficiency. Our vision for future research breaks down into three major streams: (1) increased understanding of the bi-directional relationship between policy and the invention and commercial design of technologies with important energy use implications; (2) increased understanding of the bi-directional relationship between policy and the adoption and diffusion of technologies with important energy use implications; and (3) advances in forecasting (e.g., agent-based modeling, prediction games/markets, expert elicitation, etc.) regarding technologies with important energy use implications.

We would like to more deeply understand to what extent imperfect competition is present in industry value chains of relevance to energy demand and to understand how the nature of competition relates to inventive activity and technology diffusion. And we would like to understand how innovation designed to reduce energy use can result in quality benefits in non-energy aspects of product design as well as in cost improvements.

International Energy Modeling and Analysis

The Sweeney book – *Energy Efficiency: Building a Clean Secure Economy* – focused sharply on the United States energy efficiency history and the possibilities for carrying the trends forward in time. But the same phenomena appear to have been present for many other countries, as suggested by the more limited data published by the International Energy Agency. It is likely that we will collaboratively conduct, or at least catalyze, parallel in-depth examinations of other countries. By studying energy efficiency in other countries, we broaden our understanding of barriers and opportunities and promote the adaptation and application of solutions-oriented approaches internationally.

For example, Anupam Khanna, who will be a visiting scholar at PEEC this spring, will be considering whether he could work with PEEC to develop such a parallel historical analysis for India. After receiving his PhD in Engineering-Economic Systems at Stanford, Anupam spent his career the World Bank until the mandatory age-related retirement, returned to India where he served as Chief Economist and Head of Policy Outreach at National Association of Software and Service Companies (NASSCOM). He has the connections, geographic location, intellectual skills, and interest to work collaboratively with PEEC to complete this parallel analysis for India. We have begun discussions with World Bank analysts, about whether they can work with various country groups to use the Sweeney book as a starting point for parallel analyses in their countries. If that is successful, we anticipate working with them.

A second international effort would be developed jointly with the Energy Modeling Forum (EMF). It would be useful to create a set of plausible energy efficient futures scenarios for major countries and the world. These could be created by projecting forward the historical framework from the Sweeney paper, either by designing a simple model to do this, modifying someone else's model and/or setting up model comparisons. And if the parallel analyses of the last paragraph come to fruition, the projections could be based on results from the various specific country analyses. The last round of the EMF studies included one energy efficiency scenario, but it was only a stretch scenario picked primarily by the modeling community with very informal interactions with the EE/behavioral research community. Collaboration between these two communities in the context of an EMF study could be quite productive.

Key Areas for Expanding the Impacts of PEEC Research

International Partnerships

Another goal of the Center is to expand its research, collaborations, and visiting research personnel to a more international scale. Ideally there would be one to three visiting researchers at PEEC at a time from different countries and backgrounds exchanging ideas and methods to better develop solutions to serious energy efficiency barriers in various markets. PEEC also seeks to further outreach of the BECC conference and similar efforts to organizations and researchers abroad, such as has happened with BECC Japan.

Educational Leadership

PEEC will increase its educational efforts, attracting more students from Stanford departmental and multidisciplinary programs to the study of energy efficiency. We hope to include another seminar and further outreach activities, such as an industry-focused workshop on consumer behavior in the energy market, to strengthen our relationship to different government and corporate sectors.

PEEC Conferences

The conferences (discussed in more depth below) have been important instruments for PEEC increasing its connections with industry, students from around the world, government agencies, and NGOs. They have been important in enhancing the PEEC reputation.

We plan on continuing the two major conferences – BECC and Silicon Valley Energy Summit – and on continuing to be a part of the Vail Global Energy Forum.

We expect to increase the impact on industry through the Silicon Valley Energy Summit (SVES). This annual conference allows us to reach out directly to industry in Silicon Valley and indirectly to industry around the United States. The planning committee includes leaders from local industry, NGOs, and research institutions. That structure assures that our annual event is closely linked to the energy issues being faced by industry. We currently have online video recordings of all sessions of the SVES. However, we can increase the impacts of SVES by breaking some of the sessions into UTube videos. To do this, however, will require hiring additional people with strong communications capabilities.

Another way of reaching out to industry is through cutting edge focused workshops on specific topic areas, such as we have done with energy feedback devices, and energy disaggregation. We expect that such workshops would be planned in conjunction with representatives from industry.

We expect to increase the impact on world-wide research and application of behavioral intervention through the Behavior, Energy, and Climate Change (BECC) conference. We are in the process of expanding the scope of BECC to include more energy efficiency behavioral interventions in corporations and other organizations.

PEEC in More Depth

So far, "Precourt Energy Efficiency Center: Going Forward" has laid out the PEEC mission, discussed the reasons for and successes of energy efficiency, and has described the PEEC emphasis areas in terms of the various fields of knowledge and the various energy consuming sectors to which these fields are being applied. The document has turned to our vision of the PEEC future for the next five years, giving our strategic goals, our key areas of expanded research, and key areas for expanding the impacts of PEEC research.

A Guide to What Follows

In the remainder of the document we describe many of these issues in greater depth. We start with a discussion of the various core activities of PEEC: Research within PEEC, Research within Stanford, Education, Conferences and Workshops, International Connections, and Policy Analysis and Advocacy.

Many of these core activity discussions are supported by extensive appendices.

Appendix A provides a multiple-page table of the various seed grants and funded projects from PEEC, which details the research area, research description, year of funding, and the investigators and partners of each project. In addition, where possible, we have indicated the resulting potential applications and completed deliverables.

Appendix B gives seventeen examples of past PEEC projects, describing these projects in much more depth than would be possible in the tabular form of Appendix A.

Appendix C lists the publications that we have been able to identify from the various PEEC projects. We believe that there are more publications than the 186 that we have listed here. We have included books, journal articles, conference proceedings, as well as papers under revision.

Appendix D provides additional history of PEEC and a timeline of Stanford energy institutions.

Appendix E provides a summary of PEEC governance and a listing of the PEEC advisory council members.

Appendix F provides profiles of the senior staff members of PEEC, with discussions of some of their future research plans, and lists PEEC faculty who have been funded by PEEC and/or have asked to be listed as a PEEC affiliate. Appendix F also lists 60 of the students who have worked with PEEC or on PEEC projects. In contrast to the lists above of students who received their PhD working closely with PEEC, it includes undergraduates and masters students. We believe there are more students, but are records are incomplete.

Appendix G ends the documents by describing more generally the Stanford energy research community.

PEEC Core Activities in More Depth

PEEC activities, all in support of the basic mission, can be grouped into six different core activities: research within PEEC, research within Stanford, education, conferences, and international collaboration, and policy.

Research within PEEC

PEEC research is designed to create knowledge that enables the development of meaningful solutions to pressing energy efficiency issues at the individual, corporate, and government levels. These solutions include the human choices that shape the penetration and adoption of energy-efficient technologies, systems, policies, and practices. By identifying behavioral and economic barriers to implementing energy efficient technologies, PEEC is able to describe what methods and policies have worked in the past, what are working presently, and what may help forward progress in the future. Director James Sweeney's forthcoming book: *Energy Efficiency: Building a Clean Secure Economy*, illustrates how many state and federal government efforts to change behavior and reduce energy usage have been successful to some degree, such as changes in standards, tax incentives, and subsidies. PEEC seeks to continue to examine what policies have and will encourage energy efficient behavior. For example, PEEC has sponsored research on institutional barriers to the design and construction of energy efficient buildings, including notable efforts by affiliated Professor of Civil and Environmental Engineering Martin Fischer.

Within PEEC, internal research staff resources and visiting researchers are utilized to maintain a continuing research program. Currently two faculty members – James Sweeney and John Weyant – and three researchers – Carrie Armel, Dian Grueneich, and Margaret Taylor – maintain the continuity of the research within PEEC[5]. This team is augmented by a visiting faculty member – Andreas Schäfer, Professor of Energy and Transport at the UCL Energy Institute, University College London – who spends each summer at PEEC. Two other Stanford faculty members – Martin Fischer (Civil and Environmental Engineering Department) and Byron Reeves (Communications Department) play a continuing but smaller percent time role. PEEC normally includes up to three post-doctoral students conducting research before they go to a more permanent position. Visiting PEEC scholars currently include Ross Chanin, a Nonresident Senior Fellow with the Atlantic Council's Global Energy Center and CEO of American Efficient, a venture-backed software platform for U.S. regulated utilities and the deregulated power sector. Visiting scholars have included Tobias Schmidt, now an assistant prof. in energy policy/politics in the Social Science Department of ETH Zurich, and Erin Baker, a professor and director of Wind Energy IGERT, of the University of Massachusetts, and Louis-Gaëtan Giraudet, a research fellow at CIRED, in Paris.

These researchers and associated scholars publish both journal articles and papers as well as material directed specifically towards decision makers in the public and private sectors to foster discussion and progress. Some of the work has been completed entirely within PEEC. Other research has been in collaboration with other organizations and individuals, both inside and outside of Stanford.

Appendix B provides examples of some of the past PEEC projects. Appendix C provides a listing of publications stemming from PEEC research.

[5] Carrie Armel is full time at PEEC; Dian Grueneich is one-quarter time at each of PEEC, the Stephenson-Shultz Energy Policy Task Force at Hoover Institution, and Precourt Institute for Energy; Margaret Taylor is half-time at PEEC and half time at Lawrence Berkeley National Lab.

Research within Stanford

PEEC facilitates and sustains synergistic work on energy efficiency by numerous departments/organizations within the University, including Management Science and Engineering, Economics, Civil and Environmental Engineering, Electrical Engineering, Mechanical Engineering, and the Hoover Institution.

PEEC has provided funding in the form of faculty seed grants for faculty/student teams starting into new areas of energy research. Seed grants provide opportunities to allow for higher risk, higher reward research that encourages scholars at Stanford to apply theories or methods to energy efficiency research, which may be a completely new field of study for them. This increases diversity of perspectives, techniques, and solutions surrounding energy efficiency and types of scholarship investing in solving these important problems.

For the first eight years of PEEC operations these seed grants were awarded based on formal calls to the faculty for research proposal plus a group of smaller, individually established projects. Recently PEEC has not issued formal solicitations but is relying on discussions with individual faculty/student teams who are interested in starting new energy efficiency research. Notable areas of collaboration include cognitive behavioral science, civil engineering, and management science and engineering. The impact is heightened through connections with the greater Stanford Energy Research Community that includes GCEP, PIE, Woods, and other entities.

PEEC has also been instrumental in obtaining external research grants that fund research teams including scholars and analysts from across the university. The largest of these, our Sensors & Behavior project, funded by the Department of Advanced Research and Project Agency for Energy (ARPA-E), involved 20 projects in technology, behavioral interventions, and data interventions and modeling. The project includes faculty and senior researchers from eleven different Stanford departments and programs.[6] This project is discussed as an example in Appendix B.

Appendix A includes a list of the seed grants and externally funded projects that have been developed through PEEC leadership. Appendix B includes examples of some of these projects. Appendix C includes publications stemming from the internal PEEC research and the research within Stanford. To date we have been able to identify, 186 publications stemming from PEEC sponsored projects, both from within PEEC and from throughout Stanford. Appendix C provides a list of these publications.

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[6] Departments and programs included Civil & Environmental Engineering, Communication, Computer Science, Education, Electrical Engineering, Management Science & Engineering, Mechanical Engineering, MediaX, Pediatrics, Psychology, Symbolic Systems Program. Faculty and senior researchers included: Balaji Prabhakar, Banny Banerjee, Byron Reeves, Carrie Armel, Greg Walton, Hamid Aghajan, James Sweeney, Jeff Shrager, Jeremy Bailenson, June Flora, Manisha Desai, Martha Russell, Martin Fischer, Nicole Ardoin, Phil Levis, Ram Rajagopal, Samuel McClure, and Thomas Robinson.

Stanford has a long and distinguished history in collaborating with industry to accelerate the penetration of new technologies and practices into the marketplace. The notion of taking technologies and inventions into the marketplace and putting them into the hands of users is part and parcel of the culture at Stanford: "ideas to actions" is a paradigm that is valued and rewarded.

Within both research activities (within PEEC and within Stanford), PEEC works to accelerate penetration of new technologies and practices into the marketplace, directly collaborating with industry. PEEC has been working actively with personnel from several companies and NGOs, such as Bidgley, Clean Tech Open, C3 Energy, Electric Power Research Institute, Hara Software, Ohm Connect, NRDC, Oracle, PG&E, Southern California Edison, SRI International, Sustainable Silicon Valley, and Urban Engines. Urban Engines, was established based on research seeded at PEEC.

Education

PEEC contributes to energy efficiency education at Stanford. PEEC plays a critical role in education of Stanford students, including post-doctoral scholars, graduate students, and undergraduates. Many, if not most, of these students will continue to create and apply knowledge that enables the development of meaningful solutions to pressing energy efficiency issues at the individual, corporate, and government levels. PEEC has helped fund the education, training and dissertation research of nearly 100 students.

Most PEEC research teams are faculty-led teams that include graduate and sometimes undergraduate students, as well as post-doctoral scholars. PEEC has helped fund the education, training and dissertation research of nearly 100 such students.

During the last few years, the PhD graduates who worked closely with PEEC and were at least partially supported by PEEC in the development of their dissertations, include:

- Adrian Albert (now at C3 Energy)
- Marilyn Cornelius (now at d.cipher)
- Victor Gane (now founder of AestheticLink)
- Kenneth Gillingham (now at Yale University)
- Sebastien Houde (now at University of Maryland)
- Ozge Islegen (now at Northwestern University)
- Benjamin Welle (now at Perkins+Will)
- Saniya LeBlanc (now at George Washington University)
- Ali Nouri (now at Google)
- Yueming Qui (now at Arizona State University)
- Anshuman Sahoo (now at Boston Consulting Group)
- Dhruv Sharma (now at PricewaterhouseCoopers LLP)
- Anant Sudarshan (now at University of Chicago)
- Nik Sawe (now a post-doc at PEEC)

Scholars who worked at PEEC, either as a post-doctoral scholar or as a visiting scholar sponsored directly by PEEC during the last few years include:

- Qimin Chai (from Tsinghua University, now at NDRC China)
- Yang Chen (From MIT, now at World Bank)
- Regina Clewlow (from MIT, now at Ride Scout)
- Micah Fuller (from UC Davis, now at PG&E)
- Louis-Gaëtan Giraudet (from CIRED, Paris, now at CIRED)
- Diana Ginnebaugh (from Stanford, now at Mineral Acquisition Partners
- Wei-Shuen Ng (from Berkeley, now at OECD)
- Annika Todd (from Stanford, now at Lawrence Berkeley National Lab)
- Nik Sawe (from Stanford, now at PEEC)
- Frances Sprei (from Chalmers Institute of Technology, now at Chalmers)

In addition, post-doctoral scholars who were supported by PEEC, but sponsored by faculty working on PEEC projects include:

- Zico Kolter, supervised by Andrew Ng, (now at MIT)
- Hilary Schaffer-Boudet, supervised by Tom Robinson
- Sam Borgeson, supervised by Ram Rajagopal (from UC Berkeley)

In addition, more than 200 students, primarily from colleges and universities around the world, have received Precourt Fellowships to attend the annual Behavior, Energy and Climate Change conference.

Dian Grueneich has helped launch the new Stanford Energy Internship in California (SEIC) program which is placing ten graduate and undergraduate students in California energy agencies this summer. She is teaching a new seminar this spring (California Energy Agency Roles and Policies) to the SEIC interns and a small number of other students. Key aspects of the internships and seminar focus on energy efficiency.

PEEC hosts the Sustainable Mobility Seminar (formerly the Sustainable Transportation Seminar) series, a weekly discussion that brings together leading experts in research, industry, and policy to foster knowledge transfer and collaboration. This seminar is discussed more fully below.

Conferences and Workshops

PEEC educational efforts do not stop with Stanford students, but reach out to a much broader community. Through strategic outreach, PEEC fosters discussion of energy efficiency research and promotes policy, institutional, and behavioral solutions. PEEC research is communicated broadly through two major conferences we organize each year, our weekly sustainable mobility seminar, as well as through participation in other related conferences and workshops. Such interaction ensures that PEEC remains closely linked with industry, government, non-governmental organizations, and other research institutions.

Silicon Valley Energy Summit. PEEC hosts the annual Silicon Valley Energy Summit (SVES) at Stanford and brings together over 400 participants from companies involved in tech, Silicon Valley startups, investment funds, utilities, government agencies, research communities, and environmental organizations. The summit is focused on finding workable solutions to make industry, communities, and organizations more long-term sustainable and address the threat of climate change and growing energy security concerns.

Notable past speakers have included Former U.S. Secretary of State, Treasury and Labor George Shultz and DOE National Renewable Energy Lab's Dan Arvizu. The topics discussed each year range from clean energy and mobility options to economic modeling and data science. Overall it is an opportunity for leaders in different sectors to share and discover new ideas and to bring those ideas back to their own organizations and improve sustainability.

Videos of the past Summits are available on the PEEC web site and are accessible from the "Previous Conferences" box at http://sves.stanford.edu. The ninth annual SVES will be hosted at Stanford University June 3, 2016.

Behavior, Energy and Climate Change (BECC) Conference. PEEC convenes the annual BECC Conference, jointly with University of California Berkeley and the American Council for an Energy Efficient Economy. Focused on understanding individual and organizational behavior and decision-making related to energy usage, greenhouse gas emissions, climate change, and sustainability, the BECC conference beings together over 700 participants to discuss innovative policy and program strategies, share important research findings, and engage in building dynamic new networks and collaborations.

Key goals of the conference include expanding support for social science research, identifying lessons about behavior and decision-making that advance energy and climate solutions, and finding real energy savings that will benefit the economy, security, and environment. BECC helps establish what questions and research needs are most pressing in the energy research community and reviews policies, technologies, and strategies to bridge fields in the pursuit of a more energy efficient future.

BECC has been building a broad international community of academics and practitioners who are interested in behavioral interventions to promote energy efficiency and clean energy supply. BECC conference attendees include researchers, decision makers, utilities, consultants, designers, media, community organizations, non-profits, and many others from a variety of fields engaged in energy and climate efforts.

BECC has spawned a growing set of allied conferences in Europe and Asia, including BEEC Japan, which started in 2014. The European conference series, BEHAVE, is a "sister" conference.

BECC typically hosts more than 40 plenary and topic sessions showcasing over 150 presenters selected through a competitive abstract process or invited by the organizing committee from any relevant discipline concerned with human behavior, society, and culture; particularly work from social and behavioral psychology, behavioral economics, applied anthropology, organizational behavior, political science, communications, and the cognitive sciences.

The BECC Conference is now in its tenth year and will be hosted October 20 – 22, 2016 in Baltimore, MD.

Vail Global Energy Forum. PEEC plays a major role each year in planning the Vail Global Energy Forum, a "mini-Davos" for energy. This forum draws leaders from around the world to discuss North American improvements in energy efficiency, sustainability, clean energy technologies, energy security, and supply. The Vail Global Energy Forum, now in its fifth year, will take place January 29-31, 2016.

Sustainable Mobility Seminar. PEEC hosts the Sustainable Mobility seminar series, meeting weekly throughout the academic year, which explores the changing face of personal and freight mobility, and the energy and economic consequences of the institutional and behavioral changes. This weekly discussion brings together leading experts in research, industry, and policy to foster knowledge transfer and collaboration. The seminar is open to the public and students are encouraged to attend. Regular participants of the seminar include faculty, staff, and students from Stanford and other universities, corporate personnel located in Silicon Valley, and people from government agencies.

Other Conferences and Workshops. PEEC also hosts and participates in other meetings, workshops, seminars, and gives a number of talks each year that highlight PEEC's role in energy efficiency research and education. Carrie Armel has led several specialized PEEC workshops, addressing issues that were cutting-edge issues at the time the workshops were held. In some cases follow-on workshops were spawned at other institutions.

- Energy & Feedback Workshop: End-Use Energy Reductions through Monitoring, Feedback, and Behavior Modification, September 4 & 5, 2008, Menlo Park, CA http://peec.stanford.edu/energybehavior/events_end-use-workshop.php

  Smart meters and other emerging electricity measurement technologies offer great potential – perhaps even a paradigm shift - for reducing energy demand when augmented with novel tools for consumers, researchers, and utility program designers. This workshop brings together professionals from academia, industry, utilities, and government to envision these tools and to identify next steps for developing them.

- Disaggregation workshop, May 28, 2010, Stanford, CA
  http://peec.stanford.edu/energybehavior/events_disagg.php

  Most agree that better data into home energy usage is an imperative to tame growing demand. Disaggregation potentially offers a low-cost, scalable solution. However, research, technology, and policy barriers may prohibit, or at best delay, the most promising solution(s). This workshop focused on identifying and addressing needs in order to bring the technology to fruition as quickly as possible. This was a "working" meeting so that each session began with a short presentation followed by facilitated discussion to collaboratively develop answers.

- Data Jam Workshop, November 11, 2013, Stanford, CA
  http://peec.stanford.edu/energybehavior/events_datajam.php

  The workshop aimed to help participants develop innovative algorithm and application ideas, with the goal of achieving deep and widespread energy savings. The process formulated for this experimental workshop was designed to multiply, accelerate, and increase the effectiveness of energy-saving applications: We started with the Data Jam + Hackathon concept (workshops where ideas and apps are born), build in market analysis and product design workflow, and add out-of-the-box design thinking methods. To expand the idea space, we provided expert-compiled cheat sheets listing everything from available data sets, to behavior design principles, to example energy apps to serve as inspiration.

Future such specialized workshops may include those on Artificial Intelligence, the future of energy program evaluation (using sensor and online data and new analytic approaches and how to facilitate regulatory approval on these), and behavioral economics and energy.

PEEC also hosts conferences with international partners.

- PEEC partnered with the Australian government to hold the “United States-Australian Dialogue on Energy Efficiency” in 2012 and 2013

- PEEC partnered with the Polish Ministry of Foreign Affairs and the Polish National Centre on Research and Development to host the “Research Opportunities and Challenges” conference in 2014

- PEEC organized an ad hoc workshop for the French Energy Efficiency Trade Delegation, for executives from the China National Petroleum Corporation, and from the Chinese State Grid, all in 2015.

Informal Briefings. Finally, PEEC conducts frequent informal briefings with governmental policy-makers or private sector leaders. These typically are conducted by individual members of PEEC. A very partial listing of governmental officials briefed by PEEC personnel follows:

U.S. Senator Jeff Bingaman,
California Governor Arnold Schwarzenegger
California Governor Jerry Brown
U.S. Defense Secretary Ash Carter
U.S. DOE Secretary Ernie Moniz
California Air Resources Board Chair, Mary Nichols
California Energy Commission Chair, Robert Weisenmiller
U.S. Navy, Vice Admiral Philip Cullom
President and CEO, California Independent System Operator, Stephen Berberich

International Connections

PEEC invests in scholarship and collaboration with other researchers around the world. Through visiting researchers, PEEC gains further expertise in energy efficiency-related fields and that informs ideas and methods within PEEC and the greater Stanford energy community.

In addition, PEEC frequently hosts delegations from other countries. For example, we have hosted delegations from Australia, China, the EU, France, Germany, Japan, UK.

Some of the more formal international connections are included in the following table:

Country	Organization
Australia	Energy Efficiency Council
China	Local governments (Jiangsu province, Nanjing city), NDRC, State Grid, petroleum producers China University of Petroleum, Beijing Tsinghua University
France	CIRED (Prof. Jean-Charles Hourcade , Prof. Gaetan Giraudet)
Japan	BECC Japan; Tokyo Gas Company (Toshiya Okamura); Oil retailers
Korea	KAIST (Prof. Eom Jiyong , Prof. Ahn Byunghoon)
Poland	National Center for Research and Development of Poland
Singapore	National Univ of Singapore (Industrl & Systms Eng dpt., Energy Studies Cntr)
Sweden	Chalmers University (Professor Frances Sprei)
Switzerland	ETH Zurich (Professor Tobias Schmidt)
UK	University College London (Prof. Andreas Schäfer)

Table 2. PEEC Ongoing International Connections

Policy Analysis and Support

PEEC works to analyze energy policy options and to advance positive policy changes. Such policies can be international, US-wide, state-wide, or local.

