Calculation of Emissions Reductions From Energy Efficiency and Renewable Energy Programs

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Based on a presentation by Dr. Jeff Haberl on his work with Dr. Charles Culp and Mr. Bahman Yazdani

Figure 1: This nighttime picture of an industrial park provides a visual indication of its emissions.

Introduction

Over the last decade, energy conservation and the use of renewable energy has propelled itself to the top of the international agenda. The world's dependence on unsustainable energy sources poses serious risks for both the developed and developing world. The international community has reacted to the proliferation of research on negative impacts of the world's energy consumption by making a strong commitment to stabilize and reduce the world's energy output. Achieving international goals requires strong individual country commitments. An emphasis on energy reduction is particularly acute in the United States. Although its share of world energy consumption has steadily declined from 28 percent in 1980 to 22 percent in 2005,[1] the United States (population 301 million)[2] still consumed more energy than all of the European Union countries (population of 490 million)[3] by a factor of 1.25 in 2005. Rising energy prices, stark environmental degradation, and mounting health issues associated with increasing energy demands have exacerbated the need for comprehensive policies and programs that provide incentives for energy conservation.

Commercial and residential buildings consume approximately 71 percent of the electricity in the United States.[4] Therefore, any practical energy reduction plan put forward by the nation must incorporate energy saving techniques into the building process. Energy savings can be realized through the building's design (i.e. positioning structures on a lot to maximize efficiency), construction, and the installation of renewable energy sources (i.e. utilizing solar panels to reduce reliance on the electrical grid). Policymakers, engineers and architects have responded collaboratively, integrating energy-efficient policies into building codes and providing financial incentives for the use of retrofits and the installation of renewable energy sources. These policies are essential if energy conservation concepts are to be incorporated into mainstream building design. However, polices are not sufficient on a stand-alone basis.

It is critically important that evaluation methodologies are in place to measure the efficacy of energy-efficient building policies. Evaluation of energy policies and programs is the link that will provide policymakers, architects and engineers with evidence to help drive improvements in building codes, material choices, and construction processes. Without sound evaluation methodologies it will be nearly impossible to know the net energy impact of policies and programs.

This paper presents the collaboration between the state of Texas and the Energy Systems Laboratory (ESL) at Texas A&M University as a case study on how evaluation techniques

can be incorporated into energy efficiency programs to enhance policy. ESL is nationally recognized as an industry leader in the area of quantifying energy savings and reductions in nitrogen oxide (NO_x) emissions from energy efficient/renewable policies and programs in the electric sector.

NO_x emissions

What is nitrogen oxide (NO_x)?

NO_x is the generic term for nitrogen oxides, which are formed through the mixture of two gasses: nitrogen and oxygen. NO_x mixtures are both colorless and odorless and thus cannot be detected by human senses. They are emitted into the air through the combustion process; examples include motor vehicle exhausts, the byproducts of the electricity generation process (i.e. burning of coal or natural gas), and many of the industrial manufacturing processes. NO_x gases are also a component of greenhouse gases and thus contribute to global warming.

According to the Environmental Protection Agency (EPA), in 2002 Texas emitted nearly 2 million tons of NO_x into the environment, which represented 9.3 percent of the total NO_x emissions in the United States. As shown in Figure 3, the vast majority of NO_x emissions in Texas derive from cars, industrial processes, combustion, and electricity generation.

How does NO_x affect the environment and our health?

NO_x is most often correlated with ground level ozone. When sunlight is present, the chemical reaction between NO_x and volatile organic compounds (VOCs) creates the ozone chemical. It is a misconception that all ozone is bad.[5] When ozone is concentrated 10-30 miles above the earth's surface it is considered "good" because it protects people from harmful UV rays. However, ground level ozone is "bad" because it infects our air quality with smog. High levels of ground level ozone are associated with various respiratory conditions, such as asthma, and cause a general reduction in lung function. Lung tissue can also be damaged due to prolonged exposure to ground level ozone. The build up of ground level ozone is cited as one of the worst side effects of NO_x emission.

Aside from ground level ozone, NO_x presence in the atmosphere increases acid rain, leads to deterioration in water quality, and reduces crop yields.[6] Acid rain caused by NO_x emissions degrades the water quality of streams, rivers, and lakes, making the water uninhabitable for many species of fish.[7] It also disrupts the ecosystem of water systems by distorting the chemical balance of nutrients that plants and animals use to survive.[8] Additionally, acid rain corrodes the surface of cars, buildings, and historic monuments.[9] Researchers have strong evidence linking increased levels of NO_x to lower crop yields.[10] Geographical areas with low NO_x emissions can also be susceptible to ozone because wind currents can transport the chemical from one region to another. As a greenhouse gas, growing levels of NO_x could exacerbate the long-term effects of global climate change.