At the state-wide level, particular attention is focused on California. California is often at the forefront in the creation of programs, laws, and policies that specifically address climate change, such as the state's passage of AB 32, the California Global Warming Solutions Act of 2006, which requires California to reduce its greenhouse gas emissions to 1990 levels by 2020 or approximately 15 percent below what was projected for that year. Staff and affiliated PEEC faculty were deeply involved in discussions regarding the implementation of AB 32 through the state agency Climate Action Team and other vehicles. Through this involvement, PEEC highlighted the need to focus on energy efficiency for progress on reducing emissions in the short term. The document "Analysis of Measures to Meet the Requirements of California's Assembly Bill 32" developed a marginal abatement curve for California greenhouse gas emissions, emphasizing the provision of AB 32 requiring the mitigations to be cost-effective.

PEEC scholar Dian Grueneich, a former Commissioner of the California Public Utilities Commission, is spearheading an increased focus at Stanford on state regulatory policy governance. Dian will continue to lead PEEC's research and activities on state energy efficiency policies and regulatory frameworks. Working with Stanford students, she is finalizing the remaining sections of the Next Level of Energy Efficiency research for publication in the *Electricity Journal*. She will continue to present the research both within and outside Stanford and has already been asked to do so in several venues (ACEEE's 2016 Summer Study, the annual Symposium of the Northeast Energy

Efficiency Partnership, the annual meeting of the World Business Council for Sustainable Development). She plans to focus further research on new energy efficiency policy frameworks that support whole building system approaches and competitive procurement of efficiency savings.

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Appendix A: Seed Grants & Funded Projects

PROJECT NAME	RESEARCH AREA	INVESTIGATORS & PARTNERS	PROJECT GOALS & RESEARCH DESCRIPTION	YEAR
Behavior and Decision-Making Research Related to Energy Efficiency and Climate Change	Human Behavior	Armel, Bad Wound, Dudek	This project developed an interdisciplinary website and integrated literature database containing key research relevant to energy decisions and behaviors, for behaviors occurring at the individual and group levels.	2007
Incentive Mechanism for Reducing Congestion-related Costs in Transportation Systems	Human Behavior	Prabhakar, Merugu, Gomes, Venkataramanan	Researchers developed and implemented an incentive mechanism to reward 14,000 employees at Infosys Technologies, Bangalore, India to commute in off-peak times to reduce commuting times and congestion costs. The mechanism was successful in moving commuters to the off-peak hours: the number of off-peak hour commuters increased to around 9200 from around 4500 during a 6-month period. This later led to the Stanford Transportation Lottery, which then led to the "Insinc" project for Singapore.	2008
Measuring Travel/ Driving Behavior Modification through Real-time Fuel Consumption Information and Incentive/Disincentive Transportation Programs	Human Behavior	Chiu, Carr	This research is a parallel study with three Korean universities to determine to what extent dashboard mileage gauges and other behavior modification techniques improve driver efficiency. It examines psychological/behavioral strategies, which target/enhance individual psychological awareness to encourage voluntary travel behavior changes.	2008
Increasing Energy Efficiency Behaviors among Adolescents	Human Behavior	Robinson, Armel, Cornelius	This work involved a randomized, controlled trial designed to assess a school-based program to increase energy-efficiency behaviors among ninth graders. Researchers found that students in the intervention classrooms significantly improved their total energy efficiency behaviors compared to controls.	2008
Summer Energy Feedback Infrastructure Project	Human Behavior	Banerjee, Klemmer, Armel	The project made progress in developing research plans for a behavior, energy, and sensor program that leverages sensor data in order to achieve widespread energy reductions. The program will include a platform for prototyping, experimentation, and data collection; an initial set of interventions and supporting work aimed at promoting energy reductions within households; and larger-scale analysis of behavior and HAN deployment through economic and engineering analyses.	2009
A Randomized Intervention Field Experiment to Reduce Home Energy Use	Human Behavior	Walton, Klemmer, Paunesku	Determining the most effective strategies for presenting home energy information to consumers so that they change their behavior and reduce energy use. This work used descriptive social norms to help residents decrease energy use or water use. It included three separate projects, each of which used a field-experimental methodology to test how	2009

			various social- and social-norm related messages influence environmental behaviors relative to control messages.	
Serious Games and Energy Use Behavior	Human Behavior	Reeves, Armel	This project sought to create an online multiplayer computer game that links state-of-the art energy sensing (e.g., smart meters and possibly other home, car, and building monitors) and encourages participants to change their decisions about energy consumption.	2009
Energy Behavior Taxonomy	Human Behavior	Flora, Boudet, Roumpani, Armel	This project created a database of over 250 energy saving actions, their attributes and impact, and barriers. Properly characterized and clustered behaviors can aid scholars, policy makers and energy industry professionals in prioritizing desired behaviors, targeting appropriate consumers and understanding relevant barriers.	2010
Identification of Innovative Energy Behaviors*	Human Behavior	Armel, Cornelius, Ardoin, Plano, Bridgeland, Morton, Chang, Allen	This project involved interviewing "extreme users," like energy experts, historians, do-it-yourself people aiming for very large energy reductions, and people who have lived in harsh climates, to create an opportunity map identifying energy reducing practices and technical insights from other cultures and time periods, and quantifying their potential energy saving impacts across U.S. climate zones, if adapted for developed nations.	2010
Multiplayer Online Game*	Human Behavior	Reeves, Cummings, Scarborough, Kuma Games	This project developed an online, multi-player game called “Power House,” which displays players’ actual energy use data from smart meters and other sensors. Players are challenged with energy efficiency tasks and rewarded for real-life actions with points in the game. By utilizing real world energy data, social competition, and retraining of habits through reinforcement, the game showed in both laboratory and field studies that participants use significantly less energy while they play the game.	2010
Collective Action Feedback Interface*	Human Behavior	Walton, Sparkman, Clark, Paunesku, Armel, Luo, Flora, Home Energy Analytics, City of Mountain View	This research focused on whether consumers viewing their actions as part of a collective effort would be motivated to use less energy. The project involved a web application that helps consumers track energy use and receive tips. Researchers separated messages about communal effort from descriptive norms to determine which was more effective. When energy-saving tips were organized thematically, the collective-action frame led to greater reductions than descriptive norms or the thematic recommendations alone.	2010
Visual Metaphors in a Virtual Immersive Environment*	Human Behavior	Bailenson, Bailey, Flora, Armel, Voelker, Reeves, DraftFCB	This project involved experimental evaluation of the utility of an immersive virtual environment in promoting energy saving behaviors, with results suggesting that vivid visualizations of energy consumption (e.g., amount of coal instead of KWh) may be more important than the personalization afforded by avatars.	2010
Motivationally Framed Facebook Applications*	Human Behavior	Banerjee, Flora, Sahoo, Bhansali, Greenspan, Khak-wana, Liptsey-Rahe, Madres, Manley, Omer, Rajendra, Scalamnini, Wong, Stehly, Voelker	This project built, tested and diffused three energy reduction applications on Facebook to stimulate a body of work that uses design and behavioral principles to advance innovations regarding energy reduction.	2010

Appliance Calculator*	Human Behavior	McClure, Houde, Armel	This project explored the ability of energy and cost messaging to nudge consumers to purchase energy-efficient refrigerators that have higher price tags, but save money in the long term. Researchers built an appliance recommendation website and calculator application and had 60,000 users via Google Ads. Messaging with a strong energy focus was successful in nudging consumers toward more energy-efficient models.	2010
Transportation Lottery*	Human Behavior	Prabhakar, Merugu, Pluntke, Gomes, Mandayam, Yue, Atikoglu, Albert, Fukumoto, Liu, Wischik, Rama, NUS, LTAS	This project, “Insinc,” involved online software that incentivized Singapore commuters to travel at uncongested times by giving them different numbers of credits (corresponding to cash) for shifting to off-peak travel, mode shifting (from private to public transit), or recommending a friend as monitored through transportation sensors. Researchers found that 10% of trips were shifted off peak to reduce congestion and associated fuel waste.	2010
Girl Scout “GLEE” Program*	Human Behavior	Robinson, Ardoin, Boudet, Flora, Armel, Girl Scouts, People Power	Working with the Girl Scouts of Northern California (30 troops), this project developed two curricula on reducing energy use at home and in food and transportation choices. The results showed significant changes in self-reported home energy saving actions for both girls and their parents.	2010
Experiments with Appliance Choice	Human Behavior	Knutson, Sawe, Sahoo	This work, which is included in PhD dissertations by Nik Sawe and Anshuman Sahoo, uses a combination of national econometric and psychometric surveys and neuroimaging behavioral experiments to study consumer purchases of energy-efficient products and the effect of the Energy Star label. The ongoing neuroimaging work has found that the Energy Star label activates the brain's "reward pathway", associated with positive emotions, in a similar (and additive) way to low prices.	2011
Integrative Project*	Human Behavior	Armel	This project will be an integration of some of the most effective pieces of the initial projects in the Stanford Sensors & Energy Behavior Initiative, as well as new components such as narrative and added diffusion strategies.	2013
Promoting Sustainable Vehicles.	Human Behavior	Levav	This study investigates whether drivers will buy more environmentally friendly vehicles in response to information about present benefits rather than future environmental gains. Researchers will supplement not very useful sticker information with operating cost comparisons with comparable cars, and bundling the cost of the car with the cost of operating it.	2013
Supply Chain Design under Uncertain Production and Transportation Costs	Institutional Analysis	Plambeck, Islegen	This research employs mathematical theories of stochastic dominance, monotone comparative statics, and optimization under uncertainty to derive insights on optimal facility location and design and address uncertainty in production and transportation costs, as well as investment in energy efficiency and renewable energy for managers and policymakers.	2009

Efficiency and Group Behavior in Power Distribution Networks	Institutional Analysis	Johari, Rajagopal	Many local devices that can either generate electricity, like rooftop solar panels, or store energy, like electric cars, are expected to help reduce the costs of the traditional system, especially as intermittent renewable energy provides a bigger fraction of our energy use. This study examines the "micro grids" that owners of these resources likely will form for negotiating with their local utilities.	2013
Improving Energy Efficient AEC Decision Making Through Statistical, Model-Based, Search of Multidisciplinary Impacts	Modeling and Data Analysis	Haymaker, Clevenger	As strategies are implemented or proposed, need arises to measure and compare guidance provided by competing strategies on different challenges to support their selection and improvement towards achieving high performance designs. This research provides evidence that guidance can be assessed and it demonstrates that the Design Exploration Assessment Method is an effective at measuring and comparing the guidance provided by various strategies for energy efficient design.	2007
Increasing the Effectiveness of Investigation, Definition and Execution of Retrofit Projects to Increase Building Energy Efficiency	Modeling and Data Analysis	Tatum, Gilligan	This project which is included in PhD dissertation work by Brien Gilligan created an enhanced model for the energy efficiency process explained using the Narrative program developed by CIFE at Stanford that serves as a tool that can provide a clear and compelling argument for facility owners to undertake energy efficiency projects, specifically retrofit projects, and thus make efficiency and sustainability more attractive to a wider base of end users.	2008
Wireless Sensor Networks Technology for Smart Buildings	Modeling and Data Analysis	Goldsmith, Boyd, Aghajan, Katz, Lee	Research developed enhanced energy usage models and solutions for home and office buildings based on modern sensing and wireless networking technologies. Energy usage automation is a compelling application of sensor technology due to the universal need for energy usage optimization in homes and office buildings. The study found that at least an order of magnitude better performance and energy consumption can be obtained through optimization of networking protocols for sensor networks.	2007
Analyzing and Optimizing Supply and Demand of Intermittent Renewable Electricity through Transmission Load Flow Modeling	Modeling and Data Analysis	Jacobson, Archer, Dvorak, Hart, Ketefian	This research focused on the feasibility of and quantifying the effects of combining solar, wind, geothermal, and hydroelectric power with remaining conventional power to meet demand while also meeting an aggressive carbon emissions reduction target. Investigators examined the effects of injecting power from large renewable plants directly onto high-voltage transmission lines using power flow modeling of the California transmission system. They found that, with increased capacity in 31 transmission lines, renewable energy sources could provide at least 70% of CA’s electricity on a typical summer day.	2007
Projecting LED Competitiveness	Modeling and Data Analysis	Sweeney, Powley	This work involved assessing when white LEDs are expected to be more economical than the existing competing technology given the uncertainty about the rate of improvement of solid state lighting and what key parameters influence the cost of light in various lighting applications in various markets. Researchers probabilistically modeled the cost of light to address these questions and by having direct involvement with CREE and other LED manufacturers, were able to influence corporate planning decisions with their results.	2007

Deconstructing the "Rosenfeld Curve"	Modeling and Data Analysis	Sweeney, Sudarshan	This PhD dissertation by Anant Sudarshan examines the structural determinants of electricity consumption to investigate what fraction of the California vs. nation difference in electricity consumption intensity might reasonably be attributed to policy interventions. The research's econometric model indicated about 20% of the state nation difference in the residential sector may owe to program effects.	2007
Improving Energy Efficiency of High-Rises through Requirements-Driven Parametric Modeling	Modeling and Data Analysis	Fischer, Haymaker, Bazjanac, Gane	This project developed a Design Scenarios methodology, a comprehensive set of parameters, to build and analyze multi-objective parametric models. Researchers performed retrospective analysis of five high-rise projects, which revealed shortcomings in the existing conceptual design process. Researchers developed DS to address current conceptual design process shortcomings and enable an evaluation and comparison of the novel process.	2009
Energy Economics and Policy, Stochastic Modeling of Electric Systems	Modeling and Data Analysis	Sweeney, Mokrian	This PhD dissertation by Pedram Mokrian is dedicated to the modeling and assessment of initiatives within electricity markets using the underlying hourly market dynamics. The dissertation presents two separate frameworks that take a bottom-up approach for assessing benefits associated with various demand-side initiatives and other emerging interventions in power markets. Models in support of each framework are presented, and numerical results are used to highlight some impacts based on hourly dynamics.	2009
Incentives and Politics of Utility-Based Energy Efficiency Programs in California	Modeling and Data Analysis	Sweeney, Eom	This PhD dissertation by Jiyong Eom explores (i) the implementation of utility-based energy efficiency programs that employ a shared-savings incentive mechanism and (ii) the interest-group politics of shaping the incentive mechanism. Analyses of the economic models developed in this dissertation offer two major policy implications for California energy efficiency programs: a higher-than-adopted incentive rate would achieve not only a greater net social benefit but also greater bill savings for customers; and social efficiency would be better achieved by customizing incentive mechanisms for individual utilities and updating them on a regular basis.	2009
Google Powermeter Evaluation*	Modeling and Data Analysis	Houde, Sudarshan, Todd, Flora, Armel	Using the feedback technology Google Powermeter, this project provided an estimate of the potential for electricity savings for households that have access to real-time feedback technology. It also documented how this technology changes consumption profiles and impacts the persistence of energy savings. Over period of the field trial, a statistically significant reduction in electricity use was found but overall statistically significant reduction effects lasted for four weeks.	2010

Social Media Analytics with Twitter Explorer*	Modeling and Data Analysis	Russell, Rubens, Flora	This study demonstrated feasibility of using data mining techniques to gather and analyze vast amounts of data from ongoing social media conversations and of analyzing the data for meaningful metrics that describe conversations about energy consumption behavior. Twitter data with more than 3 billion filtered tweets that used relevant terms was collected. Through content analysis of the full Tweets, network analysis of co-occurring hashtags, and semantic analysis of the co-occurring, discernable patterns were discovered.	2010
Diffusion Modeling of Behavioral Interventions*	Modeling and Data Analysis	Shrager	This project used computational simulation models to estimate the differential efficacy of behavioral manipulations on energy usage applied in various environments. Researchers developed a general methodology to enable analysts to propose a novel intervention and then rapidly explore its potential efficacy under different conditions, and rank these predictions against other proposed manipulations. The ranking, crossed with cost, would be used in choosing which manipulations to employ.	2010
Santa Clara County Jail-Energy Efficiency Retrofit, Monitoring, and Modeling	Modeling and Data Analysis	Fischer, Maile	This project built an energy consumption model for the Santa Clara County Jail facility and evaluated possible retrofit projects to see which contributes most significantly to reduced consumption. The model illustrates heating, cooling, lighting, ventilating and other energy flows within the jail. Following an analysis, researchers proposed an initial set of 33 possible energy efficiency retrofit measures to Santa Clara County (SCC). SCC is in the process of completing the retro-commissioning effort.	2010
Paying for Good Deeds: Using Financial Incentives to Achieve Energy Efficiency	Modeling and Data Analysis	Harding	The project developed a theoretical model of consumer demand. Evidence from the residential energy saving programs was difficult to reconcile with standard preferences and broadly consistent with a model of present biased consumers with reference-dependent preferences. It was found that the need for commitment was correlated with program adoption, higher pre-adoption consumption, and lower responsiveness to goals.	2010
A Robust Mechanism to Dynamically Provide Grid Services with a Fleet of Plug-in Electric Vehicles	Modeling and Data Analysis	Ye, Taheri	Researchers constructed an automated mechanism that defines the participation of plug-in electric vehicles on a smart grid, by implementing Demand Response (DR) services with a fleet of PEVs. The developed algorithm uses a simple adjusted pricing scheme to instantly assign charging schedules to vehicles in a fleet as they plug-in. This can reduce the consumer cost by over 30% when compared to standard charging.	2012
Trip Estimation Techniques to Better Manage Hybrid Vehicle Batteries	Modeling and Data Analysis	Fox, Dally, Levav	This project will develop techniques to predict the most probable trip a car is taking based on the driver, time of day, location, trip starting point and other parameters. Such predictive ability could help maximize the electric part of the car and minimize the gasoline side. The project is underway and appears to significantly reduce energy use for plug-in electric vehicles.	2013
Visualization of Smart Meter Data for Critical Peak Pricing	Modeling and Data Analysis	Rajagopal, Flora	Using data from 2,000 businesses, this work will build software to identify businesses that are good candidates for financial incentive programs to reduce electricity use or shift usage to off-peak times. The system will include a visualization and interaction front end for engaging selected customers.	2013

Designing Mechanisms to Involve Financial Demand in Wholesale Electricity Markets	Public Policy Analysis	Wolak, McRae	Researchers conducted a dynamic pricing experiment that compared the performance of three popular pricing programs–hourly pricing, critical peak pricing, and critical peak-pricing with a rebate–for a representative sample from the population of households in the District of Columbia. They found that customers on all of the dynamic pricing programs substantially reduce their electricity consumption during high-priced periods.	2007
Appliance Efficiency and Long-Run Energy Demand	Public Policy Analysis	Harding, Rapson	Research uses existing data to investigate the extent to which individuals may be subject to incentive problems, such as split incentives, when making energy use decisions. Researchers conducted a detailed investigation of existing datasets to establish their suitability for estimating structural models for energy. Findings include that when tenants do not pay for heating, they do not keep the settings inordinately high but also do not change settings as often. An in-depth statistical analysis of the EIA-RECS database was conducted and severe oversights in data collection were documented.	2008
Contributing to CARB's AB 32 Cost-Effectiveness Determination	Public Policy Analysis	Sweeney, Weyant, Chowdhary, Palavadi Naga, Chan, Sathe, Westersund, Gillingham, Guy, Lambie, Sudarshan	Researchers developed a marginal abatement cost curve for AB 32 interventions and successfully pushed the California Air Resources Board to do incremental analysis of the various policy options.	2008
Analysis of U.S. Policies to Improve Automobile Fuel-Economy and Reduce Gasoline Consumption and Analysis of U.S. Policies to Reduce Greenhouse Gas Emissions	Public Policy Analysis	Goulder, Zhou, van Benthem, Dworski, Hafstead	This work reveals significant unintended consequences from state efforts to reduce greenhouse gas emissions through limits on greenhouse gases per mile from new cars. Researchers show that while such efforts significantly reduce emissions from new cars sold in the adopting states, they cause substantial emissions increases from new cars sold in other (non-adopting) states and from used cars. The costs per avoided ton of emissions are approximately twice as high once such offsets are recognized.	2008
Evaluating Design Options For Two U.S. Policies To Reduce Greenhouse Gas Emissions	Public Policy Analysis	Goulder	This research involved two projects to evaluate alternative design options for U.S. policies aimed at reducing emissions of greenhouse gases in the U.S.: developing a model to assess the proposed limits on greenhouse gases per mile for light duty vehicles; and developing and applying a computable general equilibrium model that considers the dynamics of productive capital to assess the impacts of alternative cap-and-trade programs at the federal level.	2009
Intertemporal Incentives for Carbon Abatement: Combining Market and Nonmarket Forces	Public Policy Analysis	Weber, Cherazi	This research investigates the dynamic aspects of the regulator's problem of implementing ambitious carbon abatement goals over a 20 to 40-year horizon, given a rational response of the private sector to boundary conditions set by the regulator. The new aspects investigated in this study include regulatory commitment, carbon-allowance trading with banking, irreversible investment in R&D, and the design of derivative carbon securities.	2009

The Dynamic Effects of the Light Bulb Ban	Public Policy Analysis	Benkard, Reguant, Wibulpolprasert	Research to examine the dynamic implications of policies regulating light bulbs by exploring the potential of dynamic preference changes for consumers that arise from policy as well as studying the role for government policy in spurring innovation. Investigators will compare the social and private incentives to invest in light bulb technologies and will consider the question of whether recent innovation in light bulbs would have been likely to happen absent government policy intervention.	2012
Better Decision Making for Policies and Programs to Reduce Electricity Use	Public Policy Analysis	Pea, Bernstein, Russell	This project seeks to aid decision making in energy-efficiency initiatives – from government policies to business campaigns – by identifying critical changes in public opinion regarding efficiency technologies and their adoption.	2013
Energy-Efficient Biodegradable Foams for Structural Insulated Panels	Engineering/ Technologies	Frank, Billington, Liao	This research developed energy-efficient, biodegradable foam materials for structural insulated panels that significantly improve heating and cooling efficiency in homes and commercial buildings. Preliminary experiments showed that uniform microcellular structure foam with 1/3 the bulk density could be obtained using PHAs, a material family that is famous for fast and complete biodegradation and that could be produced from a wide variety of feedstocks through bacteria fermentation.	2008
Process Integration and Design Optimization in Support of Energy Efficient, High Performance Building Design	Engineering/ Technologies	Haymaker, Welle	This project developed a collaborative methodology and tool for process and building analysis that reduces time required for project teams to complete meaningful design iterations. The methodology helps designers define sustainable design goals, generate many options rapidly, and evaluate tradeoffs in areas of energy, thermal comfort, daylighting, and cost. The research emphasizes that sustainable building design requires a new paradigm of performance-driven design processes.	2008
Novel Materials and Packaging for Thermoelectric Waste-Heat Recovery in Buildings and Transportation Systems	Engineering/ Technologies	Goodson, LeBlanc, Gao	This research focuses on thermoelectric power conversion for waste heat recovery in building and automotive systems by addressing the lack of interface and packaging materials that yield acceptable system efficiency, the need for thermoelectric materials combining optimal thermal, electrical, and mechanical properties at high combustion temperatures, and the absence of detailed impact assessments for consumer systems such as water heaters.	2008
Open Extensible Communication Network*	Engineering/ Technologies	Levis, Kazandjieva	This work helped establish the first Internet standard for home area networks (HANs), which is being adopted by industrial consortia such as WirelessHART and ZigBee, and is designed to support innovation. It also developed a wireless power plug meter that automatically joins a self- assembling, ad-hoc wireless mesh network; the deployed network of 200 meters allowed the team to publish detailed data at a large scale, and is informing future energy standards for computing systems.	2010
Stanford Energy Services Platform*	Engineering/ Technologies	Armel, Reeves, Bonsai Dev Corp.	This research involved improving the ease of implementation and evaluation of energy saving interventions that use sensor data via a software platform that includes data collection services, a database, analytics, and graphical user interface templates for behavioral program deployment and experimentation at Stanford and beyond.	2010

Energy Consumption Forecasts*	Engineering/ Technologies	Fischer, Rajagopal, Albert, Kavousian, Google, PG&E	This project involved creating software to segment commercial and residential customers based on their smart meter data energy consumption patterns. This information can be strategically and cost-effectively used to target customers for energy savings. Researchers used data from about 900 Google PowerMeter participants measuring electricity use every 10 minutes and a PG&E sample of approximately 12,000 customers with hourly smart meter data.	2010
Advanced Learning Automation*	Engineering/ Technologies	Aghajan, Khalili, Chen	This research looks at how automation can improve efficiency with minimal user input. The project built an automated light and TV control implementation using a network of wireless switches based on detecting the location of a user and their pose with a number of cameras. Investigators also developed a web-based user interface to capture the user's input about the automation setting and build a context-aware user profile, which was used to adapt the setting according to the user's preferences.	2010
Disaggregation Survey Paper*	Engineering/ Technologies	Armel, Gupta, Shrimali, Albert, Bidgely, Venrock	This research was designed to support development of algorithms for improved demand side management (DSM) and involved a comprehensive survey paper assessing the benefits of disaggregation (i.e., the statistical separation of the whole building energy signal into appliance level energy use data), overview of state of the art algorithms and their performance, and smart meter data suitability for these algorithms.	2010
Residential Energy Disaggregation Dataset (REDD)*	Engineering/ Technologies	Kolter, Chadwick, Armel, Flora, Enmetric	The project collected an energy data set, standardized the collection process, and made the data set publically available for developers to improve, train, and test disaggregation algorithms. REDD has been downloaded by numerous academic researchers and commercial developers. The related paper has been cited by over 85 published studies.	2010
Disaggregation Algorithms*	Engineering/ Technologies	Ng, Kolter	This project developed new algorithmic techniques that can breakdown electricity use more accurately than previous approaches, using data at a variety of different time scales. Disaggregation algorithms were developed using sparse coding methods to advance the state of the art.	2010
Identifying and Mitigating Structural Barriers to Diffusion of Energy-Saving Technologies in the Building Industry	Engineering/ Technologies	Levitt, Plambeck, Gavrieli	This research explains construction industry structure barriers to energy-saving technologies, documents successful interventions, and investigates new business models. The research describes how companies can profitably reduce GHG emissions in their supply chains, provides example case studies of different types of companies, and directs readers to additional means for reducing GHG emissions and establishing new supply chains for renewable energy and other “zero”-emission products.	2010
Improving Airflow Parameterizations within Energy Simulation Using CFD and Building Measurements	Engineering/ Technologies	Iaccarino, Fischer, Hult	This research gives guidance on selecting airflow parameters such as the discharge coefficient for windows using analytical and computational fluid dynamics (CFD) modeling as well as comparison with previous data. The research involved modifying the formula in EnergyPlus to calculate the effective area of pivoted windows to include airflow through the sides and bottom of an open, horizontally-pivoted window. Investigators found that EnergyPlus may underestimate the cooling capacity for passive ventilation by 50%.	2011

Improving Predictions of the Efficiency of Natural Ventilation in Buildings	Engineering/ Technologies	Iaccarino, Fischer	Designing buildings that rely on natural ventilation for temperature control is a relatively new science and has often resulted in uncomfortable occupants. This work seeks to advance the design and operation of such buildings to yield increased overall building efficiency without sacrificing comfort.	2013
Miniature Thermoacoustic Engines to Capture Waste Heat from Computers	Engineering/ Technologies	Hesselink, Scalo	This project will first assess the feasibility of miniature thermoacoustic engines to convert waste heat from computers and other electronic devices. The researchers will then design a preliminary version of the device, which they think could recoup at least 20 percent of the wasted heat. If fully commercialized, such technology could save $6 million dollars in electricity per day in the United States alone.	2014
Conditions for Comparison of Predicted and Measured Operational Performance of HVAC Systems	Systems Analysis	Fischer, Bazjanac, Maile	This research seeks to automate as much as possible the continuous evaluation of HVAC systems performance to provide building operators with feedback needed to run the HVAC systems more efficiently based on comparing predicted and measured HVAC system performance data. The research presents the Energy Performance Comparison Methodology (EPCM), which enables the identification of performance problems based on a comparison of measured data and simulated data representing design goals.	2007
An Integrated Conceptual Design Process for Energy, Thermal Comfort, and Daylighting	Systems Analysis	Fischer, Haymaker, Welle	This research sought to reduce the time required to complete performance-based analysis methods supported by product models during the conceptual design phase. The research demonstrated that multidisciplinary analysis (MDO), a process which has been used heavily in the automotive and aerospace industries, can be applied to the architecture, engineering, and construction industry for CAD-centric energy and daylighting simulation on a large scale and within the time constraints typical of building conceptual design.	2008
Development of a Thermo-dynamically Based Method of Incorporating Environmental Impact into Decision Making for Energy	Systems Analysis	Edwards, Simpson	This research developed an analytical method for quantifying the environmental performance of energy technologies based on thermodynamics using the concept of exergy as a form of free energy to extend the models and techniques used in technical exergy analysis to the environment. The extension enables locations, magnitudes, and types of environmental impact caused by energy systems to be evaluated on a level playing field across resources used and outputs produced.	2008
Improving the Efficiency of Combined Cooling, Heating and Power Systems	Systems Analysis	Fischer	Combined cooling, heating and power systems (CCHP) theoretically use 90 percent of the primary energy going into them, but in reality their efficiency is usually just a little better than large coal-fired power plants. This project will find out how much the efficiency of large CCHP plants (greater than 10 megawatts) can be increased by planning new campuses, neighborhoods, industrial zones, etc., with CCHP considered in early planning.	2014

*Denotes research projects that are part of the Advanced Research Projects Agency-Energy (ARPA-E)-funded Sensors and Energy Behavior Initiative

Appendix B: Examples of Some PEEC Past Projects

Behavior and Energy Efficiency

Like each of the research areas focused on through PEEC, behavior and energy efficiency studies assess what barriers exist, such as cost, time, access, and lack of information, specifically for individuals, to the efficient use of energy and what existing and potential options there are to overcome those barriers. PEEC Research Associate Dr. Carrie Armel focuses much of her research in this area, particularly on establishing energy behavior characteristics of individuals in the residential market, through methods such as surveys, and assessing what motivates certain populations to increase or decrease their energy usage.

We describe some of the behavior and energy efficiency projects in what follows.

Summer Energy Feedback Infrastructure Project

Development of this work formally began with a planning grant jointly from PEEC and Woods Institute during the summer of 2008, to professors Banny Banerjee and Scott Klemmer, and Carrie Armel. It continued with workshops as well as meetings between faculty, students, and industry and government representatives, such as Google and PG&E. The project made progress in developing research plans for a behavior, energy, and sensor program. The plans spanned the work of numerous faculty and disciplines. The project was motivated by the observation in 2008 that energy sensing technologies would soon becoming pervasive: electricity and gas smart meters are being installed in great quantities; home area networks (HANs) had been commercialized; transportation sensors that quantify miles per gallon, mode (e.g., biking or driving), and number of trips (e.g., FastTrak) were available; and HVAC diagnostics derived from sensor data were being developed.

In a different vein, work in public health and psychology had shown that quantification serves as a powerful tool in promoting behavior change. This is achieved directly by providing specific feedback, such as on the amount of electricity one consumes, and also indirectly, by enabling incentive programs, markets, competitions, visualization, quantification in game and social networking applications, automated appliance control and behavior change guidance, and many other techniques. It was believed that coupled with a well-planned behavioral program, the billions being spent on sensor technologies could be leveraged to significantly reduce U.S. energy use; without such a program the investment is jeopardized because sensor information is complex and dull, and will be underutilized.

This project served as one of the seed projects that helped inform the ARPA-E Energy Behavior Initiative and other sensor-related efforts. Without this seed project, it is unlikely that the ARPA-E project described next would have even been proposed.

The ARPA-E Project

Improved human decision making, habits, and behavior are essential to improving energy efficiency. By developing and analyzing behavioral interventions that educate and motivate people to save energy, PEEC is taking scientific research a step further and creating real world solutions, particularly in the residential market for electricity.

In 2010, the U.S. Advanced Research Projects Agency for Energy (ARPA-E) through the U.S. Department of Energy charged PEEC and Stanford's Human Sciences & Technology Advanced Research Institute (H-STAR) with forging effective ways of integrating behavioral science into smart grid technology in order to achieve meaningful energy savings. Byron Reeves was Principal Investigator for the original agreement; James Sweeney became Principal Investigator for the "Plus up" second stage; Carrie Armel was Project Director for both phases. The project is scheduled to end this spring.

The "Sensors and Energy Behavior Initiative" set out to develop a comprehensive, human-centered solution that leverages the widespread diffusion of energy sensors to reduce energy use significantly. The initiative combined known behavioral techniques with human-centered design, computation and technology in the new field of energy behavior.

The goal of the project is to leverage pervasive sensors, such as smart meters, in combination with behavioral approaches to achieve large-scale energy savings. Though currently focusing on the residential sector, this effort is applicable to transportation, water, and commercial applications as well. The Initiative is comprised of 20 projects, overseen by teams spanning technical and economic departments, including computer science, electrical engineering, and management science and engineering, as well as other fields such as psychology, education, communications, symbolic systems, and behavioral epidemiology through the School of Medicine. The projects fall within three main categories: technology, behavioral interventions, and evaluation.

Technology projects include creating the first Internet standard for home area networks (HANs) as well as an open-source reference implementation of the standard for others to copy, extend, re-use, and improve. This technology will provide greater freedom in data collection, representation, storage, and communication between devices of different manufacturers, as well as lower the barriers to entry, all leading to innovations and improvements in human interfaces to sensor-actuator networks. Behavioral intervention projects include creating a multiplayer online game and supporting social media for use in experiments and deployment in utility smart meter trials. Power House incorporated real world energy data into some of the game play, leveraged social competition, and retrained habits through reinforcement. In a laboratory experiment and field study, participants respectively increased their short-term energy efficient behaviors (turning off devices) and used significantly less energy during the weeks they used the game. This project received Phase II funding to deploy the game through Facebook. Evaluation projects included the Google Powermeter evaluation. Over 1000 individuals participated in a randomized controlled trial and showed an average of 6% energy savings in the first month or two of using the interface, which resembled many interfaces used on utility or other energy feedback websites. The study thus provided a benchmark for the comparison of other interventions, as well as a rigorous example of experimental and analysis methods for such work.

The 20 projects included in the ARPA-E funded Sensors and Energy Behavior Initiative are illustrated in Figure 6.

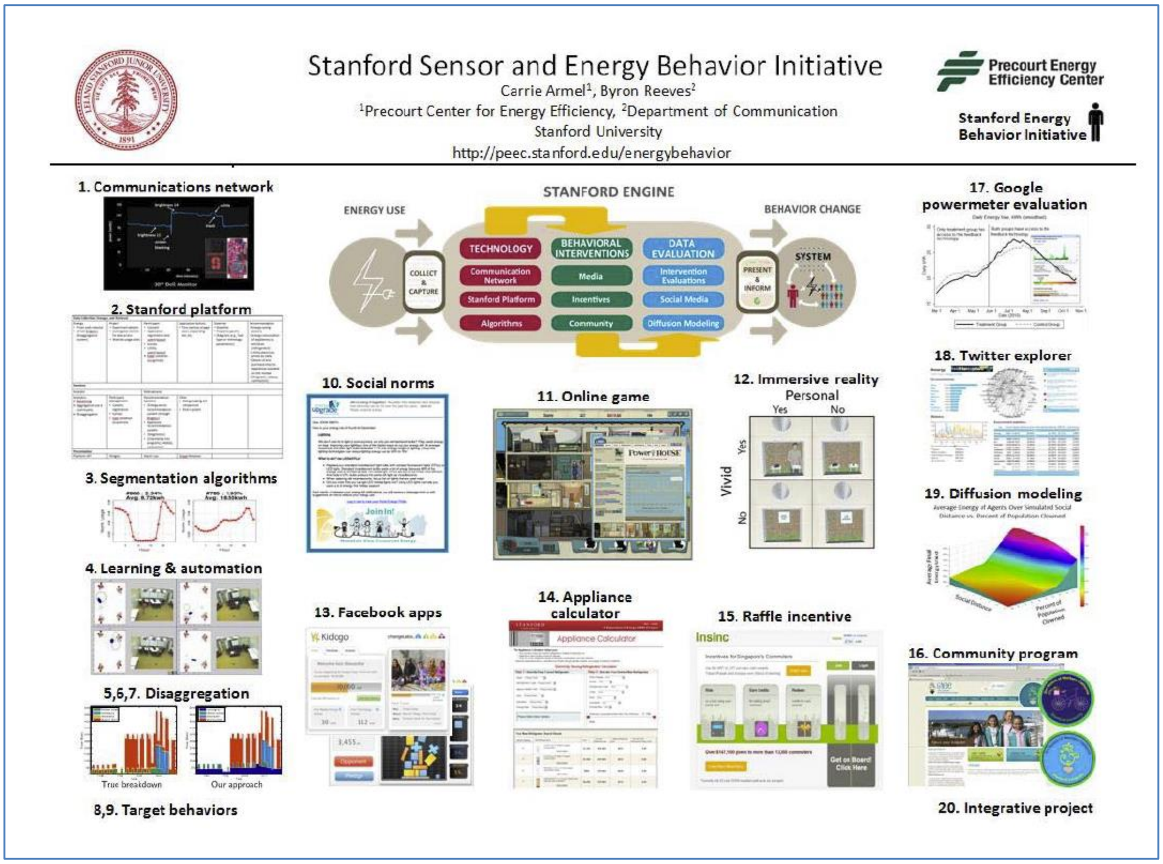


Figure 6. Projects for the ARPA-e Initiative

These projects include:

<u>Technology</u>

- Open extensible communication network
- Stanford energy services platform
- Energy consumption segmentation and forecasting
- Software to customize HAN automation
- *Disaggregation:*
  - Disaggregation survey paper
  - Residential Energy Disaggregation Dataset (REDD)
  - Disaggregation algorithms

Behavioral Interventions

Target Behaviors:

Energy behavior taxonomy
Identification of innovative energy behaviors

Media Interventions:

Multiplayer online game
Collective action feedback interface
Visual metaphors in a virtual reality environment
Motivationally framed Facebook applications

Policy Interventions:

Appliance calculator
Transportation lottery

Community Interventions:

Girl Scout “GLEE” program

Data Evaluation and Modeling

Google Powermeter evaluation
Social media analytics with Twitter explorer
Diffusion modeling of behavioral interventions

Some of these projects will be discussed more fully in what follows.

Power House: Multi-Player Online Game

The 400 million people worldwide who play multiplayer online games are surprisingly diverse, with more in their 40’s or 50’s than in their teens. Games offer a compelling new context for home energy information that may engage families and change behaviors.

One major ARPA-E project developed and tested an online, multi-player game, “Power House,” designed to display players’ actual energy use data from smart meters and other sensors. Investigators were Byron Reeves, James K. Scarborough, James J. Cummings, Leo Yeykelis, June Flora, Dante Anderson

In Power House, players are challenged with energy efficiency tasks and rewarded for real-life actions with points in the game. In the virtual home, immediate feedback in points develops efficiency habits, like always thinking about a light switch when leaving a room. Users can compete with friends on Facebook. For example, one can challenge their friends to a “lights out night” and then see who won based on the actual energy consumption data. Embedded within the overall game is a smaller game. In one mini-game, the user races around a virtual house, trying to achieve all the goals of the household members while turning appliances on and off so as to use the least amount of energy.

The laboratory experiment randomly assigned 40 participants to play Power House or a similar but non-energy game for 30 minutes. The experimenter announced that they had to leave and requested that subjects "close the office" when they were finished with the game and questionnaire. In the field study participants played the game in their homes over the course of one week to one month while their smart meter provided home energy consumption data for analysis. Participants in this study would typically play the game within a real social context. For example, while playing the game via Facebook, players were able to post in-game achievements and energy savings for their Facebook friends to see.

Among the findings:

- In the initial laboratory study, playing the game for 30 minutes resulted in significant increases in energy efficient behaviors after play ended, compared to playing the comparable non-energy focused game. In the energy game condition an average of 2.55 (out of 5) appliances were turned off when subjects left the room; in comparison, an average of .55 where turned off after playing the non-energy game. Subjects reported no conscious connection between game play and the measured energy behaviors.

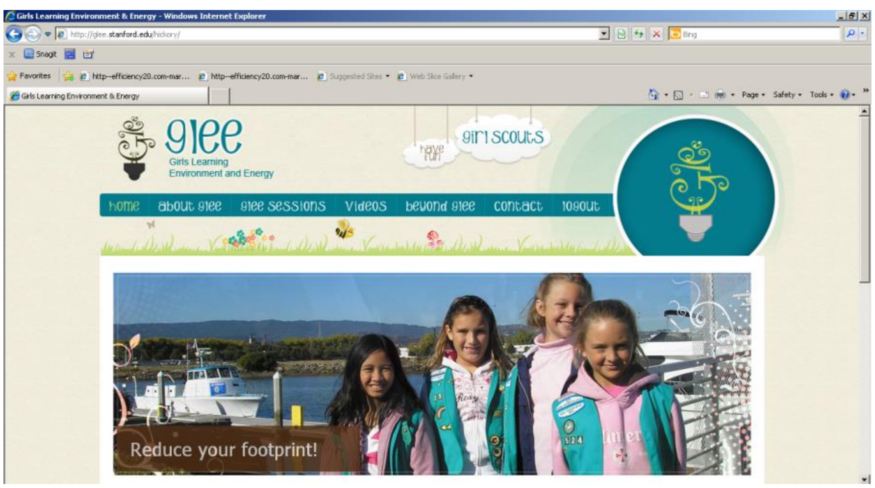
- In the broader field study, results suggest that participants use significantly less energy while they play the game.

- In the field study, energy use reduction was stronger for those participants who started with a lower energy baseline than those with a higher energy baseline. This difference might be explained by the presence of a high energy consuming device such as a pool or by a higher number of occupants in the home.

Girls Learning Environment and Energy (GLEE)

PEEC also focuses on creating solution-oriented products that create meaningful change while complimenting traditional academic research. One such example is part of the ARPA-E initiative: Girls Learning Environment and Energy (GLEE). Glee is a behavior change program developed by energy and environmental experts including those at PEEC, environmental educators, and child and family behavior change researchers at Stanford University. GLEE was developed by a team consistent of Tom Robinson, Nicole Arduin, Hilary Boudet, Carrie Armel, June Flora, and Manisha Desai.

In conjunction with 30 Girl Scout troops in northern California, this project evaluated two programs for teaching girls and their families about how to reduce energy use. One program focused on behaviors the scouts and their families could do at home. The other focused on food and transportation choices. Each troop had five sessions of activities to learn about actions people can take. The girls then created a “news” video telling others how to reduce energy. Their families could view the videos on a website that included information for parents about the program, next steps, offers for efficiency devices and audit discounts, and the ability to link in smart meter data.



Among the findings:

- Substantial changes occurred for behaviors that required adult assistance, such as adjusting refrigerator and hot water heater temperatures, replacing incandescent bulbs with compact fluorescent light bulbs, and adjusting tire pressure.

- Preliminary findings suggest increases in child-reported knowledge of energy issues from both curricula.

- Preliminary results also indicate differences in child-reported behaviors between the two treatment groups for both sets of behaviors.

This project addressed the need for energy-efficiency programs to develop more engaging community interaction and to work with youth. Key advantages of working with community programs, like the Girl Scouts, include the ripple effect from word of mouth, enhanced learning and mastery through direct experience or observation of others, and the ability to provide personalized messaging. This project worked with young people because attitudes and values start developing at an early age and are difficult to change once established. Also, the earlier children embrace sustainable lifestyles, the longer they have to influence families, schools and communities to embrace sustainable activities and policies.

All participants were given a pre-trial survey, five sessions of the relevant curriculum, a post-trial survey and a follow-up survey several months later.

The researchers partnered with the Girl Scouts of Northern California to develop and test the program. Researchers developed a curriculum for potential expansion throughout Girl Scouts USA. Although originally developed for Girl Scouts, the GLEE program could easily be adapted to other learning environments and the curriculum is publically available.

Energy consumption, segmentation and forecasting

Another major project with the ARPA-E initiative focused on statistical analysis of energy consumption time patterns, that would allow utilities to segment their customer base, forecast the impacts of demand-side-management programs, and therefore cost-effectively target programs to specific classes of customers. This project was led by Ram Rajagopal and included Martin Fischer, June Flora, and students Jung Suk Kwac, Adrian Albert, Amir Kavousian, and Jeff Wong.

Currently, electric utilities generally market demand-response and energy-efficiency programs to very broad groups, such as residential customers and small businesses, without knowing which programs are reducing consumption during periods of very high demand or, in the case of efficiency, eliminating waste. A major promise of smart grid meters is to make such programs more effective, yet using the vast amounts of data from smart meters for this is poorly understood. This project experimented with several methods to process data to inform groups of customers about the most worthwhile efficiency measures to consider, to understand the demand-response potential in particular circumstances, and to help utilities provide energy at minimum cost and with minimum environmental impact.

This project segmented utility customers into groups that exhibit similar energy consumption behaviors, based on a detailed history of energy consumption, plus information about building locations, demographics and weather conditions at the time of consumption. It used data from about 900 Google PowerMeter participants measuring electricity use every 10 minutes and a PG&E sample of approximately 12,000 customers with hourly smart meter data. Among the findings:

- A population of about 1,000 users can be segmented into about 10 groups for demand response, and a scalable clustering technique that uses a statistically meaningful distributional metric was developed.
- Using hourly electricity and weather readings to characterize residential customers' temperature-dependent consumption such as air conditioning or heating, segmentation and targeting of users may offer savings twice that of current demand-response programs.
- About 900 households users may be described with good confidence by 13 patterns, with certain types of appliances and behaviors related to appliance operation affecting consumption patterns most. Consumption statistics may be used to target residential energy efficiency programs to achieve greatest impact in curtailing cost of service.
- Inferring occupancy states from consumption time series data showed that temporal patterns in the user's consumption data can predict user consumption at a population level.
- The number of refrigerators and entertainment devices (e.g., VCRs) are among the most important determinants of daily minimum consumption, while the number of occupants and high-consumption appliances such as electric water heaters are the most significant determinants of daily maximum consumption.
- Acknowledging climate change as a motivation to save energy showed correlation with lower electricity consumption.
- Contrary to some previous studies, the researchers observed no significant correlation between electricity consumption and income level, home ownership, or building age.
- Some otherwise energy-efficient features such as energy-efficient appliances, programmable thermostats and insulation were correlated with a slight increase in electricity consumption.

As a part of the project, the team developed a software engine, Stanford Energy Visualization and Insight System for Demand Operations and Management (VISDOM), that has now been implemented within PG&E. VISDOM is a versatile web-based platform that provides tools to enable users to quickly and interactively analyze and visualize statistics of large data to design and evaluate demand side management programs at the utility scale.

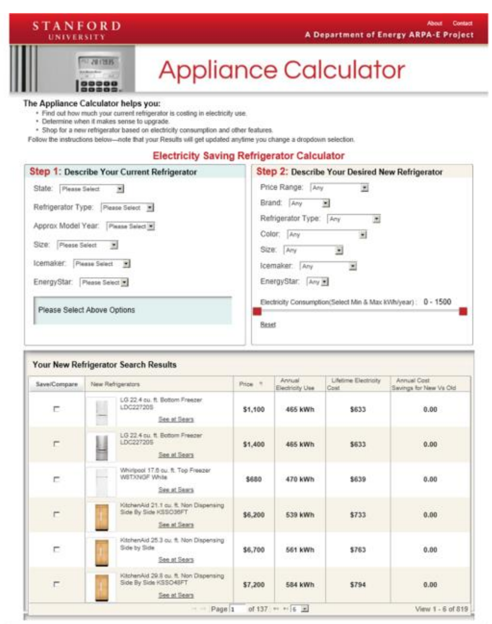
The team has received an Innovation Transfer grant from TomKat Center to try to commercialize VISDOM.