Regulating emissions

In 1970, Congress enacted the Federal Clean Air Act, which authorized the EPA to regulate maximum allowable concentrations of air pollutants. The EPA in turn established National Ambient Air Quality Standards that detailed maximum allowable levels of carbon monoxide, lead, nitrogen dioxide, particulate matter, ozone, and sulfur dioxide. The EPA holds every state and county accountable for meeting the requirements set forth by the National Ambient Air Quality Standards. In Texas, the Texas Commission on Environmental Quality has been delegated the task of monitoring and reporting the state's air quality to the EPA.

Texas and air quality

Texas is notorious for its poor air quality. Of the 254 counties in Texas, 41 have been designated as non-attainment or affected areas under National Ambient Air Quality Standards guidelines. Dallas, Harris, Tarrant, and Bexar are four of the biggest counties classified as non-attainment areas, and these counties account for approximately 40 percent of the state's population. Not surprisingly, motor vehicle use, industries, and housing starts are all concentrated in the counties with the highest populations, thus exacerbating their poor air quality.

Figure 2: Smoke stack pollution

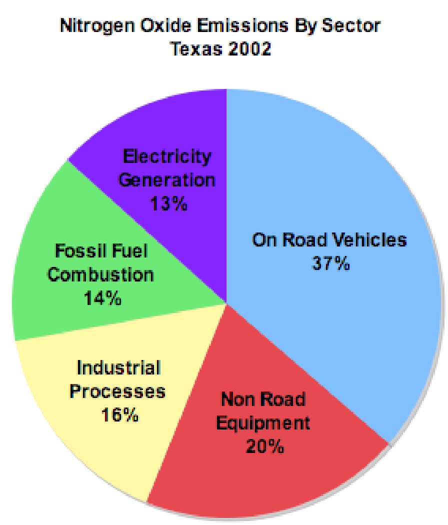

Figure 3: Nitrogen oxide emissions in Texas

Senate Bill 5

In 2001, the Texas Legislature passed Senate Bill 5 establishing the Texas Emissions Reduction Plan, which is administered by the Texas Commission on Environmental Quality. This plan, which has been amended three times since being passed in 2001, is Texas's comprehensive energy plan. It aims to reduce diesel and motor vehicle emissions through incentive programs, create a technology and research development program, create an energy efficiency grant program and develop building energy performance standards. The legislation specifically targets the reduction of ozone by regulating NO_x area emissions.

A vital piece of the bill requires the creation of evaluation techniques and metrics for the state's energy efficiency programs. These programs call for reducing energy use and demand by integrating the International Energy Conservation Code into building codes, utilizing renewable resources, and imposing energy conservation measures on specific utility companies.

The role of the Energy Systems Laboratory (ESL) in relation to Senate Bill 5

The Energy Systems Laboratory has been commissioned by the Texas Commission on Environmental Quality to report energy savings from the Texas Emissions Reduction Plan. In this capacity ESL is responsible for determining how emissions reduction credits from the "State Implementation Plan" can be obtained as a result of reductions in electricity use due to energy efficiency and renewable energy projects, with an emphasis on peak summertime electric demand.[11] State Implementation Plan credits are a policy mechanism that the state utilizes to motivate energy conservation, because they provide builders with financial rewards for building energy efficient structures.

In 2004, the EPA issued a framework for the quantification of air emissions benefits but did not go so far as to create exact specifications. ESL has developed precise quantification methodologies that are in line with the EPA's guidelines and has created on-line tools that allow builders to analyze the change in energy consumption as a function of a number of variables. This mechanism not only attributes credits to companies, but it also allows for the evaluation of energy polices and programs.

ESL simulations

ESL has developed several simulation models for calculating the energy savings and emissions reductions from changes to building codes in single- and multi-family units and commercial buildings that were mandated under federal and state laws. Additionally, ESL has also developed the capability to quantify energy and emissions reductions from retrofits to streetlights, traffic lights, wastewater and water supply systems and from renewable energy technologies such as solar thermal, solar photovoltaic and wind power generation. ESL has interfaced these simulation models with simple web-based applications that are accessible to the public through their website. These energy simulation models allow builders, architects, engineers and policymakers to understand and work together on improving energy efficiencies.

ESL's simulations currently focus on reductions in NO_x emissions due to energy savings. However, it is conceivable that ESL will expand its models to capture reductions in other air quality factors such as CO_2. The excess levels of this particle in the atmosphere is the leading cause of global warming. Considerable emphasis has been placed on the reduction of CO_2 in international and domestic agendas. It is therefore of urgent importance to put evaluation methodologies in place to measure the efficacy of domestic and international CO_2 reduction policies. ESL's simulation model to quantify reductions in NO_x emissions is a clear step in the right direction. The hope is that other state and international governments will expand on the example set by the state of Texas and ESL to derive evaluation techniques that will accurately measure the impact of energy polices and programs.