ARPA-E Integrative Project

Discussions with utilities and VC firms have indicated that a main issue with getting our Stanford Energy Behavior Initiative programs tested in a utility trial or pursued for commercialization is that none create a sufficiently comprehensive solution. Carrie Armel proposed this ARPA-E Plus-Up project and is its lead investigator. The goal is to integrate individual projects from the Initiative in order to create a comprehensive solution to achieve both deep energy savings on a per household basis, and widespread adoption. We expect success because the original portfolio of projects was strategically selected with this aim in mind, substantial learnings have been acquired over the course of the Initiative, and these learnings have improved upon the components and informed the design of an over-arching system. The Integrative Project is organized into four system components:

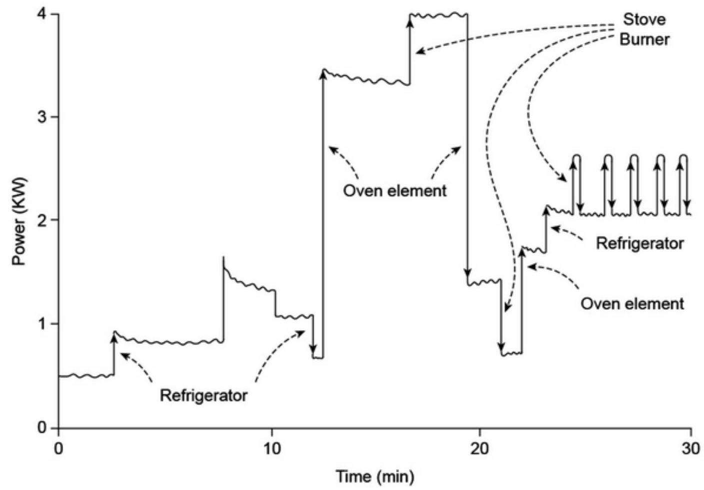
The first component focuses on <u>Energy Saving Actions (ESA) through an Applet Centered Design</u>. Having users perform energy saving actions, such as changing settings or replacing appliances, is essential for actually achieving energy savings. Yet, to date, others' energy saving programs primarily attempt to increase general motivation and at best list actions users can take to achieve savings, leaving the actions themselves boring and the barriers to be overcome and steps required to accomplish the actions up to the user. In contrast, we aim to create applets focused on quickly and engagingly overcoming barriers and moving the user through the required steps to action.

We strategically implement this approach within applets (or small applications) to allow for modularity. We are leveraging some of our existing projects to accomplish this, such as the Appliance Calculator and game module of PowerHouse. Additional applets will be required to cover a suite of actions.



The second component is the use of <u>analytics in the Central Hub</u> to guide users on *which* applets to use and actions to perform. This is key because we believe the single biggest factor in preventing energy efficiency upgrades in the residential sector (and perhaps small and medium business sector as well) is that the cost of labor required for auditing personalized recommendations is greater than earnings that can be generated through the identified efficiency improvements. The knowledge and effort required for the vast majority of individuals to determine this on their own is infeasible.

The analytics will generate personalized recommendations through an automated system. The key analytics required to support such an automated system includes disaggregation (informed by Armel and Kolter projects, as well as Flora behaviors project, although we would interface with the system of our commercial partner Bidgely for this project) and segmentation based on energy consumption patterns (Fischer and Rajagopal project).



The third component is the layering of narrative on the system, to create engagement and stickiness. In addition to increasing engagement and stickiness, the narrative serves a variety of purposes in this project; for example, it provides cohesion across otherwise unrelated applets, and provides a framework for users to understand their own journey and goals through the system. Based on engagement potential and technical constraints and opportunities, we selected as a narrative the ‘Energy Whisperer’ reality show concept to test. This is intended to be a humorous spoof on the popular Dog Whisperer TV show, in that the charismatic whisperer Cesar helps ‘train’ animated appliances that become unruly when ‘consuming’ too much energy. This novel use of media is hoped to increase engagement in and of itself.

These three components are primarily focused on achieving deep energy savings on a per household basis. We are working on the challenge to get people to the system in first place, i.e., achieve widespread adoption.

In summary, this attempt to realize the energy saving potential of the work performed on the Stanford Energy Behavior Initiative involves integration of multiple projects, within an architecture that includes several innovations. The three components are summarized in Table 3.

Integrative Project System Component	Relevant Projects from Existing ARPA-E Portfolio
Energy Saving Actions (ESA) in an Applet Centered Design	Appliance Calculator, game module of PowerHouse game
Analytics in a Central Hub	Disaggregation and behavioral recommendations, segmentation, the energy services platform; Learnings from PowerDown and ChangeLab's cognitive interface
Narrative	Learnings from the metaphor project
Use of Multiple Existing Low-Cost, High Diffusion Channels	Learnings from and elements developed in Appliance Calculator (Google AdWords), PowerHouse, ChangeLabs projects (Facebook), and GLEE (large community-based networks)

Table 3. Systems Components for Integrative Project

Behavior and Energy Website: Bibliographic Database and Other Tools

The interdisciplinary website and integrated literature database contain key work relevant to energy decisions and behaviors, for behaviors occurring at the individual and group levels. The goal of the site is to accelerate the adoption and sustained use of energy-efficient technologies and climate-positive actions. The tools enable visitors to increase the effectiveness of policies, research, and programs, and to foster interdisciplinary and trans-sector communication and work. The audience includes researchers, policymakers, and program/communication designers at universities, businesses, and governmental or non-governmental organizations. The research is compiled from currently disparate areas including psychology, behavioral economics, diffusion of innovation, marketing, program evaluation, technology commercialization, and others. To the best of our knowledge, this is by far the most comprehensive website and database for behavior, energy, and climate change.

Experiments with Appliance Choice

Beyond the research being conducted within the Sensors and Energy Behavior Initiative, PEEC has also contributed seed funding to faculty members, students, and post-doctoral fellows to create more nuanced understanding the "energy efficiency gap." The "energy efficiency gap" describes the observation that consumers and businesses seem to make decisions that lead to more energy use than that which would apparently minimize their cost to achieve the given level of energy services. It generally believed that the "energy efficiency gap" arises from the various behavioral barriers shows in Table 1.

One sequence of projects involves experiments with appliance choice led by Psychology Professor Brian Knutson, his graduate student Nik Sawe, and Research Associate Anshuman Sahoo. This suite of experiments on appliance choice tests for heterogeneity in decision-making processes among consumers and examines the role of behavioral nudges such as the eco-labeling of appliance alternatives in shifting consumers' decision-making modalities

This work uses a combination of national econometric and psychometric surveys and neuroimaging behavioral experiments to study consumer purchases of energy-efficient

products and the effect of the Energy Star label. Survey work has revealed that high mathematical ability is associated with initially undervaluing savings from energy efficiency, while strong pro-environmental attitudes are associated with overvaluing those savings. The Energy Star increases willingness-to-pay for energy efficiency in both groups, mitigating undervaluation in those with high math skills. The ongoing neuroimaging work has found that the Energy Star label activates the brain's "reward pathway", associated with positive emotions, in a similar (and additive) way to low prices. This reward pathway activation significantly predicts the purchasing of CFL light bulbs in both the neuroimaging and national populations, indicating that neuroimaging of a small sample (36 individuals) can successfully predict energy-efficient consumer behavior at scale (1,550 survey respondents), and is able to do so more accurately than the conscious choices of the same 36 individuals. This is in keeping with recent neuroimaging findings for everything from music sales to the efficacy of anti-smoking ad campaigns and microloan funding campaigns, where the neural data from small focus groups has predicted national behaviors better than the groups' conscious decisions. Work in the near future will concentrate on optimizing the design of eco-labeling and energy conservation messaging, and attempting to predict behavioral effects from energy conservation interventions at the population level using brain imaging.
An implicit assumption in much of policy design is that nudges do not alter the decision-making methodology a consumer employs. However, this sequence of studies implies that behavioral economic policy design and analysis will need to consider the impact of policy on the distribution of decision making processes and the normative implications of subsequent choices.

Resources, programs, and tools developed at PEEC and available on the website

Carrie Armel has organized an extensive set of resources in the PEEC website, including a bibliographic database, foundational readings, PEEC programs and interventions, PEEC program development and evaluation tools, and tools developed within the ARPA-E initiative.

- Readings
  - Bibliographic database (see below for more detail)
  - Foundational Readings. Based on the most common inquiries PEEC receives regarding behavior and energy, we provide a bibliography – and links to articles when legitimate to do so – for the foundational readings in each area: Reviews on Behavior and Energy, Integrated Intervention Approaches, Communication, Social Psychology, Diffusion, Technology Design, Behavior as Related to Economics and Modeling
- PEEC Programs/Interventions (Corresponding publications can be viewed here: http://peec.stanford.edu/behavior/library.php)
  - High School Curriculum (adapted by others such as the Sierra Club) http://peec.stanford.edu/behavior/HighSchoolCurriculum.php
  - Girl Scouts Learning Environment & Energy (GLEE) (Nationally disseminated) https://healthimprovement.stanford.edu/GLEE/

  - Appliance Calculator (60,000 users in first year; temporarily disabled for upgrades)
  - Integrative Project combining effective elements of ARPA-E programs ("Energy Whisperer") http://energywhisperer.org/ and https://howpower.org/ (~1500 clicks and 300 engaged users per month; major enhancements in process)
- PEEC Program Development and Evaluation Tools
  - Detailed stand-alone Program Development resources derived from a Hackathon workshop where these were tested http://peec.stanford.edu/energybehavior/events_datajam.php
  - 350 Residential Building Energy Actions Database & attributes ratings to aid program developers in selecting actions and clusters of actions to target http://authors.elsevier.com/a/1SlS-_6se4FPpw
  - Survey for measuring self-reported energy actions http://www.stanford.edu/group/peec/cgi-bin/docs/behavior/research/Stanford CCBehav Survey final.pdf (Corresponding publication: http://peec.stanford.edu/behavior/library.php)
  - Survey to supplement sensor measures, and utilized in Google Powermeter Energy Journal paper http://www.stanford.edu/group/peec/cgi-bin/docs/behavior/research/FieldExperimentPowermeter_vrevised_May2012_authors_vf_pdf.pdf
  - Intervention paper w/guidance on application of behavioral principles and designing interventions (see High School Curriculum publication above)
- PEEC Disaggregation Resources
  - Disaggregation policy recommendations, short overview video and detailed paper (30k downloads in the first year) http://peec.stanford.edu/behavior/library.php
  - Reference Energy Disaggregation Dataset (REDD) Database, and Protocol for data collection (for others to replicate), to aid researchers in improving disaggregation algorithms: http://redd.csail.mit.edu/ and a larger 30 home set available (enabled many papers on the topic and additional datasets, like BLUED)
  - Our first workshop on the topic spawned ongoing bi-annual workshops
- ARPA-E Energy Services Platform, a computational platform, supports the development, implementation, and evaluation of web-based behavioral programs
- Learnings from Phase I ARPA-E Sensor, Energy, & Behavior projects
  - Website: http://peec.stanford.edu/energybehavior/index.php
  - 100 page summary: http://www.energy.ca.gov/2015publications/CEC-500-2015-056/CEC-500-2015-056.pdf

Bibliographic Database. Accessing literature related to behavior and decision-making vis-a-vis energy or climate change is difficult through traditional academic databases and web searches: not only are practitioners typically unfamiliar what disciplines or techniques might be relevant for their situation, but even scientists working in behavioral fields find it difficult to locate articles given they are spread across more than a dozen disciplines, each with its own terminology for sometimes overlapping concepts. Our database (Figure 7, pictured below) pulls together over 1000 of these publications, spanning the myriad of disciplines (see below for examples), and includes work on individual, group, and institutional behavior, specifically pertaining to either energy or climate change. For disciplines that currently have few papers on environmental topics, literature includes reviews or seminal papers on theory and findings that could be translated into the energy domain. The entries in the database typically include the citation elements, abstract, and a permanent link to the article when available (i.e., stable or persistent URLs or permalinks, or when those are not available then Google Scholar links) for easy access.

- Social Marketing
- Behavioral Economics
- Anthropology/Ethnographic Research
- Risk Evaluation
- Energy Program Evaluation especially Process Evaluation
- Public Opinion Polling
- Advertising/Communication Research
- Consumer Behavior Research
- Technology Commercialization
- Diffusion of Innovation
- Psychology (e.g., Social, Cognitive, Conservation Psychology)
- Education
- Public Health (e.g., including successful anti-smoking campaigns or diffusion research in behavioral epidemiology)
-

Figure 7. PEEC Behavior Bibliographic Database

Institutional Analysis and Energy Efficiency

PEEC has engaged in a number of research projects that approach the invention, commercial design, and adoption of energy-using technologies through the related analytical frames of institutions and organizations. The scope of activities are consistent with those associated with the Society for Institutional and Organizational Economics: "Theoretical and empirical investigation of the nature, behavior, and governance of organizations and institutions using approaches drawn from economics, organization theory, law, political science, and other social sciences."

Dr. Margaret Taylor, research staff member of PEEC and the Stanford chair of the annual BECC conference since 2013, is the point person on these activities. A number of PEEC affiliates have also conducted institutional analytic research over the years, however, including: the Stanford University doctoral dissertation work of Prof. Sebastien Houde (Univ. of Maryland) on the effects of labeling highly efficient appliances under conditions of imperfect competition and research by Stanford Prof. Martin Fisher on integrated building delivery. In addition, several PEEC seed grants and funded projects fit into an institutional analysis framework, including research on the manufacture of high-efficiency lighting by Stanford Graduate School of Business faculty.

The following is a partial listing of relevant projects led by Dr. Taylor.

Producers, Intermediaries, and Innovation and the Energy-Efficiency Gap

The economic justification for energy efficiency policy primarily focuses on the market failures and barriers that prevent energy consumers from undertaking privately valuable investments in efficiency. These consumer-focused market imperfections are the subject of a substantial and growing body of research regarding the incentives that influence the demand for energy-efficient technologies. The literature has focused much less, however, on the producers of energy-using technologies who supply, on the basis of competitive forces, the potential technology choice sets for consumers to adopt. Relevant issues include decisions regarding research and development activities, supply chain management, risk management, marketing approaches, etc.

In this project, Dr. Taylor worked with Dr. Carl Blumstein, the director and one of the founders of the California Institute for Energy and Environment, to focus on the question: How could supplier strategy issues help explain the observed "energy efficiency gap" between the privately optimal energy efficiency of goods and services and the observed energy efficiency of goods and services? The project began by reviewing the literature on the energy-efficiency gap and the different intellectual paradigms that have been brought to bear on it. The project team then considered examples of apparent market imperfections on the supply side of energy-efficient technology development, with particular attention on the concentration of the industries involved in the manufacture of appliances and other products that energy-efficiency policy address. A central point of the paper that resulted from the project was the observation that the efficiency gap is dynamic, changing over time and with the processes of innovation; the invention of new, more energy-efficient technologies can widen the gap, while the refinement and take-up of such technologies can narrow it. The paper concluded with a discussion of interventions on the supply side that could encourage a reduction in the energy-efficiency gap.

Shifting the Focus from Emissions to Competitive Strategy: Towards a New Conceptual Framework of Climate Policy and Innovation

The dominant framing of current climate policy efforts is based on resolving the market failure of pollution associated with economically productive activities by employing "market-based" instruments that attempt to internalize the costs of pollution. This framing treats incentivizing innovation as an issue of indirect and secondary importance, although many argue that changing the current rate and direction of technological change is the most important lever to achieve climate stabilization while meeting the needs and aspirations of a growing global population. In this project, Dr. Taylor worked with Dr. Tobias Schmidt, a professor at ETH Zurich, to try to reconceive the framework of climate policy to emphasize the incentivizing of innovation as a top priority. Unfortunately, several leading schools of innovation scholarship tend to be descriptive and do not easily lend themselves to the sort of prescriptive policy modeling that underlies the policy design process. Rather than incorporate these schools fully into a new framework, Dr. Taylor and Dr. Schmidt focus on three aspects of how innovation occurs in industry.

First, the design, production, and diffusion of new technologies are crucially dependent on value chains that span various actors, industrial sectors, and geographies, as organized through market transactions. Second, sources of and barriers to innovation emerge from the individual strategic concerns of each actor in a value chain. Third, innovation can be affected by transactions between actors in value chains that are not "arm's length" market relations, but involve imperfect power dynamics (e.g., issues of trust, hierarchies, etc.). The papers that have resulted from this project, to date, consider the implications of this reconceptualization – and related observations of the pervasiveness of imperfect competition in energy supply and energy demand-related value chains – for policy, political science, and for climate modeling (to a lesser degree).

New Directions for Energy and Behavior: Whither Organizational Research?

In this project, Dr. Taylor worked first with PEEC research staff member Dr. Armel and then with Dr. Kathryn Janda, a senior researcher at the Environmental Change Institute at Oxford University, to provide practical, theoretical, and structural grounding for research on organizations in the energy system. By engaging with two of the leading frameworks for structuring behavioral research in energy, the project illustrated the importance of organizations in the energy system. The project also reviewed the existing research on organizations in the energy literature, with an emphasis on the action-orientation of the organization studied (specifically, organizations that consume energy-using goods and services and organizations that create such goods and services through value chains). The project also reviewed both internally-oriented and externally oriented theories related to the behavior of organizations, outside the energy domain, and provided two energy domain examples where applying a theory-driven approach led to novel insights. The paper that resulted from the project, coauthored by Dr. Taylor and Dr. Janda, provides a structure that ties together organizational actions in the energy system with organizational theory orientations. The hope is that this structure will help make the literature more accessible and expose important knowledge gaps.

Confronting Regulatory Cost and Quality Expectations: An Exploration of Technical Change in Minimum Efficiency Performance Standards

This project departed from the focus of the previous projects, which considered the organizational ecosystem for innovation in energy efficiency. Instead, the focus of this project was on how the legal institutions of energy efficiency policy affect innovation in energy-using technologies. For the purposes of this project, the innovative outcomes of interest pertained to product design and the price and quality of products purchased in the U.S. after regulation.

In this project, Dr. Taylor collaborated with Dr. Anna Spurlock and Ms. Hung-Chia Yang from Lawrence Berkeley National Laboratory (LBNL) to conduct a "retrospective review" of U.S. minimum efficiency performance standards (MEPS) for five energy-using products (room air conditioners, refrigerator/freezers, dishwashers, clothes washers, and clothes dryers). The team explored seven research questions centered on whether and how product price, quality, and design changed after regulation, and how the results compared to regulatory expectations. Six of the research questions were informed by hypotheses drawn from various literatures; the seventh was fully exploratory, focused on how well the MEPS rulemaking analysis process treats product design.

The empirical nature of this retrospective review project, which was co-funded by PEEC, Resources for the Future, and Lawrence Berkeley National Laboratory (LBNL), represented another point of departure from the other research projects described above. The project team drew on an extensive amount of data in the course of this project. *Ex ante* (expectations) data included rulemaking analyses and other documents in the regulatory docket. *Ex post* (observations) data included rich, often high resolution data covering several aspects of product price, quality, and design: (1) extensive 2003-2011 U.S. point-of-sale data on appliance models matched to model energy use data (for all but clothes dryers) which facilitated construction of a monthly panel of model-specific prices, quality characteristics, and market shares; (2) author-constructed datasets from independent third party appliance testing and product reliability surveys; and (3) an author-constructed dataset of the features identified in the product manuals of 1,109 clothes washer models sold in the U.S. in 2003-11 (these models represented 95% of the identifiable models in the point-of-sale data, which account for 29% of U.S. units sold over that period).

Key findings, which were generally consistent with hypotheses, included: (1) MEPS rulemaking analyses significantly overestimated observed product prices; (2) the energy efficiency of products purchased after regulation generally exceeded the regulated standards (as well as rulemaking expectations of market share for the one case appliance for which these expectations existed); (3) unregulated aspects of product quality at the time of sale often improved in conjunction with MEPS events, at least according to available models reported on in third-party testing; (4) product reliability generally improved over the period of time the products have been regulated; (5) within-model price declines (i.e., product-level price declines without consideration of model entry or exit) occurred across products, and these declines were better differentiated by product architecture than by energy efficiency levels for the two products we analyzed; (6) the dominant design of one product, clothes washers, adapted in only a few years to MEPS that were originally expected to be so "technology-forcing" that they were deemed likely to eliminate that design from the U.S. market; and (7) for one product, clothes washers, highly correlated product features contributed both to regulatory performance and to unregulated aspects of product quality.

The project results indicate several possible implications of relevance to the economic justification for MEPS, including: that the positive economic impacts of MEPS on consumers may have been underestimated; that the initial price of efficient products may not be of as great a concern as its analytical priority in the rulemaking process suggests, given the existence of lower-than-expected product prices that decline as regulated models remain on the market; that the projected energy savings of MEPS may have been underestimated; that the MEPS process may have generally succeeded in ensuring the retention of product utility and performance under regulation; that the part of regulated product maintenance costs that is tied to significant repair events may have declined over time across products; and that the concept of product architecture may be more useful to technical elements of MEPS cost analyses than a disaggregated approach to product design at the level of product features (i.e., design options, product components, etc.).

The project results also raise several questions for future research. Questions of relevance to MEPS policy include: what makes a product architecture more or less adaptable to a stringent standard; how can MEPS technical feasibility criteria better avoid a present-day bias in identifying efficiency-enabling design options and overly pessimistic expectations about future commercial viability; what are the most appropriate combinations of design options for developing cost-efficiency relationships. Questions of relevance to the relationship between regulation and innovation include: whether the innovation purpose of energy reduction might prompt systemic design changes that could tie to the Porter Hypothesis; what is the nature of the political economy of "technology-forcing," "performance-based," and "technology-based" regulation in the MEPS context; how does information asymmetry affect the MEPS rulemaking process; and what is the role of human behavior in regulatory cost and benefit errors.

Several follow-on projects and academic papers are expected for this product, which has so far been the source of a 100+ page report and the anchor of a session Dr. Taylor coordinated at the Academy of Management in August 2015, “Environmental Governance and Technology: Opening the Black Box.” This session brought some of this research (“Product Regulation and Innovation in the Marketplace: Confronting Expectations with Empirical Evidence in Durable Goods” together with papers on energy storage innovation and supply-chain sustainability by Prof. Schmidt and Prof. Tim Smith of University of Minnesota, respectively. The discussants were Prof. Magali Delmas of UCLA and Prof. Stu Graham of Georgia Tech.

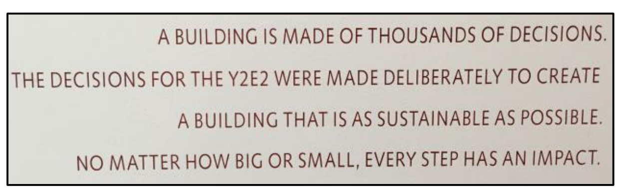
Building Energy Use

Energy used by and within residential and commercial buildings account for 40% of all energy used in the United States, and commercial buildings account for the largest portion of peak demand in most regions. Energy intensity (Btu/sf) and electric intensity (KWh/sf) in commercial buildings during the years 1990 – 1999 increased by 12% and 18% respectively over previous thirty-year averages, and residential energy use is predicted to increase another 27% by the year 2025.

The heating, cooling, lighting, and use of electrical appliances in commercial and residential buildings emit about a third of the greenhouse gases in modern economies. Appliances have risen significantly as a portion of the energy used in households, while heating and cooling no longer make up a majority of U.S. household energy use. Many energy saving technologies can have quick payback on investments for both old and new construction, yet they have not been fully implemented.

PEEC is a globally recognized center of excellence in performance-based models and metrics of building operations, process, and design. PEEC research seeks to reduce energy waste through improved building design, construction and operation. There are existing technologies and knowledge that could be used to create better, high-performance buildings. In fact, combined with better systems integration, they could cost-effectively achieve savings as high as 50% in new buildings, as compared to minimally code compliant structures. Existing retrofit technologies and retro-commissioning practices could provide economically efficient additional energy savings in the range of between 5% and 20% in existing buildings.

Energy efficiency in buildings is governed by a multitude of human decisions in the building design, construction, and operation. This point is made eloquently by a sign painted on the wall of the Yang and Yamazaki Energy and Environment (Y2E2) Building at Stanford University, and shown in the box to the right.



Fragmented Design, Construction, and Operation Practices

One PEEC-funded study, for example, showed that advancements in energy efficiency in the residential and commercial building sectors in California and the United States are currently falling short of the potential. Professor of Civil and Environmental Engineering Raymond Levitt, Professor Erica Plambeck of Stanford's Graduate School of Business, and graduate student Dana Gavriell showed how fragmented design, construction, and operation practices and phases impact the timely and effective implementation and integration of these energy efficiency methods and technologies on every new building and renovation project. Levitt, Plambeck, and Gavriell hypothesized that the extremely slow diffusion of energy-saving building technologies with positive short term paybacks for both new and existing buildings is a result of the horizontally and vertically fragmented structure of the building industry, its susceptibility to extremely large fluctuations in demand, its tradition of partitioned competitive bidding, and the broken agency between decision-makers involved in capital vs. operating decisions in this industry. Their work involves identifying and documenting the key organizational, inter-organizational, and industry barriers to widespread adoption of energy-saving building technologies.

In addition to cost, aesthetics is the other main criterion for decision making about design alternatives in the early phases of a project. The process minimizes cost at every step and focuses mostly on what can be seen. The consideration of other criteria, such as energy concerns and end-user needs, is not adequately incentivized leading to ineffective building design, ineffective operations, and a limited feedback between the design phase and use phase in the life of a building.

That same study showed that integration of supply chains from manufacture through maintenance can help overcome the barriers of the decentralized U.S. building industry. The study provides case studies to document examples of governmental regulations or incentives and corporate strategies that have successfully overcome these barriers. Through this understanding, they recommend strategic and policy interventions that can overcome these barriers and market those recommendations to industry leaders through executive education.

Performance-based Models for Energy Efficiency in Building Design

Energy performance issues in building design often result because architects and engineers lack the time, money, processes, and tools to consider a wide enough variety of design options. Design teams trying to optimize energy, thermal comfort, daylighting, cost, and other forms of building performance require far more systematic, iterative, and collaborative design processes and tools. Significant progress has been made in many forms of building performance models. For example, structural analysis and daylighting software yield highly accurate predictions of building performance for specific criteria. Other performance models, such as energy prediction and building ventilation, continue to progress, although the gap between predicted and actual building performance can often still be large. Other, more subjective or difficult to formalize models of building performance, such as building egress, constructability, durability, and even aesthetics, continue to evolve.

Over the past nine years, PEEC researchers have been working extensively in these areas, drawing on the expertise at the Center for Integrated Facility Engineering (CIFE) at Stanford. CIFE has been developing performance-based models since 1988. PEEC takes this expertise available at Stanford and focuses research on performance-based models developed explicitly for assessing energy efficiency and on integrating energy efficiency concepts into other performance-based models. Civil Engineering Professor John Haymaker[7] and Graduate Student Benjamin Welle developed and tested a collaborative methodology and tool, for both process and building analysis, that reduces the time required for project teams to complete meaningful design iterations. By improving modeling and optimization options, their research provides design teams the tools and processes they need during early concept design that take into account a project's participants, goals, preferences, schedule, budget, and building delivery process to dramatically increase the number of design options considered.

These researchers have been developing and testing guidelines and methods for building owners and design teams to incorporate energy efficiency and end-user input into the design process. The application of these methods needs to span from early project definition through design development, construction, commissioning, operation, and disassembly and must consider not only the energy performance of buildings (the "product" that is designed, built, and used), but also the organizations that plan, design, build, and operate a building and the processes of the various project stakeholders. These performance-based models will enable project teams to design and manage the product, organization, and process (POP) for a project in an integrated way, and provide guidance for the timely and effective incorporation of specific energy efficiency technologies and design methods by specifying the appropriate design steps, stakeholders, and decision criteria at each point along the way. PEEC research includes performance-based models and metrics of the building product, including components, systems, spaces, occupants, and operators; performance-based models and metrics of the organizations and processes that design and manage buildings; methods for integrating these product, organization, and process models into projects that consistently deliver effective, energy efficient buildings; and implementation, verification, and calibration of these models, methods, and metrics in education and practice.

Barriers to Energy Efficiency Stemming from Building Operators

Some of Haymaker's other work addresses the issue that well-founded models of building operants are largely missing from the early phases of the design process by studying actual building operants and comparing them to the design assumptions to improve both the values and variables used to describe building operants. Operants' misuse and misunderstanding of energy efficiency technology is a key factor in building

[7] Professor Haymaker is no longer at Stanford University, but now is Perkins+Will's Director of Research.

underperformance. PEEC envisions a design process in which the project team first designs a realistic model of the building operants, and then designs and analyzes building performance taking into account the behavior of these stakeholders. These models have to be flexible and probabilistic to anticipate changing building demands, but without a better model of the drivers of our buildings, we cannot realistically hope to achieve buildings that are efficient and effective.

Virtual Design Teams for Building Performance

To design and manage an effective building, a project must also design and manage an effective organization and process to deliver that building. PEEC affiliated faculty Raymond Levitt et al. have developed the Virtual Design Team model that represents the design organization and the process that an organization must execute, and analyzes the model for schedule and design error risk which leads to ineffective building performance. PEEC affiliated faculty Martin Fischer et al. have pioneered the use of 4D modeling, enabling design and construction professionals to integrate their 3-dimensional designs with time-based processes to identify efficient project phasing and scheduling strategies and identify costly and ineffective processes.

Such process and organization models help project teams design, visualize, and analyze the multidisciplinary performance of their projects (products, organizations, and processes). PEEC will continue to develop such models and apply them to the design and construction of energy efficient buildings. These organization and process models will highlight when specific decisions with respect to energy efficiency need to be made, who needs to be involved when in a project, what tasks they will perform based on what input, etc. In summary, these organization and process models will provide a roadmap for implementing energy efficient methods and technologies and complement product-based guidelines for installation of a particular technology.

A major challenge to professionals will be how to integrate the growing list of requirements and models into multidisciplinary design and analysis processes that produce effective buildings. Collaboratively between PEEC and CIFE were designed Narratives that describe the products, processes, and organizations employed to develop effective, energy efficient buildings. These Narratives can then be reused and adapted to suit unique project requirements and can evolve to incorporate new performance models as they are developed. Our view is that integrated POP (Product, Organization, and Process) models, methods, and metrics are needed to achieve far-reaching and quantifiable industry results of decreased energy use and increased environmental quality in constructed buildings. To achieve these results, PEEC worked with students and industry to implement these models, methods, and metrics in education and practice, and to verify and calibrate their performance.

Unparalleled industry partnerships available through CIFE and created through PEEC see implementation and evaluations on ongoing actual building design, construction, and operation projects. Through PEEC, CIFE's current work in improving the building delivery process and its underlying mission to speed the transfer of the integration and virtual design and construction technologies into practice will be applied to directly advance the goal of energy efficiency in built projects.

PEEC works with the Stanford Department of Civil & Environmental Engineering (CEE), CIFE, Construction Engineering & Management Program at Stanford, and the Stanford Architectural Design Program to lead the field in sustainability, with a focus on the core issue of energy efficiency.

Cleantech Operations and Supply Chain Management

A follow-on to the research on fragmented design, construction, and operation practices was published in the Journal *Manufacturing & Service Operations Management.* That study describes operations management challenges faced by five "cleantech" companies (i.e. firms that have a technology and/or business model for serving an existing market with a reduced environmental impact) and illustrates how companies can reduce greenhouse gas emissions in a cost-effective or even profitable way under their direct and indirect control. It also describes operations and supply chain management literature that shows insights on other ways that companies can reduce greenhouse gas emissions and establish new supply chains for renewable energy. By focusing on and changing operations and the supply chain, this research has effective implications that can be used immediately by various corporations and organizations to increase efficiency.

Energy Modeling

Developing meaningful solutions to pressing energy efficiency issues often involves modeling in order to forecast future demand for electricity, natural gas and oil. With accurate energy policy models, we can design, evaluate, and understand novel energy policy approaches and the impact of energy technologies currently under development through simulations and studies. PEEC has included several energy modeling projects.

Energy Efficiency in the Residential and Commercial Sectors of the National Energy Modeling System

For many years has been reason to expect that the way existing large scale energy models are calibrated may lead them to underestimate of the future rate of adoption of energy efficiency measures. One attempt to explore this potential model bias was a research project by a group of advanced PEEC and Energy Modeling Forum graduate students working with John Weyant. This work looked at how the residential and commercial sectors are represented in the National Energy Modeling System (NEMS) which is maintained by the Energy Information Administration in the U.S. Department of Energy and is the most widely used U.S. energy model maintained federal government.

Through an initial series of experiments, the research team demonstrated that this model was extremely insensitive to future energy price and energy efficiency technology cost assumptions. Further investigation revealed that this was the result of a requirement projections from this model to match actual energy consumption quantities in the base year (then 2010), with the model historically over-predicting energy efficiency improvements and, consequently, under-predicting energy demands without adjustments. This calibration was implemented by increasing the rates of return (or hurdle rates) required to justify energy efficiency investments by consumers whose behavior was represented in the model and those rates were increased until the demands from the model matched the historically observed levels.

Although this made the base year demands match actual demands perfectly, this procedure attributed all of the gap to different required rates of return in the model than energy consumers actually require (often straining credibility) and not to the many other barriers and information asymmetries that have been the focus of most of the PEEC research program. Therefore, to the extent these other factors are important, the rate adjustment calibration method employed lead to exactly the unrealistically low responsiveness to future market or policy driven changes in fuel prices or technology costs that was observed.

This work had an impact on the NEMS team almost immediately as Weyant was then on the American Statistical Association's independent advisory board to the EIA and was asked to have the team present the results of this work to one of the bi-annual meetings of that committee even before publication (it was alleged that this was the first time the committee had seen the results of experiments run on NEMS by an outside group) and, as an editor of the journal in which the work was published, he imposed a requirement that two individuals at EIA who worked on the residential and commercial modules serve as reviewers.

Energy Efficiency Research and Large-Scale Energy Modeling; Home Insulation Retrofit and Transportation Energy Efficiency Decision Making

PEEC Deputy Director John Weyant has been active in research designed to get the energy modeling communities to formulate models and develop scenarios that reflect the potential influence of the kind of advanced energy efficiency research PEEC does on future energy use. This is challenging as most energy modeling is, on way or another, built on assuming historical relationships between energy prices and demands will continue into the future perhaps with improvements in efficiency would play out at historical rates were energy prices to remain constant, whereas the majority of PEEC research is designed to find ways businesses and policy makers can change these historical relationships.

An example of research on EE barriers was the dissertation of Dhruv Sharma which was supervised by Weyant with support from PEEC and EMF in which data from EIA's residential energy survey product was used to econometrically estimate the "inconvenience factor" associated with home insulation retrofits for the first time. This provided an alternative, more structural, explanation to the "rate of return" explanation for the apparent over-estimation of the rate of energy efficiency improvement in this part of the models when not calibrated with implications for projections and policy analysis. Another insight that emerged from this work was that the provision of lower cost financing for such retrofits would not induce mid and high income households to implement them, but would have a substantial impact on the propensity for low income households to do so.

Weyant also managed a five year million dollar grant to PEEC from the Environmental Protection Agency which had as an explicit goal developing better ways to represent energy efficiency potentials in large scale energy models. This money was used to support work by PEEC staff like Lee Schipper, and PEEC visitor (now part time research staff) like Andreas Schaefer who have contributed greatly to the foundations of the PEEC transportation research program (as well as directly to the EPA's modeling efforts). In addition, PEEC visitor Erin Baker was also supported on this grant and did innovative research which lead to published papers on a financial options approach to formulating models of energy efficiency investment behavior, providing yet another alternative to the simple rate of return adjustment procedure used to calibrate NEMS and other energy system models.

Advanced Energy Efficiency Scenarios in Major Model Inter-Comparison Studies

Historically, lack of knowledge and understanding about energy efficiency decision making has meant that the demand sides of most energy models are either simple trend extrapolations or strictly technology oriented representations of end-use efficiency that have greatly over-predicted actual energy efficiency trends. Thus, while individual models and major model comparison studies have been doing systematic sensitivities on energy supply side assumptions for several decades this has not generally been done on the energy demand side of the models. This has led to critiques of the supply side oriented studies for not considering alternative energy demand futures as well and, in fact, some debate about whether the assumptions made about the energy demand side of the system were too optimistic or pessimistic.

By 2010, PEEC and other advanced energy efficiency research had not yet been routinely incorporated into most major models, but enough had been learned about the impacts of behavioral and institutional oriented policies to permit optimistic and pessimistic assumptions to be made about how successful these programs and measures might be over time. Thus, in the three major Energy Modeling Forum climate policy studies executed for the U.S., E.U. and global models under the direction of John Weyant during 2010 to 2014, alternative energy efficiency rates of change scenarios were explicitly included alongside the supply sensitivities for the first time. Partly owing to Weyant's position on the Scientific Advisory Boards on some parallel model comparison studies organized within the European Union, a similar architecture was implemented in them as well. Finally, though the Integrated Assessment Modeling Consortium (co-founded by Weyant and now including about 60 global modeling teams), this global modeling work was further coordinated and became the core of the IPCC Fifth Assessment Reports Working Group III Chapter 6 on energy sector transition pathways.

Energy Efficiency in U.S., E.U., Asian, Latin American and Global Modeling Consortia

The Integrated Assessment Modeling Consortium (IAMC) was founded nine years ago to help the global integrated assessment modeling community coordinate its activities. The organization's membership currently includes about 60 modeling centers from all over the world, a scientific steering committee, an annual research conference and a web site. John Weyant is one of the three founders of the IAMC and has served as chairman of its scientific steering committee for the past eight years. He has given several plenary and breakout session talks overviewing PEEC research at IAMC meetings.

Energy efficiency has also been a main focus of the two regional integrated assessment model comparison projects – the Asian Modeling Exercise (AME) and the Latin American Modeling Project (LAMP) run by Pacific Northwest Laboratory for USEPA and USAID,. Through advising these projects run by MS&E alumni Leon Clarke and Kate Calvin, John Weyant has continued to support inclusion of advanced energy efficiency scenarios in this work.

Weyant has also served as chairman of the Scientific Advisory Board for three major EU integrated assessment projects starting with the EU's "Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates (AMPERE)" and "Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies (ADVANCE)" research programs.

AMPERE ended in 2013, just as the "Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies (ADVANCE)" project started. This four-year project on improving IAM methodologies began three years ago and Weyant is on its Scientific Advisory Council. Weyant participated in the January 21-23, 2015 ADVANCE "all hands" meeting in Utrecht, the Netherlands. ADVANCE includes major research thrusts in energy demand determinants and behavioral research related to energy demand projections and policies. Thus, at the time of the January 21-23, 2015 ADVANCE "all hands" meeting in Utrecht, the Netherlands, Weyant co-organized a special back to back workshop on advanced energy efficiency workshop that featured presentations by PEEC behavioral research lead Carrie Armel, PEEC advisory board member Cathy Zoi, and noted NRDC energy efficiency expert Robin Roy along with three leaders in European energy efficiency research.

Some of this work will continue during the new four year EU CD-LINKS project on climate and development, which held its first PI meeting in Vienna in October 2015, with subsequent PI meetings planned for May 2016 in Venice and December 2016 in Beijing. Weyant is again serving on the four-person CD-LINKS Scientific Advisory Board.

Permanent vs Transient Demand Reductions

PEEC seeks to apply econometric, data mining, and other statistical techniques for modeling economic relationships to the demand for energy and discover and understand relationships between measures of economic activity and transient and permanent reductions in energy use. Many of the existing models provide estimates of the short-run and long-run price-elasticity and income-elasticity of demand or elasticity of demand with respect to other measures of economic activity. However, relatively few of these models have been estimated so as to differentiate between behavioral changes in use of energy services and technological changes in the energy-using capital equipment. Yet it is likely that investment in energy efficient capital equipment will lead to permanent reductions in energy use, while purely behavioral changes in use of energy services may lead to only transient changes.

We believe that it is important to understand in depth both the permanent and the transient reductions, since many policy choices depend on that understanding. For example, the advantage of real-time pricing of electricity is that it provides incentives for transient changes in electricity usage, generally motivating reductions in the use of energy services at peak periods of the day shifts use to those times of the day when marginal costs of electricity generation are relatively low. Non-time-differentiated increases in the price of electricity may motivate both reductions in the average use of energy services and improvements in the efficiency of energy-using capital equipment. Reductions in the use of energy services may occur very quickly – over the course of minutes, hours, or days – in response to changing conditions, while changes in the energy using capital equipment occur only much slower. And policy interventions which lead to long-term reductions in the use of energy services may reduce economic welfare while policies that promote the adoption of energy-efficient equipment can be expected to increase economic welfare.

Electricity Storage as Arbitrage

A line of inquiry initiated by Graduate Student Pedram Mokrian is dedicated to the modeling and assessment of initiatives within electricity markets using the underlying hourly market dynamics to create a framework for assessing grid-level storage motivated by profitable arbitrage. Two separate frameworks (stochastic optimization modeling and dynamic market equilibrium simulation modeling) are presented which take a bottom-up approach for assessing benefits associated with various demand-side initiatives and other emerging initiatives in power markets. Mokrian developed and presented models in support of each framework, and numerical results were used to highlight some impacts based on hourly dynamics. Stochastic optimization models explore the economic feasibility of grid-scale energy storage from the perspective of a price taking, profit maximizing firm facing uncertain market dynamics. This model was extended to incorporate intermittent wind generation, demonstrating how storage can be used as a potential substitute for transmission capacity. The research suggests that forward-looking, dynamic strategies are needed in the proper assessment of arbitrage operating profits, because deterministic strategies were only capable of capturing a small fraction of available operating profits. The key insight is that storage does not appear to be a financially prudent investment for arbitrage alone; the substantial capital and fixed operating costs are greater than the operating gains.

Mokrian implemented a new dynamic market equilibrium simulation model to address broader economic and environmental impacts of various demand-side initiatives including: energy efficiency, distributed generation, and plug-in hybrid electric vehicles. The general model was calibrated for the California electricity market and used to estimate impacts of the various interventions, taking into account varying market adoption levels and fuel prices. Numerical results have helped highlight the systematic gains in cost savings and emissions reductions that are made possible through demand side initiatives.

Demand Response to Out of Historical Range Price Changes

Another promising approach is to estimate energy demand models whose functional form allows different responses to energy price changes depending upon whether reductions in energy use are due to behavioral or technical factors. In a study of more than 70 different countries, Gately and Huntington (2002) demonstrated that energy demand responded much more strongly to more permanent energy price changes that exceeded previous maximum levels than to price changes that fluctuated over a range previously experienced. Presumably, these larger effects were due to fundamental technical changes in energy-using equipment that occurred during the 1970s and early 1980s. Asymmetric responses to energy price changes (both increases and decreases) are an important research methodology that could be fruitfully applied at a more disaggregated level to explore these issues.

Deconstructing the Rosenfeld Curves

Since the early 1970s electricity consumption per capita in California has stayed nearly constant, while rising steadily for the United States as a whole, with U.S. energy consumption per capita rising in the United States as a whole by 50% as of 2008. The differences were widely attributed to energy efficiency policies in California. PhD candidate Anant Sudarshan and James Sweeney addressed whether this difference was the result of California's policy as widely asserted. Their analysis used federal and state data to decompose the differences between California and the U.S. per capita electricity consumption trends. The work estimated that at most 23% of the difference (that is, 23% of the 50% difference) could be attributed to policy measures aimed at saving energy. The remainder was explained by major structural changes. For example, the large influx of immigrants into California led to more people living in each household, therefore reducing the measured per capita electricity consumption, but not reducing the actual electricity consumption. The average temperate climate in California implied that the growth of air-conditioning in the U.S. had not been matched in California. In the commercial sector the reduction in electricity per capita was entirely because the commercial floor space per capita has declined relative to the United States; the electricity use per square foot of floor space in California remained the same as in the entire US. In the industrial sector, the growth of high-tech industries and the decline of heavy industry accounted for the difference.

This paper has been used on two sides of the energy efficiency debate. Some have used it to argue against energy efficiency[8]. On the other side of the debate, some have used the paper to explain the importance of California policy. In an article in the October 2009 *Atlantic* magazine, entitled "The California Experiment" Ronald Brownstein wrote:

> James Sweeney, who runs Stanford University's Precourt Energy Efficiency Center, has calculated with Anant Sudarshan, a colleague, that much of that difference can be explained by factors such as California's temperate climate, less heavy industry, and even smaller-sized households. But, Sweeney says, the state's policy decisions still account for a substantial amount—roughly one-fifth to one-fourth—of the gap in electricity usage between California and the nation.

However, Sweeney's interpretation is that if one would like to increase the rate of energy efficiency above the rate that has been prevailing throughout the United States it is necessary to implement stronger measures than implemented in California. California's policy has made a significant impact on energy efficiency, but over-estimating its impact could easily lead to complacency.

Transportation

PEEC research also addresses one of the greatest challenges facing cities today: the need to develop sustainable transportation solutions that are safe, reliable, affordable, resilient, efficient, and have a limited impact on our environment. The transportation sector is one of the largest contributors to greenhouse gas emissions in the United States (about 25%). In California, 38% of greenhouse gas emissions come from transportation. The sector relies heavily on fossil fuels. Our research explores the energy and climate impacts of transportation, behavioral aspects of mobility decisions, and transportation and energy transformations that can inform strategies, policies, and new technologies for a more sustainable transportation future.

Current major research themes include:

- Shared-use mobility
- Vehicle electrification and vehicle-grid integration
- Automated and autonomous vehicles
- Engineering/technology
- Transportation demand management and behavioral incentives

[8] See for example, Joseph Toomey, *An Unworthy Future: The Grim Reality of Obama's Green Energy Delusions,* 2014.

As mentioned previously, PEEC hosts a weekly seminar on Sustainable Mobility and many of the speakers address these themes either as researchers or leaders of the public and private sectors.

Today, there are three important shifts happening in personal mobility in the United States: the production of efficient electric vehicles; the advent of ridesharing options; and the growing technology surrounding autonomous vehicles.

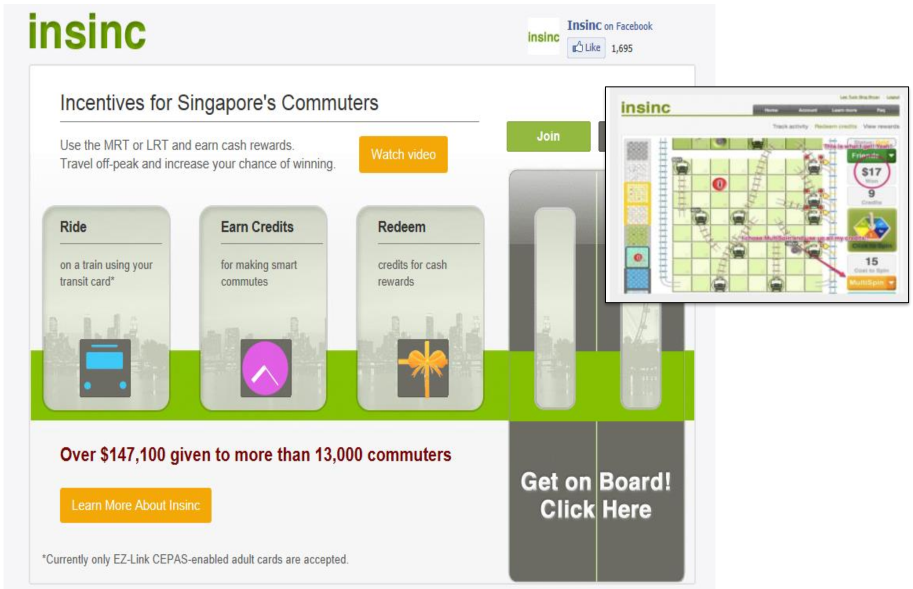
Stochastic Rewards and Travel Patterns

A notable case study in mobility behavior is the transportation lottery. Professor Balaji Prabhakar received seed funding from PEEC to research a general approach for influencing the behavior of commuters by incentivizing them to travel at times of low congestion. The research looks at whether people are motivated more by a small chance at a big prize than by a guaranteed small reward. To ease traffic congestion, which wastes a lot of energy and contributes to pollution, this project shifted travel away from rush hour using novel monetary incentives, gaming and a social network.

A lottery-based system to pay out large prizes instead of lower, deterministic payouts can attract more participation in the incentive mechanism. This is especially true when the deterministic payouts are small, such as a kWh of energy saving only about 10 cents. If such an incentive mechanism were developed, it could be applied in a variety of contexts: time shifting of electricity use in the home, recycling, wellness programs for increasing exercise, and many more.

In 2012, with a $3 million research grant from the U.S. Department of Transportation, a new system called Capri (Congestion and Parking Relief Incentives) was deployed at Stanford designed by Prabhakar’s group that allowed people driving to campus to enter a daily lottery, with a chance to win up to an extra $50 in their bi-weekly paycheck by shifting their commute to off-peak times. The program proved very popular and received a substantial amount of news coverage in mainstream media.

This project had a further follow-on called “INSINC,” which incentivized Singapore commuters to travel at uncongested times by giving them different numbers of credits (corresponding to cash) for shifting to off-peak travel, mode shifting (from private to public transit), or recommending a friend monitored through transportation sensors. Then individuals could choose to participate in a simple game of chance online to win a shot at a larger amount of money. Formative work on the project showed that adding a simple game of chance and social networking greatly improved engagement with the system.



In the initial pilot study, INSINC's 7.5 percent of INSINC's 27,000 users' trips were shifted off peak. Participants who made regular peak-hour trips before joining Insinc shifted their peak trips by more than 11 percent. Entering individuals into a lottery and compensating only a small number of lottery winners achieved significantly shorter commute times and reduced fuel consumption and congestion. This project has been further invested in by the government of the city state of Singapore which has 11 million public transport journeys a day.

The Impact of Scale on Energy Intensity in Freight Transportation

Freight transportation energy intensity (energy use per revenue ton-km) can differ widely, even for one and the same mode. However, only very few studies have attempted to interpret these differences, and none has tried to quantify them. Against this background, this research conducted by Andreas W. Schäfer and PhD candidate Michael Gucwa,analyzed energy intensities of ships, diesel–fuelled railways, trucks, and aircraft, using basic physics and publicly available data with the goal to quantify differences in energy intensities.

This analysis suggests that differences in operation, not technology, explain most of the variation in energy intensity within and across modes. Among the operational characteristics, most important is the amount of cargo weight transported per vehicle and therefore the scale of the respective transportation system.

Figure 8 depicts the relationship between energy intensity and the average amount of cargo carried for the four freight transportation modes. Energy intensities decline with an increasing amount of load carried, i.e., increasing revenue tonne-km (RTK) over vehicle-km travelled (VTK), which is the product of vehicle capacity ($RTK_{available}$/VKT) and the freight load factor ($RTK/RTK_{available}$). The inverse relationship between energy intensity and vehicle capacity can be attributed to the square-cube law, which applies to all modes but aircraft. Energy intensity also declines with a rising freight load factor ($RTK/RTK_{available}$): although the higher payload mass increases E/VKT, it can be shown that it reduces VKT/RTK more strongly, thus resulting in an overall decline in E/RTK.

As can be seen from **Figure 8** the energy intensity of each mode develops within one respective envelope. All other factors equal, those transportation systems carrying the smallest amount of goods (light trucks) account for the highest level of energy intensity, whereas those exploiting scale to the largest extent (large water vessels) account for the lowest amount of energy used per tonne-km. However, other important factors affect energy intensity too. The generally lowest energy intensity of ships results from their very large scale, as manifested by their—compared to railways—higher energy intensity at a given payload, e.g., 1,000 tonnes. This does not come as a surprise in light of the lower (wheel-on-rail based) rolling resistance of trains compared to a ship's hull resistance. Similarly, the compared-to-trucks higher energy intensity of dedicated freight aircraft mainly results from their one order of magnitude higher speed of operation.

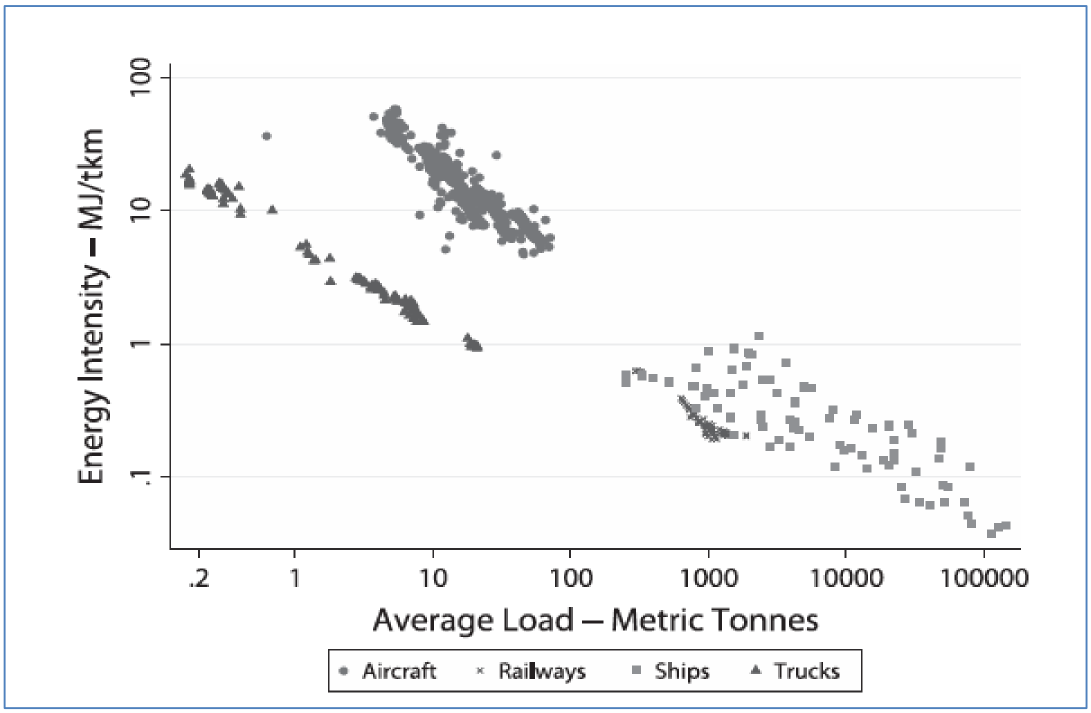


Figure 8. Energy Intensity of Freight Transportation Modes over the Average Carried Load per Vehicle.

The relationship depicted in **Figure 8** has several important implications. First, because of the dependence on average load, modal energy intensities in isolation of other metrics do not convey a meaningful description of the energy use characteristics of a transportation system. For example, differences in country level energy intensities can be largely determined by the composition of the surface and air vehicle fleets, and not by technology.

Second, because of the influence of scale on the energy intensity of surface transportation modes, an apparently straightforward approach to reduce energy use would be to design larger transportation systems, increasing the load factor of existing transportation systems, and shifting to systems that operate at larger scale. However, each of these options can experience severe limitations. For example, a move towards larger transportation systems can be incompatible with trends in the economy: just-in-time inventory management and increasing home deliveries lead towards smaller average truck sizes, thus leading to higher energy intensities over time. Similarly, an increase in load factors can be challenging because of asymmetric trade flows and the need for increasingly specialized vehicles. Finally, a shift towards modes that operate at larger scale would not necessarily reduce energy intensity, as the typically higher-value, lighter product would reduce RTK/VKT, thus leading to higher energy intensities. In addition, higher value products are typically more time sensitive and thus transported by faster, more energy intensive modes.

Third, because scale parameters differ by mode, any increase in scale needed to reduce energy intensity by a given amount varies. This study's econometric analysis finds that an increase in cargo capacity of a transportation system by 10% leads to a roughly 8.3% reduction in rail energy intensity and to a 5.5% reduction in truck and shipping energy intensity. For aircraft, the estimates show that an increase in load-factor by 10% would reduce energy intensity by 6.4%.

Costs of Mitigation CO_2 Emissions from Passenger Aircraft

In response to strong growth in air transportation CO_2 emissions, governments and industry have explored and implemented mitigation measures and targets since the early 2000s. Most recently, the U.S. Environmental Protection Agency (EPA) has started a process to regulate aircraft CO_2 emissions. However, in the absence of rigorous analyses assessing the costs for mitigating CO_2 emissions, these policies could be economically wasteful. This research, led by Andreas Schäfer, identified the cost-effectiveness of CO_2 emission reductions from narrow-body aircraft, the workhorse of passenger air transportation. It considers technology options (five retrofit options, one intermediate generation aircraft type and two next-generation aircraft types), cellulosic biomass-based synthetic fuels (biomass-to-liquids (BTL)), air transportation management measures (five strategies that consist of bundles of measures), and airline operational strategies (nine measures).

An aircraft fleet composition model generates the fleet age distribution, energy use, and CO_2 emissions in absolute terms and per revenue passenger kilometer (RPK). It takes as inputs the projected narrow-body aircraft fleet size at any year along with the econometrically estimated energy intensity level of new narrow-body aircraft.

This research concludes that in the US, natural fleet turnover and a combination of fuel burn reduction strategies could reduce the 2012 level of lifecycle CO_2 emissions per passenger kilometer by around 2% per year through mid-century. These intensity reductions would occur at zero marginal costs for oil prices between US$50–100 per barrel. Even larger reductions are possible, but could impose extra costs and require the adoption of biomass-based synthetic fuels. The extent to which these intensity reductions will translate into absolute emissions reductions will depend on fleet growth.

Figure 9 shows the associated wedge diagram of annual CO_2 emissions, where some of the families of measures are broken down and ranked broadly according to their cost-effectiveness. The introduction of new, highly fuel-efficient aircraft technologies in 2035 is of paramount importance to outpace the anticipated growth in air transportation demand.

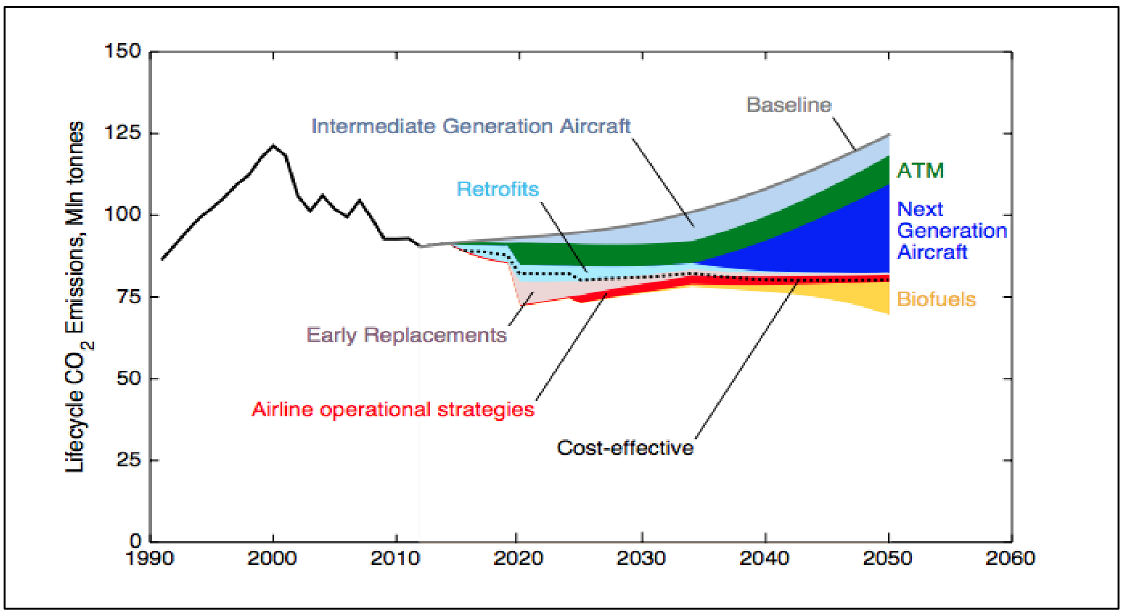


Figure 9. Lifecycle CO_2 emissions, historical trend (1991–2012) and future projections (2013–2050) of the mitigation potential by category of

Additional significant emission reductions could be achieved from synthetic cellulosic biomass-based fuels. The same figure also shows the emission mitigation benefit of retrofits and early aircraft replacements is only short-term; by 2050, their effect over time has virtually evaporated, as by then nearly all of the retrofitted and the early replaced aircraft would have been substituted. Yet, owing to the long atmospheric lifetime of CO2, the cumulative emission reductions remain beneficial. If only introducing cost-effective options at a fuel price of US$2.0-3.1 per gallon, the 2050 narrow-body aircraft CO2 emissions could decline to a level of 77 million tonnes, a roughly 10% decline relative to the 2012 level (dotted line).

In light of the anticipated fleet growth rate of 1.5% per year, lifecycle CO_2 emissions from the U.S. narrow-body aircraft fleet could be reduced by about 10% between 2012 and 2050, even without the introduction of synthetic fuels from cellulosic biomass.

Long-term Trends in Domestic U.S. Passenger Travel

Andreas Schäfer, in work done at PEEC, has shown that since 1900, U.S. domestic passenger-km traveled per person has grown at an average rate of nearly 3.3% per year, reaching about 25,000 km in 2010. This enormous growth was enabled by systematic shifts towards ever-faster transportation modes. While electric streetcars and steam-powered railways dominated the U.S. transportation system in the early 20th century, light-duty vehicles experienced a peak in market share at around 1960, and then dropped to around 87% in 2010 because of the stronger growing domestic air travel. Schäfer has shown that over the entire historical time period, the average amount of time spent on travel by the U.S. population has remained roughly constant at around 1.2 hours per person per day.

The question underlying this research is how the historical growth in per capita travel demand and its distribution across modes may continue to evolve over the next 90 years if the underlying key determinants remain largely unchanged. Answering this question is important for transportation infrastructure planning and policies aiming to mitigate oil import dependence and environmental impacts.

Based upon a long-term historical data set of U.S. passenger travel, a model was estimated to project aggregate transportation trends through 2100. One of the two model components projects total mobility (passenger-km traveled) per capita based on per person GDP and the expected utility of travel mode choices. The second model component has the functional form of a logit model, which assigns the projected travel demand to competing transportation modes. An iterative procedure then ensures the average amount of travel time per person to remain at a pre-specified level through modifying the estimated value of time.

Using the regression results and projected values for the key independent variables (gross domestic product, population, travel costs and speeds by transport mode), passenger-km traveled per person was projected through 2100. In the absence of structural breaks, a fixed travel time budget constraint implies that the long-term historical trends toward higher levels of mobility and faster travel modes observed over the past 110 years may continue well into the future. Assuming an average growth rate of GDP per capita of 2% per year, U.S. travel demand per person could increase by 30–50% by 2100 over the 2010 level, depending on the assumed average amount of time spent on travel. If also accounting for the anticipated 90% growth in population during that period, total travel (passenger-km) could multiply by a factor of 2.5–3.0 by 2100.

The projected growth in total travel is mainly due to the increase in air transportation, which, over at least the next 20 years was found to be consistent with UN and aircraft industry projections. In contrast, light-duty vehicle travel per person is projected to saturate and gradually decline; the year at which saturation occurs depends on the average amount of time spent on travel; the higher that amount, the later the year of ‘‘peak car’’. However, despite the saturation of per person light-duty vehicle travel, the expected growth in population would continue to increase light-duty vehicle travel, albeit at a significantly reduced rate. The outputs from this model can be used as a first-order estimate of a future benchmark against which the effectiveness of various transportation policy measures or the impact of autonomous behavioral change can be assessed.

Disruptive Technology Transitions: Railroad Fuels

The substitution of infrastructures and adoption of technologies is typically measured in terms of many decades. Ongoing work by Andreas Schäfer and James Sweeney have shown that several examples of energy-using technology transitions exist that occurred over comparatively short periods of time. Figure 10 illustrates the share of fuels used in U.S. railroads. At the beginning of commercial railroad operations in the early 1830s, steam locomotives were fueled with wood because of its abundance, which resulted from the clearing of forests in need of agricultural land. It took more than 60 years until the higher energy density coal has replaced wood. However, around 1900, coal began to be replaced by fuel oil in steam locomotives, due to the strongly reduced amount of sparks leaving the locomotive chimney and the reduced exposure and thus vulnerability to coal miner strikes. Yet, starting in around 1940, steam locomotives altogether began to be replaced by diesel-electric locomotives. In 1960, hardly any steam locomotive still operating.

Better understanding the conditions that led to this rapid technology transition is paramount for planning future rapid technology transitions. However, existing approaches only plotted the relative importance of competing technologies over time or constructed socio-technical frameworks that are not grounded on observed data. In contrast, this research estimates a regression model with the functional form of a mixed logit model to quantify the contribution of technological and social factors (such as coal miner strikes) that induced such drastic change.

Initial results that root on a rich database indicate that the transition depicted in Figure 10 consists of phase-displaced transitions in three submarkets, i.e., yard operations, passenger transportation, and freight transportation, which can be explained by the requirements in each market and the techno-economic characteristics of steam and diesel-electric propulsion systems. In addition, several models have been estimated, which produced promising results. In the future, this case study will be completed and complemented by other rapid technology transitions, such as the shift from piston to jet engine propulsion in aircraft, which happened around 20 years later and also lasted over around only 20 years. These case studies will be systematically compared. The identified commonalities and differences will help better understanding the set of necessary conditions for future technology transitions.

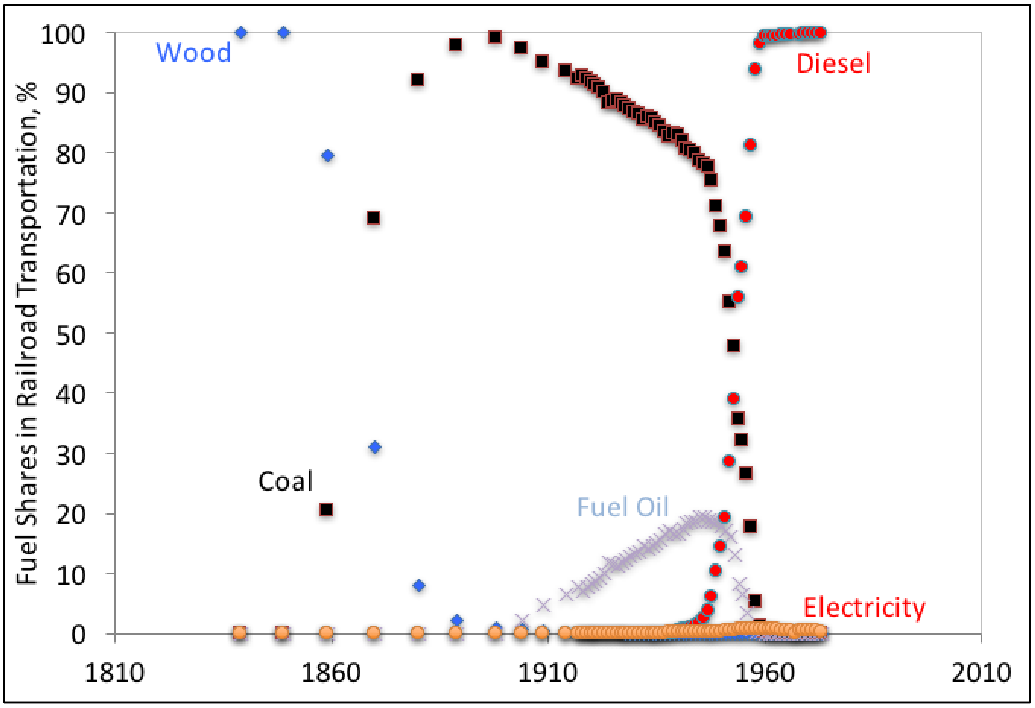


Figure 10. Shares in railway fuel from 1939 to 1973.

Shared-use mobility

PEEC Postdoctoral fellow Regina Clewlow addressed the impacts of carsharing on travel behavior and alternative vehicle ownership by utilizing the California Household Travel Survey, a recent large-scale government-funded data collection effort on personal mobility. She is investigating differences between carshare member and non-member travel behavior, including transit use, vehicle miles traveled, and ownership of alternative vehicles using discrete choice modeling, econometrics, and methods to address self-selection problems in such models. By launching a survey in five U.S. metro areas to collect data on residential choice, travel behavior, attitudes and the adoption of new mobility solutions, such as ridesharing, she will be able to study travel behavior and discover why individuals buy or retire vehicles among other important insights.

Transportation demand management and behavioral incentives:

Although technological advancements have the capacity to create low carbon transportation systems, travel behavior and demand have to be modified simultaneously in order to achieve targeted emission goals. PEEC Postdoctoral Fellow Wei-Shiuen Ng , examined a range of land use planning, transit and pricing policies, all examples of how non-technological strategies can serve as complementary measures to successfully lower transportation carbon emissions. How significant the congestion is may influence transportation activity but mode choice might be motivated by individual preferences able to be influenced by government policies, incentives, and strategies. Travel demand and behavior thus play an increasingly important role in determining future emissions, as travel patterns, which can be affected by various factors, are capable of influencing total distance traveled and determining transportation mode choice. Reductions in carbon emissions will occur when travel demand shifts to transportation modes that are less energy intensive and when distance traveled declines. Ng's research focused on the evaluation and development of policies and measures that have the potential to induce modal shifts, shorten travel distance, or reduce the frequency of private vehicle trips, and subsequently decrease energy use and carbon emissions. While at PEEC, she applied both quantitative (e.g. behavioral modeling using discrete choice analysis) and qualitative (e.g. interviews and focus groups) methods to further understand transportation demand and behavior while looking at parking and mode choice as well as the environmental and energy impact of parking pricing. She is now at the OECD in Paris, applying some of her research to OECD transportation energy demand models.

Public Policy Analysis/Support

Analysis of Measures to Meet the Requirements of California's Assembly Bill 32

In 2008 the California Air Resource Board (CARB) was in relatively early stages of developing its plans for meeting the requirements of AB32, "California Global Warming Solutions Act of 2006." PEEC received funding from The Energy Foundation and the Richard and Rhona Goldman Fund develop an objective analysis of the options. The resulting study was intended to provide guidance to policymakers involved in the implementation of AB 32.

AB 32 set out several major requirements, including:

- CARB must monitor and verify statewide greenhouse gas emissions, through mandatory reporting.
- CARB must adopt a statewide plan to reduce greenhouse gas emissions to 1990 levels by 2020.
- CARB must adopt rules and regulations to achieve "the maximum technologically feasible and cost-effective reductions in greenhouse gas emissions" in furtherance of achieving the statewide limit by 2020.

The first two requirements are clearly defined. But the third requires understanding of the way the words are used in California regulations. The study conducted by PEEC interpreted the phrase "technologically feasible and cost-effective" to mean that the rules and regulations must lead to greenhouse gas emissions reductions that are both technologically possible and cost-effective.

The paper began by interpreting the meaning of the phrase *cost-effectiveness* as written in the law, discussing its relation to other policy considerations, and providing preliminary quantification of economic costs of various implementation measures. But basically, AB 32 required that CARB set out the regulations that gave the lowest total cost to meet the overall objective.

Meeting the lowest total cost requires setting a cut-off cost per ton of carbon dioxide reduction and adopting those feasible emissions reductions whose cost per ton would be estimated as less than the cut-off and rejecting those emissions reductions with costs higher than the cut-off.

The paper discussed the concept of a *Marginal Abatement Cost curve* for emissions reductions and addressed how that concept can be used to help inform the policy process. The concept of a marginal abatement cost curve is an old one that was popularized around the time of our report by McKinsey in the curves it developed for the United States.

The primary result of our analysis was the development of a marginal abatement cost curve for emissions reductions in California in 2020. The curve presented in the study was the product of many studies of individual measures to reduce emissions in California. The estimates were drawn from both our review of existing literature and our own analyses.

The marginal abatement cost curve presented in our study appears as Figure 11. This representation included three estimates for each measure: the amount of carbon dioxide emissions possible from that measure, represented by the width of the blocks; the cost per ton of carbon dioxide reduction, represented by the height of the blocks; and our judgement about how responsive the measure would be to carbon pricing. The last issue is important because the California cap and trade policy could be expected to result in implementation of those measures that were very responsive to carbon dioxide prices. However, for measures that were minimally responsive to carbon prices, a regulatory approach likely would be needed.

The paper included a detailed description of each of our analyses with the goal of contributing to the policy dialogue on Assembly Bill 32. We viewed that our marginal abatement curve should not be the final result. Rather the curve was intended to show CARB that such a curve could be created and could be important for their policy making. That was important because as of 2008 CARB provided estimates of the average cost of the bundle of projects, but had not been focusing on using the costs of the various projects to choose which of them to recommend and which to not recommend.

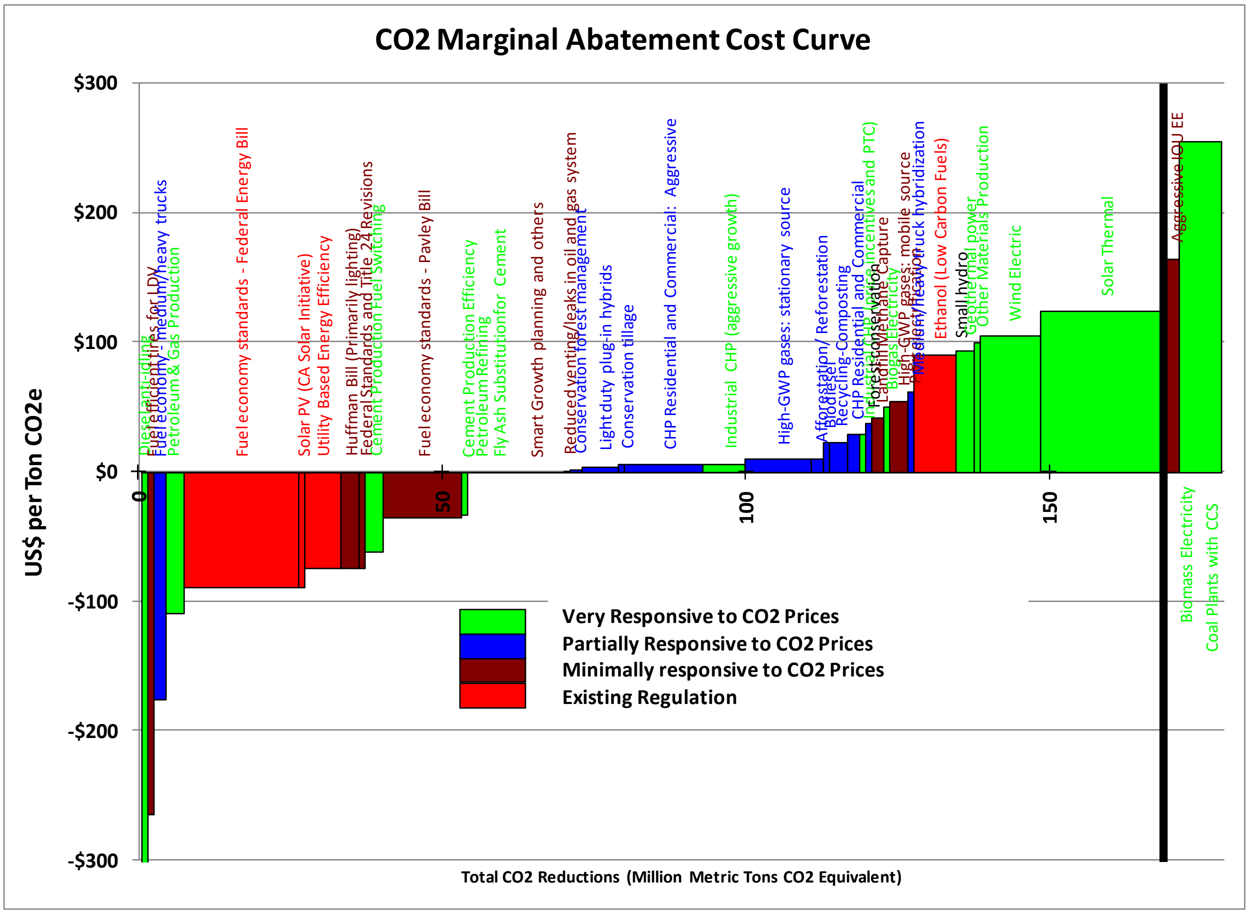


Figure 11. 2020 CO2 reduction MAC curve as of September 27, 2008

Our policy goal was only partially successful. The marginal abatement cost curve became well known to the CARB staff and some of the board members. CARB staff developed the data for their own marginal abatement but originally did not develop the marginal abatement cost curve.

Sweeney was a member of Governor Schwarzenegger's Council of Economic Advisors, and, working with George Shultz, organized a Sacramento session in which the CARB senior staff would present their economic analysis to Schwarzenegger's senior economic and policy portions of the Schwarzenegger Cabinet and to the Council of Economic Advisors. This allowed a very lively discussion among the CARB staff and the governor's staff as to why the CARB estimates of the costs of the various measures were so optimistic relative to the PEEC analysis. How much that discussion led the CARB staff to develop better economic analyses is difficult to tell.

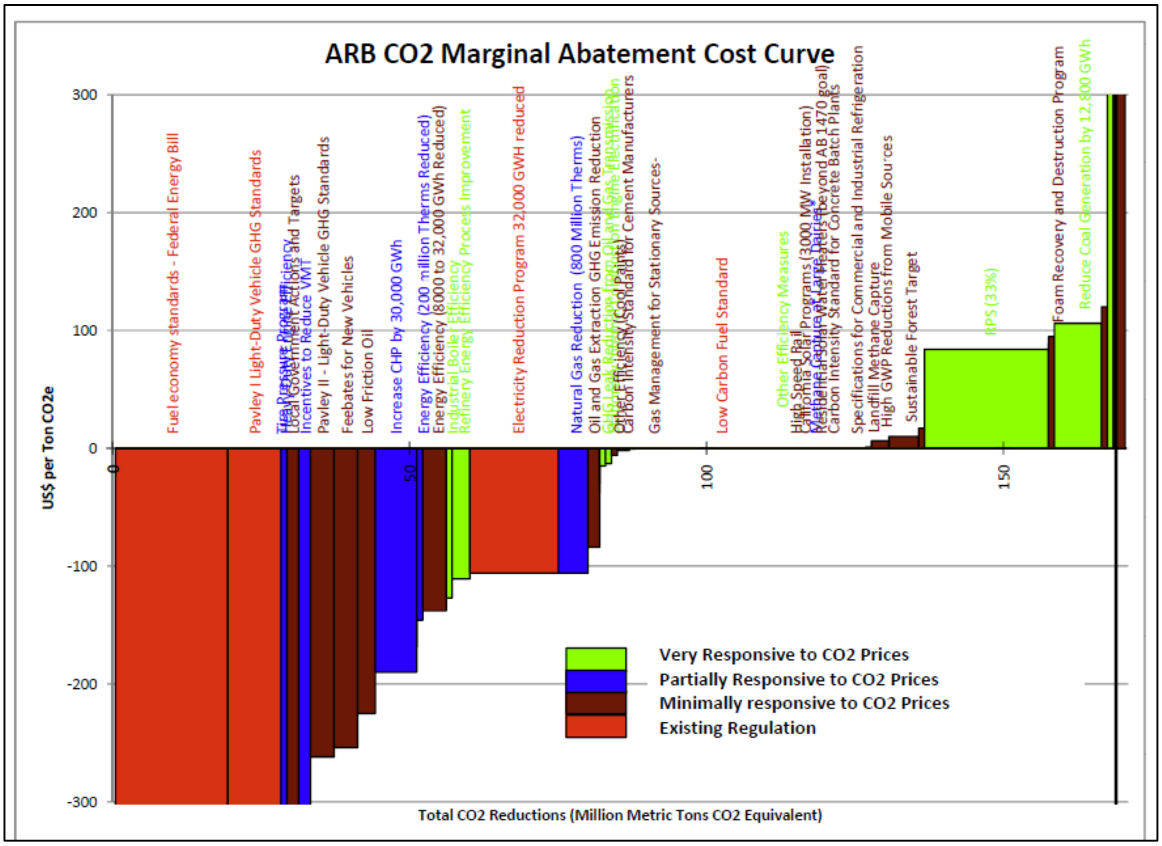


Figure 12 Marginal Abatement Cost Curve Implicit in CARB analysis

The PEEC marginal abatement cost curve continued to be brought into discussions by several advisory committees to the CARB, but most particularly by the Economics and Allocation Advisory Committee.

The study had a high educational value. The team was led by John Weyant and Jim Sweeney. The following undergraduate and graduate students played essential roles in developing and interpreting the analysis.

Tien Tien Chan	Raghavender Palavadi Naga
Raj Chowdhary	Rebecca Raybin
Kenneth Gillingham	Amul Sathe
Amy Guy	Anant Sudarshan
Sebastien Houde	Joe Westersund
Arianna Lambie	Alex Yu Zheng

The graduate students were funded as research as research assistants. At least half of the team went on to complete PhDs closely related to energy or took positions in companies where they continued an energy-related career.

The Next Level of Energy Efficiency

Dian Grueneich's major focus is on "The Next Level of Energy Efficiency" which focuses on improving state energy efficiency policies and regulatory frameworks. This program covers four areas: Challenges Ahead, New Tools and Opportunities, An Updated Policy Framework, and Harnessing Market Forces.

The first portion of her research "The Next Level of Energy Efficiency: The Five Challenges Ahead", was published in 2015 in the *Electricity Journal*. For over four decades, energy efficiency has contributed significantly in reducing customer and utility costs, creating jobs, and decreasing environmental impacts. Its role is becoming even more important as we focus on the urgent need to reduce GHG emissions and to ensure reliable and affordable grid operations. This article describes five key challenges for this "next level" of energy efficiency: 1) the **magnitude** of energy efficiency savings must increase dramatically; 2) the sources of energy efficiency savings must **diversify**; 3) **measuring** and ensuring the persistence of energy efficiency savings must become commonplace; 4) energy efficiency outcomes must be integrated with a **carbon** reduction framework; and 5) energy efficiency must be understood and valued as part of an **evolving grid**. Unless these challenges are understood and addressed, we will fall short in achieving this next level of efficiency and deep de-carbonization goals. Simply put, none of the deep de-carbonization pathways are affordable without very significant energy efficiency.

Our research at Stanford is focusing on the steps—a combination of technology, policy, and markets—needed to overcome these challenges. There are new tools—e.g., intelligent efficiency, financing, advanced technologies, better understanding of how to use behavioral interventions—that are becoming available. How to rapidly integrate these new opportunities into the historic efficiency framework and ensure they address the challenges discussed above is a critical issue and the focus of Dian's Next Level project. Institutional agency governance affects both strategy and execution around each of these elements and therefore merits further investigation as well.

Dian presented the Next Level project initially at Stanford's September 22, 2014 Energy Seminar. Since then she has given numerous seminars and briefings on the project at Stanford, including presentations to the Steyer-Taylor Center, the Atmosphere & Energy Seminar, and the Smart Grid seminar. Dian has involved several Stanford students in her research and used portions of their work in the fall 2015 *Electricity Journal* article.

Outside Stanford, Dian has presented the project to numerous organizations including EPRI, LBNL, the CPUC, the California Energy Commission (CEC), California legislators and staff, the California Emerging Technology Coordinating Council, the

ACEEE Summer Study and Intelligent Efficiency Conference, the Utility Energy Forum, ESource, various CA utilities (PG&E, SCE, LADWP, SMUD), the Presidio Business School, the annual Green Technology Conference in Sacramento, the Women Energy Associates, the Advanced Energy Economy's annual conference. Most recently she presented in a national webinar hosted by Yale University's Center for Business and the Environment and a recording of the webinar is on the PEEC website available to the general public.

Distributional and Efficiency Impacts of Increased U.S. Gasoline Taxes

By providing incentives for reduced gasoline demand, an increase in the federal tax on gasoline would confer benefits in terms of reduced emissions of local air pollutants as well as carbon dioxide, a principal greenhouse gas. And by reducing U.S. demands for crude petroleum and for imported oil in particular, a higher gasoline tax could yield benefits in terms of national security.

In PEEC-funded research, Professor Lawrence Goulder and colleagues explored the potential impacts of an increase in the federal tax on gasoline. This work explored both the overall impacts on gasoline demands as well as the differences in impacts across various household groups. In contrast with other studies, this work integrated the markets for both new and used cars in estimating the impact of gasoline taxes on gasoline demand and considered the implications of gradual changes in the car fleet on gasoline demand. Results from this project were published in the *American Economic Review* in 2009.

There were two main components of this project. First, the research employed statistical analysis to assess how various household groups – differing by income, age, ethnicity, and region – respond to changes in prices at the pump. This required development of an extensive data set showing demands for gasoline as a function of gasoline prices, regions, time, household characteristics, and the type of car owned by the household in question. The dataset allowed the project to consider household choices among a wide range of new and used cars and to distinguish households along many important dimensions. Second, the behavioral parameters obtained from the statistical analysis were incorporated in a numerical model that included links between new and used car markets. Gasoline demand depends not only on vehicle miles traveled, but also on fuel-economy – gasoline demand per mile. This implies that, to gauge the impact of a gasoline tax on gasoline demand, it is important to consider not only the effect on the fuel-economy of the new cars produced, but also the changes in the composition of the vehicle fleet as relatively new cars replace older, less fuel-efficient cars over time. The numerical model in this study took account of this dimension.

This study found that each cent-per-gallon increase in the price of gasoline reduces the equilibrium gasoline consumption by about .15 percent in the short run and .2 percent after 10 years. The reduction in demand mainly reflects reduced miles traveled by car owners; shifts in demand from low to high miles-per-gallon vehicles were much less important. The impact of a 25-cent gasoline tax increase on the average household was about $30 per year (2001 dollars). The distributional impacts of the gasoline tax increase depend importantly on how the additional revenues are recycled. In the case where the revenues are recycled. While the direct impacts of higher gasoline taxes are regressive, recycling the revenues through a rebate check of equal amount to all household would completely eliminate the regressive impact and in fact would produce a small welfare gain to the average household in each demographic group considered.

Systems Analysis

Sweeney Energy Efficiency Book

Although overcoming the barriers to complete adoption of energy efficiency practices has motivate the PEEC emphases, it is also important to recognize the actual historical contributions of energy efficiency. These contributions provide the primary focus of the book written by James Sweeney, PEEC director, entitled *Energy Efficiency: Building a Clean Secure Economy.* The book is scheduled to be published by Hoover Institution Press in August 2016.

In 1973, the world was drastically and forever altered by the oil embargo and tripling of world oil prices, with oil prices remaining very high for over ten years. Offering a historical context, Sweeney takes 1973 and the pre-crisis years as a comparison period to show energy-efficiency enhancements throughout the United States. In 1973, driven by national security and economic concerns, the United States turned attention to reducing oil imports. Today, with recognition of global climate change and carbon dioxide emissions from fossil fuel use, attention has turned toward reducing greenhouse gas emissions. Energy policy discussions since 1973 have thus centered on energy impacts to the “energy policy triangle” of the economy, the environment, and national security (see Figure 1.)

The book reviews the advances in energy efficiency within the United States since the 1973–74 oil embargo and documents the generally unheralded contributions of energy efficiency to the economy, national security, and the environment.

The fundamental impacts of energy efficiency on energy imports and thus on U.S. security are quantified in **Figure 2**, from the book, and shown at the beginning of this document. The contribution of energy efficiency to the country’s move towards net energy self-sufficiency has been more powerful than all of the increases in domestic production of oil, gas, coal, geothermal energy, nuclear power, solar power, wind power, and biofuels combined.

Similarly, the book shows the contribution of energy efficiency to the reduction of greenhouse gas emissions from the United States. Since 1973 the U.S. economy has decarbonized by 61%; that is, the carbon dioxide emissions per dollar of inflation adjusted GDP is now only 39% of what it was in 1973. *Energy Efficiency: Building a Clean Secure Economy* shows almost all of this de-carbonization was the result of energy efficiency. More precisely, since 1973, U.S. energy intensity reductions have been about nine times as important as have reductions in carbon intensity of energy consumption for reducing the carbon intensity of the economy. These impacts are quantified in Figure 3, from the book, and shown at the beginning of this document.

The fundamental importance of energy efficiency may come as a surprise because one cannot easily observe what energy use would have been without the greater efficiencies. Most energy-efficiency changes are rather invisible to outsiders (and often to insiders), and thus most improvements are unrecognized.

Much of the progress has been the result of cumulative small, broadly distributed changes, but these small changes together have greatly reduced the energy intensity of the U.S. economy. And the history presented in the book suggests that the United States can enjoy the many benefits of future efficiency gains if it maintains the interacting conditions that enabled accomplishments of the past 40 years, even though many barriers still exist to full economically efficient reductions in energy use.

Technology

Thermoelectric Waste-heat Recovery

Professor of Mechanical Engineering Kenneth Goodson and his research team received seed grant funding from PEEC to study novel materials and packaging for thermoelectric waste-heat recovery. This seed grant was followed by a significant three-year investment from the Department of Energy and the National Science Foundation’s Thermoelectric Partnership. Thermoelectric recovery is promising for improved efficiency in a broad variety of combustion systems, such as those in automobiles, but thermal interface resistances and the need for scalable and package-compatible thermoelectric materials is a major roadblock. Much of the research on thermoelectric efficiency, meaning the amount of input energy that is available for use rather than lost as waste heat, focuses on the basic thermoelectric materials that make up a thermoelectric generator with little attention paid to the packaging materials which could greatly impact the efficiency of the system. Goodson and his collaborators’ work focused on this issue and have made significant progress in developing a carbon nanotube array thermal interface material to improve thermoelectric device efficiency along with a host of other improvements in techniques to measure mechanical and thermal properties of materials, which all have positive implications for both the automotive and building sectors.

Appendix C. Publications From PEEC Research

In what follows is a listing of publications stemming from the internal PEEC research and the research within Stanford. To date we have been able to identify 240 publications stemming from PEEC sponsored projects, both from within PEEC and from throughout Stanford. The list follows.

1. Albert, Adrian, and Ram Rajagopal. "Thermal profiling of residential energy use." *Power Systems, IEEE Transactions on* 30.2 (2015): 602-611.

2. Albert, Adrian, and Ram Rajagopal. "Strategic scheduling of residential energy consumers." *Decision and Control (CDC), 2015 IEEE 54th Annual Conference on*. IEEE, 2015.

3. Albert, Adrian, and Ram Rajagopal. "Method and system for profiling and scheduling of thermal residential energy use for demand-side management programs." U.S. Patent No. 20,150,332,294. 19 Nov. 2015.

4. Albert, Adrian, and Ram Rajagopal. "Cost-of-service segmentation of energy consumers." *Power Systems, IEEE Transactions on* 29.6 (2014): 2795-2803.

5. Albert, Adrian, and Ram Rajagopal. "Thermal profiling of residential energy consumption." *IEEE Transactions on Power Systems* 99 (2014): 1-10.

6. Albert, Adrian, and Ram Rajagopal. "Building dynamic thermal profiles of energy consumption for individuals and neighborhoods." *Big Data, 2013 IEEE International Conference on*. IEEE, 2013.

7. Albert, Adrian, and Ram Rajagopal. "Smart meter driven segmentation: What your consumption says about you." *Power Systems, IEEE Transactions on* 28.4 (2013): 4019-4030.

8. Albert, Adrian, et al. "Drivers of variability in energy consumption." *ECML-PKDD DARE workshop on energy analytics*. 2013.

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10. Armel, K. Carrie, and Thomas Robinson. "Estimating greenhouse gas emissions for individual behaviors. Symposium Issue: Climate Change and Consumption." *Environmental Law Reporter* 38 (2008) 10825-10888.

11. Armel, K. Carrie, et al. "Identifying Innovative Options for Deep Residential Energy Savings." in preparation, to be submitted *Energy Efficiency.* 2016.

12. Armel, K. Carrie, et al. "Is disaggregation the holy grail of energy efficiency? The case of electricity." *Energy Policy* 52 (2013): 213-234.

13. Armel, K. Carrie, et al. "The Stanford Climate Change Behavior Survey (SCCBS): assessing greenhouse gas emissions-related behaviors in individuals and populations." *Climatic Change* 109.3-4 (2011): 671-694.

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18. Baker, Erin, and Yiming Peng. "The value of better information on technology R&D programs in response to climate change." *Environmental Modeling & Assessment* 17.1-2 (2012): 107-121.

19. Baker, Erin, and Senay Solak. "Climate change and optimal energy technology R&D policy." *European Journal of Operational Research* 213.2 (2011): 442-454.

20. Baker, Erin, and Senay Solak. "Optimal climate change policy: R&D investments and abatement under uncertainty." *Production and Operations Management* (2011).

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22. Barako, Michael T., et al. "Reactive metal bonding of carbon nanotube arrays for thermal interface applications." *Components, Packaging and Manufacturing Technology, IEEE Transactions on* 4.12 (2014): 1906-1913.

23. Barako, M. T., et al. "Thermal cycling, mechanical degradation, and the effective figure of merit of a thermoelectric module." *Journal of electronic materials* 42.3 (2013): 372-381.

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Appendix D: PEEC and Stanford Energy History

PEEC History

Established in October of 2006, the Precourt Energy Efficiency Center (PEEC) (originally named the Precourt Institute for Energy Efficiency) was founded at Stanford University through a generous gift from Stanford alumnus Jay Precourt. Under the umbrella organization of the Precourt Institute for Energy, PEEC focuses on energy efficiency, the demand side of energy markets, and economically efficient reductions in energy use and energy intensity. PEEC works together with a host of other research efforts at Stanford, including the Energy Modeling Forum, Global Climate and Energy Project, Program on Energy and Sustainable Development, Shultz-Stephenson Task Force on Energy Policy, Stanford Environmental and Energy Policy Analysis Center, Stanford Institute for Materials and Energy Science, Steyer-Taylor Center for Energy Policy and Finance, SUNCAT Center for Interface Science and Catalysis, and TomKat Center for Sustainable Energy.

Over the years, PEEC-affiliated faculty and staff have been involved with major energy-related legislation implementation, governmental program development, and other policy relevant endeavors that are designed to encourage energy efficient behavior. In terms of technology, PEEC is in a unique position to benefit from the overwhelming technological breakthroughs and contributions prevalent at Stanford and multiply those resources toward the field of energy efficiency.

Timeline of Stanford Energy Institutions

- Early 1970s – Institute for Energy Studies (IES)
- 1976 – Energy Modeling Forum (EMF)
- 1985 – IES merged into CEPR
- 2001 – Program on Energy and Sustainable Development (PESD)
- 2002 – Global Climate & Energy Project (GCEP)
- 2006 – Precourt Institute for Energy Efficiency (PIEE)
- 2006 – Stanford Institute for Materials & Energy Science (SLAC & Stanford)
- 2008 – Shultz-Stephenson Task Force on Energy Policy (Hoover);
  – PIEE becomes Precourt Energy Efficiency Center (PEEC);
  – Center for Advanced Photovoltaics (KAUST)
- 2009 – Precourt Institute for Energy;
  – TomKat Center for Sustainable Energy
- 2011 – Steyer-Taylor Center for Energy Policy and Finance;
  – Bay Area Photovoltaics Consortium (DOE)

Appendix E: PECC Governance

PEEC is an independent research center within Stanford and under the umbrella of the Precourt Institute for Energy. The governance of the Center includes: the directors, who manage and lead the organization, research, and administrative staff; Advisory Council; affiliated faculty; and visiting researchers. Director James (Jim) Sweeney, a Professor of Management Science and Engineering, Senior Fellow of the Hoover Institution, and Senior Fellow of the Stanford Institute for Economic Policy Research among other affiliations. Director Sweeney has been in this position since 2006 and has helped shape PEEC from a fledgling research initiative to a thriving center of excellence in the field of energy efficiency. Deputy Director John Weyant is a Professor of Management Science and Engineering, Director of the Energy Modeling Forum (EMF) and co-editor of the journal Energy Economics. Deputy Director Weyant has been a convening lead author or lead author for the Intergovernmental Panel on Climate Change and focuses research on technology, policy, and climate change.

PEEC Advisory Council Members

The PEEC Advisory Council is a collection of people, primarily outside of Stanford, recruited to give broad strategic advice, facilitate access to individual companies and organizations, and critique the Center's progress.

Current Advisory Council Members include the following. In going forward, we expect to consult with the various members to ascertain which wish to continue in this role and to add additional members.

George Shultz
PEEC Advisory Council Chair
Thomas W. and Susan B. Ford Distinguished Fellow: Hoover Institution

Jay Precourt
PEEC Advisory Council Vice Chair
Chair and CEO, Hermes Consolidated Inc.

John Boesel
President and CEO: WestStart-CALSTART

Joseph Desmond
Senior Vice President, Marketing and Government Affairs, BrightSource Energy

TJ Glauthier
TJG Energy Associates, LLC

Agatha Precourt
Consumer Marketing/Brand Management, Consultant

Burton Richter
Director Emeritus, Stanford Linear Accelerator Center; Paul Pigott Professor in the Physical Sciences Emeritus; Nobel Laureate, Physics

Ben Schwegler
Vice President / Chief Scientist: Walt Disney Imagineering

Erik Straser
Venture capital

Bill Valentine
Chairman of the Board: HOK

Robert E. Wilhelm
Energy Consultant, Venture Capital Investor
Retired VP and Director, ExxonMobil Corporation

Ward Woods
Retired President and CEO of Bessemer Securities

Jane Woodward
CEO: MAP

Cathy Zoi
CEO, SunEdison's Rural Electric Utility Company

Appendix F: PEEC Personnel

PEEC personnel include faculty, research staff, and administrative staff within PEEC; affiliated faculty; undergraduate and graduate students involved in PEEC activities; post-doctoral scholars; and medium-term or long-term visitors from other institutions.

Senior Staff Profiles

James L. Sweeney, Director

James L. Sweeney is Director of the Precourt Energy Efficiency Center; Professor of Management Science and Engineering; Senior Fellow of the Stanford Institute for Economic Policy Research; Senior Fellow of the Hoover Institution on War, Revolution and Peace; Senior Fellow of the Freeman Spogli Institute for International Studies; and senior fellow of the Precourt Institute for Energy. He served as chairman of the Stanford Department of Engineering-Economic Systems and chairman of the Department of Engineering-Economic Systems and Operations Research.

His professional activities focus on economic policy and analysis, particularly in energy, natural resources, and the environment. His research includes depletable and renewable resource use, electricity market analysis, environmental economics, global climate change policy, gasoline market dynamics, energy demand, energy price dynamics, and housing market dynamics. Along with Alan Kneese, he was editor of the three volume Handbook of Natural Resource and Energy Economics, part of the North Holland Handbooks in Economics series. He is the author of The California Electricity Crisis, an analytical history of the economic and policy issues associated with California's electricity restructuring and the subsequent crisis.

At Stanford he has served as Director of the Energy Modeling Forum, Chairman of the Stanford Institute for Energy Studies, and Director of the Center for Economic Policy Research (now the Stanford Institute for Economic Policy Research). He currently is on the executive committee of the Center for International Security and Cooperation and the executive committee of the Precourt Institute for Energy.

He periodically serves as a consultant or advisor to corporations, governmental agencies, non-governmental organizations, and law firms. He has served as expert witness in energy litigations in natural gas, oil, and electricity industries in the United States and in New Zealand.

He holds a B.S. degree from MIT in Electrical Engineering and a Ph.D. from Stanford University in Engineering Economic Systems. His articles have appeared in numerous books and journals, including Econometrica, Journal of Economic Theory, Resources and Energy, Management Science, Journal of Urban Economics, The Energy Journal, and International Encyclopedia of the Social and Behavioral Sciences.

John P. Weyant, Deputy Director

John P. Weyant is Professor of Management Science and Engineering, Director of the Energy Modeling Forum (EMF) and Deputy Director of the Precourt Institute for Energy Efficiency at Stanford University. He is also a Senior Fellow of the Precourt Institute for Energy and the Freeman-Spolgi Institute for International Studies at Stanford. Prof. Weyant earned a B.S./M.S. in Aeronautical Engineering and Astronautics, M.S. degrees in Engineering Management and in Operations Research and Statistics all from Rensselaer Polytechnic Institute, and a Ph.D. in Management Science with minors in Economics, Operations Research, and Organization Theory from University of California at Berkeley. He also was also a National Science Foundation Post-Doctoral Fellow at Harvard's Kennedy School of Government. His current research focuses on analysis of global climate change policy options, energy efficiency analysis, energy technology assessment, and models for strategic planning. He currently serves as co-editor of the journal Energy Economics.

Weyant has been a convening lead author or lead author for the Intergovernmental Panel on Climate Change for chapters on integrated assessment, greenhouse gas mitigation, integrated climate impacts, and sustainable development, and most recently served as a review editor for the climate change mitigation working group of the IPCC's forth assessment report. He was also a founder and serves as chairman of the Integrated Assessment Modeling Consortium (IAMC), a five-year-old collaboratory with 53 member institutions from around the world. He has been active in the U.S. debate on climate change policy through the Department of State, the Department of Energy, and the Environmental Protection Agency. In California, he is a member of the California Air Resources Board's Economic and Technology Advancement Advisory Committee (ETAAC) which is charged with making recommendations for technology policies to help implement AB 32, The Global Warming Solutions Act of 2006.

Weyant was awarded the U.S. Association for Energy Economics; 2008 Adelmann-Frankel award for unique and innovative contributions to the field of energy economics. Weyant was honored in 2007 as a major contributor to the Nobel Peace prize awarded to the Intergovernmental Panel on Climate Change and in 2008 by Chairman Mary Nichols for contributions to the to the California Air Resources Board's Economic and Technology Advancement Advisory Committee on AB 32.

Dian Grueneich, Senior Research Scholar

Dian joined PEEC in May 2014 as a Senior Research Scholar. She began her professional career in the late 1070s, after receiving her J.D. from Georgetown University and undergraduate degree from Stanford. Dian is an internationally recognized expert in energy efficiency and energy generally. She served as a Commissioner for the California Public Utilities Commission (CPUC) from 2005-2010, overseeing energy efficiency and demand response, the $1 billion annual energy efficiency budget of California investor-owned utilities, and development of the California Long-Term Energy Efficiency Strategic Plan.

At PEEC, Dian's major focus is on "The Next Level of Energy Efficiency". Her research covers four areas: Challenges Ahead, New Tools and Opportunities, An Updated Policy Framework, and Harnessing Market Forces. This project is discuss in Appendix C.

Beyond the specific Next Level project, Dian has provides invaluable expertise with Stanford on energy efficiency and energy policy general. For example she has been a guest lecturer the Emerging Technology Collaborative of PIE, Peter Ramsey's Advanced Building course), and the Stanford/SLAC Energy Week. She recently participated in a panel with Stanford President Hennessey sponsored by the Stanford Public Policy Program. Dian and Stanford Law School Professor Michael Wara hosted three internal Stanford briefings in 2014 on EPA's proposed carbon emission reduction rules for existing powerplants (111d) (the Clean Power Plan). Dian organized a 3-part mini-series on 111d for Stanford's Energy Seminar, presenting former Colorado Governor Bill Ritter, a senior electricity executive, and experts on carbon/energy modeling. She and Professor Wara mentored a student in the summer of 2015 as part of PIE's new Stanford Undergraduate Program in Energy Research (SUPER) who researched and wrote a paper analyzing New York State's Reforming the Energy Vision (NY REV) initiative. This summer, she and Professor Wara, along with Professor Stefan Reichelstein of the Stanford Graduate School of Business, will again mentor a SUPER student along with a graduate law student on research regarding changing international energy policy frameworks. In the fall of 2015, at the request of the California ISO and the California Air Resources Board, she helped organize a meeting at Stanford with the heads of three European energy grids, members of the European Union and German parliaments, California policymakers and agency staff, and others. She also organized with the Stanford Energy Club (and moderated) a panel in the fall of 2015 on new California energy efficiency laws; the panel included the author of one of the laws, the chief legislative consultant and CEC Commissioners. Students and faculty from throughout Stanford attended.

Dian lectures regularly outside Stanford on energy efficiency and energy policy. Examples include the annual University of San Diego energy symposium, a CPUC sponsored Zero Net Energy Workshop, keynote speech at a Smart Cities conference, serving as moderator for two Commissioner panels at the Western Conference of Public Utility Commissioners, and participating in a Western energy meeting of the Center for the New Energy Economy at Colorado State University. She is active on the following advisory groups: NREL's National Energy Advisory Committee, the U.S. DOE/EPA State Energy Efficiency Action Group (SEE Action), the China-US Energy Efficiency Alliance, and the U.S. DOE's Clean Energy and Empowerment initiative which co-hosts with MIT (and now Stanford_ an annual scholarship program and symposium for mid-career women in energy. She also chairs the Energy Efficiency 2.0 Advisory Group for the World Business Council on Sustainable Development and leads its annual international meeting.

Looking forward, Dian will continue to lead PEEC's research and activities on state energy efficiency policies and regulatory frameworks. Working with Stanford students, she is finalizing the remaining sections of the Next Level of Energy Efficiency research for publication in the *Electricity Journal*. She will continue to present the research both within and outside Stanford and has already been asked to do so in several venues (ACEEE's 2016 Summer Study, the annual Symposium of the Northeast Energy Efficiency Partnership, the annual meeting of the World Business Council for Sustainable Development). She plans to focus further research on new energy efficiency policy frameworks that support whole building system approaches and competitive procurement of efficiency savings. Dian plans to remain with PEEC until she formally leaves Stanford during the spring of 2017. However, we expect to continue working with Dian at a reduced level of effort even after that time.

We expect that the SEIC internships and seminar that Dian is teaching will continue and expand, possibly to include an international, as well as California, focus, even after she formally leaves Stanford. As noted above, this new internship and educational effort includes a focus on energy efficiency and will thus continue to integrate PEEC into the larger Stanford activities.

Dian is also expanding her research on the intersection of data analytics and building energy efficiency. One of the 2016 SEIC interns is working with CEC Commissioner McAllister to help build an advanced data base for analysis of data collected under California's new benchmarking law, AB 802. Dian is also seeking funding with a new Stanford engineering faculty, Rishee Jain, to develop an advanced data platform for government benchmarking efforts that will include a policy recommendation component.

Carrie Armel, Research Associate - Behavior & Energy

Dr. Carrie Armel is a research associate at Stanford's Precourt Energy Efficiency Center (PEEC) where she investigates the diverse ways in which an understanding of human behavior can lead to improvements in energy efficiency. For example, the application of behavioral principles can produce significant energy reductions through interventions implemented at the policy, technology, built environment, media/marketing, and organizational/community levels. She has developed and published on such interventions, measures to evaluate their efficacy, and tools to support others in developing interventions.

Dr. Armel serves as Project Director on the ARPA-E funded Stanford Energy Behavior and Sensor Initiative, which included 20 independent projects spanning 10 Stanford departments across five schools. This initiative involves a collaboration between academic and non-academic organizations to design and evaluate a technology technologies and programs that leverage energy sensor data and behavioral approaches to achieve widespread energy savings.

She also co-chaired the Behavior, Energy, and Climate Change Conference; oversees Precourt Institute's Behavior and Energy Bibliographic Database and Website; and has taught courses on behavior and energy at Stanford. She has organized multiple workshops relating to energy and behavior, the process of developing interventions, sensor and feedback devices, and algorithms, and has created numerous tools for practitioners and academics alike, as outlined elsewhere in this document.

Dr. Armel completed a Ph.D. in Cognitive Neuroscience from the University of California at San Diego, postdoctoral work in Neuro-Economics at Stanford, and postdoctoral work at Stanford's School of Medicine. In these programs she employed behavioral, psychophysiological (skin conductance, facial electromyography, and eye tracking), and neuroscientific (patient studies and brain imaging) methods to investigate how affect and motivation influence behavior, and also translated intervention techniques used in health promotion work into the domain of energy efficiency.

Margaret Taylor, Research Associate

Margaret Taylor is a Project Scientist at Lawrence Berkeley National Laboratory (LBNL) and an Engineering Research Associate in Stanford University's Precourt Energy Efficiency Center. She is also affiliated with several units at the University of California, Berkeley, where she served on the faculty from 2002-11 with a primary appointment in the Goldman School of Public Policy (GSPP). Margaret has a broad interdisciplinary education and professional experience that bridges engineering, the social sciences, and the environmental sciences; her degrees are from Carnegie Mellon University and Columbia University. Margaret also has legal and Capitol Hill experience in the areas of international trade, energy, and the environment.

Margaret's research, which has won awards from the Academy of Management and the International Institute of Applied Systems Analysis, explores questions at the nexus of innovation and energy/environmental policy. She believes that the mechanisms underlying the relationship between the design and implementation of public policy and the invention, adoption, and diffusion of technologies are not well understood and can have important effects on the social and economic outcomes of public policy. This drives her research agenda, which has predominantly focused on technologies and industries in which government clearly plays a strong role, such as energy and the environment, but has also encompassed industries in which government plays a more subtle role, such as nanotechnology (she is an associate director of a nanotechnology research center at UC Berkeley) and even consumer products.

Margaret's research approach is problem-driven, drawing theoretical and methodological insights from such fields as economics, sociology, business strategy, and organizational behavior. In the area of energy and environment, her work has spanned such technology domains as energy supply (e.g., renewables), energy demand (e.g., energy efficient appliances), environmental pollution control/remediation (e.g., sulfur dioxide control technologies), and transportation (e.g., advanced drive train vehicles). The policy instruments she has researched include emissions trading, performance-based standards, a regulatory sales mandate, renewable portfolio standards, investment and production tax credits, information policies, and R&D funding. When considering these instruments, she pays particularly close attention to the implications of statutory and regulatory language and related government processes for individual and organizational decision-making related to innovation, and tries to highlight strategic responses, whether they are anticipatory, same-period, or future-period.

Martin Fischer, Theme Lead - Buildings

Martin Fischer is the Buildings Theme Lead for the Precourt Energy Efficiency Center and Professor of Civil and Environmental Engineering. His research goals are to improve the productivity of project teams involved in designing, building, and operating facilities and to enhance the sustainability of the built environment. His work develops the theoretical foundations and applications for virtual design and construction (VDC). VDC methods support the design of a facility and its delivery process and help reduce the costs and maximize the value over its lifecycle. His research has been used by many small and large industrial government organizations around the world.

Andreas Schäfer, Visiting Professor, University College London

Andreas W. Schäfer is a Professor of Energy and Transport at the UCL Energy Institute, University College London. He is also the UCL Energy Institute's Director of Research and a Visiting Professor at the Precourt Energy Efficiency Center at Stanford University. He has been a member of the World Economic Forum's Global Agenda Council on the Future of Transportation for five years.

Andreas' publications cover the demand for and supply characteristics of energy and transportation systems. Examples include econometric models of national, world-regional, and global travel demand, techno-economic assessments of advanced surface and air vehicle technologies, and integrated modeling of the global air transportation system. In addition to peer review journals, his work was published in popular science magazines, such as Scientific American and American Scientist. He is lead-author of "Transportation in a Climate-Constrained World", MIT Press (June 2009).

Prior to joining the UCL Energy Institute, he held appointments at the International Institute for Applied Systems Analysis (IIASA), the Massachusetts Institute of Technology, the University of Cambridge, and Stanford University. Andreas holds a MSc in Aerospace Engineering and a PhD in Energy Economics, both from the University of Stuttgart, Germany.

Ross Chanin, Visiting Scholar, Atlantic Council's Global Energy Center

Ross Chanin is a Nonresident Senior Fellow with the Atlantic Council's Global Energy Center. He has been a member of the Edison Foundation's Institute for Electric Innovation Management and Partner Roundtable. He is a repeat entrepreneur and speaks and publishes on energy policy and market orientations.

Previously, Mr. Chanin was the CEO and Founder of American Efficient, a venture-backed software platform for U.S. regulated utilities and the deregulated power sector. He cofounded Reputation.com, a world leader in online privacy and reputation management solutions and a 2012 World Economic Forum (Davos) Global Growth Company. Mr. Chanin also served on the speechwriting staff of a major presidential campaign.

Mr. Chanin is a recent speaker at Annual Meetings of the National Association of Regulated Utility Commissioners (NARUC), Stanford University's Silicon Valley Energy Summit, the Edison Electric Institute, the South-Central Partnership for Energy Efficiency as a Resource (SPEER), and the San Francisco Emerging Technologies Summit: Accelerating Innovation in Energy Efficiency. He is a contributor to SPEER's Resource Adequacy Working Group publications on the inclusion of energy efficiency in the Electric Reliability Council of Texas's market framework, and is a Fellow with the Truman National Security Project.

Mr. Chanin is a summa cum laude graduate of the University of Pennsylvania and Stanford Law School.

PEEC Affiliated Faculty

PEEC Affiliated faculty includes those whose research and outreach activities are funded by PEEC and a larger group who understand the importance of energy efficiency, who wish to maintain close communication with PEEC, and who participate in PEEC activities. Affiliated faculty members include:

Department of Chemical Engineering
Curtis Frank

Department of Civil and Environmental Engineering
Sarah Billington
Greg Deirlein
Martin Fischer
Mark Jacobson
Gil Masters
Eduardo Miranda
Jeffrey Koseff
Clyde "Bob" Tatum

Department of Communication
Byron Reeves

Department of Computer Science
Scott Klemmer

Joint Program in Design
Shilajeet "Banny" Banerjee

Department of Economics
Lawrence Goulder
Frank Wolak

Department of Electrical Engineering
Hamid Aghajan
Stephen Boyd
Andrea Goldsmith
Martin Hellman

Department of Management Science and Engineering
Samuel Chiu
Ramesh Johari
Ross Shachter
James Sweeney
John Weyant
Yinyu Ye

Department of Mechanical Engineering
Tom Bowman
Christopher Edwards
Chris Gerdes
Kenneth Goodson
Gianluca Iaccarino
Fritz Prinz

School of Medicine
Abby King
Thomas Robinson

Department of Energy Resources Engineering
Khalid Aziz
Sally Benson
Margot Gerritsen

Freeman Spogli Institute for International Studies
Henry Rowen (since deceased)

Graduate School of Business
Erica Plambeck

School of Law
Meg Caldwell
Thomas Heller
Barton Thompson
Michael Wara

Department of Psychology
Sam McClure
Greg Walton

Students Who Have Worked with PEEC

Many students, in addition to the PhD graduates have been funded by and/or worked with PEEC. The following is a partial listing, including those students who have received their PhD while working closely with PEEC. It includes undergraduates, masters and PhD candidates, but not post-doctoral scholars.

Adrian Albert
Amy Allen
B. Atikoglu
Nishand Bhansali
Brett Bridgeland
Tien Tien Chan
Raj Chowdhary
Martin Chang
Julia Clark
Marilyn Cornelius
Matt Crowley
James Cummings
N. Fukumoto
Victor Gane
David Gar
Kenneth Gillingham
Nicole Greenspan
N. Gomes
Amy Guy
Sebastien Houde
Ozge Islegen
Ollie Khakwana
Amir Kavousian
Maria Kazandjieva
Amir Khalili
Arianna Lambie
Saniya LeBlanc
Alexandra Liptsey-Rahe
H. Liu
Tammy Luo

Raghavender Palavadi
Naga
Brett Madres
Ann Manley
G. O. M. Mandayam
Deepak Merugu
Ali Nouri
Issra Omer
David Paunesku
Larson Plano
C. Pluntke
Yueming Qui
Nikhil Rajendra
N.S. Rama
Rebecca Raybin
Anshuman Sahoo
Amul Sathe
Annie Scalamnini
James Scarborough
Dhruv Sharma
Gregg Sparkman
Shaun Stehly
Anant Sudarshan
Benjamin Welle
Joe Westersund
Scott White
D. Wischik
Brian Wong
T. Yu
Alex Yu Zheng

Appendix G: Stanford Research Community

Commitment to Interdisciplinary Research

Recognized as a world-leading research and teaching institution, Stanford has an internationally renowned faculty working with some of the brightest students from across the globe. Stanford has recently made institutional commitments to collaborative efforts by introducing new interdisciplinary initiatives in the areas of biosciences, the environment, and international affairs. The depth and breadth of Stanford's faculty and student body have positioned Stanford well to pursue such interdisciplinary initiatives.

There is a wide array of energy-related efforts at Stanford encompassing 21 academic departments (most involving engineering, earth sciences, and humanities and sciences), 13 independent research labs and programs, and 148 faculty members. The interdisciplinary research at Stanford includes collaborative work from the second ranked Engineering school in the country according to the annual *US News & World Report* college rankings. Five Stanford Engineering departments/programs are placed in the top two: the environmental engineering program within the civil and environmental engineering department (#2), electrical engineering (#1) aeronautics & astronautics (#2), computer engineering (#1), and mechanical engineering (#2). Stanford holds further five top five rankings: civil engineering (#3), materials science and engineering (#4), the industrial engineering program in the management science & engineering department (#5), and chemical engineering (#4). In terms of social science and those related to behavior studies, Stanford has a (#1) ranked psychology department and (#5) ranked economics department.

Stanford has launched eight energy-related research institutions including the Precourt Institute for Energy, TomKat Center for Sustainable Energy, and Steyer-Taylor Center for Energy Policy and Finance.

Energy Efficiency and Sustainability at Stanford

Stanford prides itself on fostering the critical link between advanced analytical and theoretical research and implementation and applications practice. The energy related research is no exception. A number of research facilities and retrofitted buildings on campus have been designed to explore the applications of energy efficiency practices in a functional environment. The Leslie Shao-ming Sun Field Station[9] on Stanford University's Jasper Ridge Biological Preserve, for example, is a building designed to minimize its energy consumption and to maximize use of solar energy.

[9] For more information on the Sun Field Station please refer to: http://jr-solar.stanford.edu/

Moreover, Stanford University has made significant headway in the promotion of energy efficiency within various facilities at Stanford. There is a collection of sustainable buildings at Stanford which have incorporated a rich array of efficiency measures, including the provision of an energy efficient thermally comfortable environment without the use of air conditioning.

The Stanford Sustainability Office (sustainable.stanford.edu) includes many other efficiency measures aimed to promote and shed light on energy conservation issues within the daily lives of the students. The office creates and updates an Energy and Climate Plan every several years, includes a Student's Guide to Sustainability, guidelines for space planning, water conservation, and recycling. The student housing association at Stanford also introduces numerous energy efficient practices annually to student residents through programs ranging from water to energy conservation and efficiency.

The university has allocated $30 million for major capital improvements to the most energy-intensive buildings on campus. The first overhaul, of the Stauffer Chemistry Building, was finished in June 2007 and resulted in a 35 percent drop in electricity use, a 43 percent cut in steam use and 62 percent fall in chilled water use. It also cut energy costs by 46 percent in the first 12 months.

As of August 2015, the university had completed 15 WBERP projects, which are saving annually 9.5 million kWh, 5 million ton-hrs of chilled water, and 71 million pounds of steam, representing over 14,000 metric tons of greenhouse gas emissions and more than $4.5 million per year. An additional 12 projects are in the pipeline, which are projected to save another $2.3 million per year. Systems retrofits to the most energy-intensive buildings on campus are expected to save $4.2 million a year and cut energy use by 28 percent.

Student and Community Involvement

The goal of educating and training Stanford graduates to become the future leaders of tomorrow begins with student life and involvement on campus. In addition to the degree programs and the physical facilities related to energy, are seminars, student groups, and internship opportunities.

The Stanford Student Green Fund provides up to $30,000 a year in one-time grants for student-led projects that improve campus sustainability. Through this program, Office of Sustainability supports student leadership by providing funding, guidance, and opportunities for hands-on experience and networking. Recently this included a project called Engineers for a Sustainable World where students lead workshops where they built their own pedal-powered bicycle light systems. By participating in the workshops, students who used their systems supported both Stanford's safe biking priorities and its goal of reducing hazardous waste, such as disposable batteries.

Furthermore, the Stanford Energy Club, founded by students at the Graduate School of Business, organizes various energy related activities for students and faculty both on and off campus. The GSB Energy Club was founded in 2003 to bring together students – the future leaders in the energy industry – with faculty and guests, the current leaders in the industry. The club organizes the Stanford GSB Energy Seminar, bringing out leaders from several sectors including oil and gas, renewables, government, venture capital, private equity, and investment banking to discuss energy-related issues. This creates an opportunity for idea exchange about the energy industry and emerging global issues in the business sector, helping to bridge the gap between industry and academia.

The Stanford Energy Club also manages the Stanford Energy Journal, an online publication published online twice a year that features 10-15 article of op-ed length ranging in topics from civil engineering, earth systems, grid storage, natural gas, and other relevant issues.

Community and corporate involvement is one of Stanford University's unique vantage points. In over eight decades, the school of Engineering alone has driven uncounted technological innovations, fostered the development of the technology industry in California, and helped found more than 800 companies. This respected and well found relationship creates tremendous opportunities for research and funding for students and faculty.

For example, the Schneider Fellowship program provides 18 3-month and three 1-year paid, high impact fellowships. The Schneider Fellows program was established in 2001 under the name "MAP Sustainable Energy Fellows." Since then, the program has provided 205 fellowships with partner NGOs, adding up to more than 78 years (full-time-equivalent) of service. This program matches students with NGOs, such as the Rocky Mountain Institute, Natural Resources Defense Council, the Union of Concerned Scientists, and Audubon Society. Students are chosen based on their efforts to identify and solve the challenges of developing a more sustainable energy future.

Acknowledgements/Authorship

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