ESL's quantification methodology

ESL is responsible for calculating the reduction in electricity output for each county in Texas. This data is cycled through the EPA's Emissions and Generation Resource Integrated Database (eGRID) to calculate the actual reductions in air pollutants such as NO_x. There are four primary quantification procedures utilized by ESL:

1. *Single and Multi-Family Residences:* Electricity and natural gas savings along with peak-day electricity and natural gas reductions are calculated based on implementation of the 2000 International Energy Conservation Code. Energy savings are compared to baseline electricity and natural gas consumption in 1999.
2. *Commercial Buildings*: Electricity and natural gas savings along with peak-day electricity and natural gas reductions are calculated based on implementation of ASHRAE Standard 90.1-1999. Energy savings are compared to baseline electricity and natural gas consumption in 1999.
3. *Utility Bill Analysis*: This procedure involves cross-checking electricity and natural gas savings from utility bills across time.
4. *Pre- and Post-Code Construction*: On-site visits are conducted to cross-check pre- and post-construction data.

Tools utilized by ESL

1. *eGRID*: This system calculates the reduction in NO_x emissions based on computed energy savings. The system is maintained by the EPA but interfaces with ESL's models to quantify reductions in emissions.
2. *eCALC*: This web-based interface was developed by ESL for the Texas Commission on Environmental Quality with support from the EPA. eCALC incorporates baseline weather data to calculate annual peak-day and average Ozone Season Day period energy savings. eCALC is also connected to eGRID, allowing the user to calculate emissions reductions in NO_x, SO_x, and CO_2 attributable to traffic light and streetlight retrofits. ESL has recently developed the International Code Compliance Calculator, which is an offshoot of eCALC. This program computes energy savings and NO_x emissions reductions for code compliant homes. The International Code Compliance Calculator automatically e-mails the results to the end user.

The following section will detail quantification methodologies for single/multi family homes, commercial buildings, traffic lights and streetlights, waste water, solar photovoltaic and thermal power generation, and wind power generation. The section will also detail average energy savings from energy efficient/renewable regulations where applicable.

Quantifying energy savings and NO_x emissions

Single and multi-family

The team at Energy Systems Laboratory has created a system of models that allows users to simulate the energy consumption of

single- and multi-family households in Texas. The simulation model runs under three circumstances:

1. A pre-code simulation that is run with the National Association of Home Builders construction characteristics.

2. A code compliant simulation that incorporates minimum 2000 International Energy Conservation Code code and its 2001 supplements.

3. A simulation based on user input.

The models also take county specific weather data into account by incorporating 1999 data from the National Oceanic and Atmospheric Administration's National Weather Service for Texas. Integrating weather data into the simulations allows builders to design a building's energy usage to peak loads and peak ozone days. The simulations designed by ESL allow developers, designers, and builders to compare the potential annual and peak day energy savings within the framework of the three scenarios.

The simulations use two general parameter types to quantify energy savings under the three scenarios: load and system parameters. Load parameters are broken down into four groups: building, construction, space and shading parameters. Building parameters are associated with the location, orientation, and dimensions of the structure. Construction variables include material properties, such as window-to-wall area ratios and glazing properties. Space parameters deal with occupancy and number of bedrooms, which are used to determine hot water consumption rates. Shading parameters are used to determine the heating and cooling loads of buildings. The model uses three types of system parameters:

1. Gas heating, gas domestic water heating, and electric cooling.

2. Electric heating, electric domestic water heating and electric cooling.

3. Electric heat pump heating, electric domestic water heating and electric cooling.

ESL has interfaced their models with a web-based design that allows open access to the system. Additionally, ESL has created an "Express Calc" simulation that allows users to compare energy outputs from pre- and code-compliant simulations with the input of only 12 parameters. Users have the option of running more detailed simulations if they choose.

Figure 4: Solar Decathlon House; Georgia Institute of Technology

The following are general observations compiled by ESL from repeat simulations. (It's important to note that these observations do not hold in every circumstance.)

- Utilizing electric heat pump heating, electric DWH, and electric cooling consumes the least amount of energy on an annual basis for both single- and multi-family buildings.

- Natural gas heating saves more energy than electric or heat pump systems.

- For single-family households, two-story buildings generally consume less energy than one-story buildings.

- For one-story single-family households, the annual percentage energy savings ranges from 13.6 percent for natural gas heating/DHW to 9 percent for electric heat pumps.

- For a multi-family building, the savings range from 12 percent for one-story gas heating/DHW to 3 percent for three-stories with electric heat pump.

Commercial buildings

ESL's simulation models use various construction types and different HVAC systems to calculate savings from either office or retail commercial spaces. Similar to the methodology for single- and multi-family units, the quantification technique utilizes three simulation modes for calculating energy and emissions savings. The pre-code simulation is based on construction characteristics from ASHRAE 90.1-1989. The code-compliant simulation is based on minimum requirements in ASHRAE 90.1-1999, and the third simulation is based on user input. Code characteristics for office and retail end buildings are determined by climate zone. The parameters for running simulations vary depending on whether the building is office or retail. However, both of the models use load and system parameters. Like the single- and multi-family unit simulation, load parameters consist of building, construction, space, and shading parameters. The system parameters evaluate the type of system, its capacity and efficiency. One significant aspect of commercial building models is that the complexity of the building code requires several simulations to be run under each scenario before the energy savings output can be computed. The commercial building models are integrated with eGRID to calculate NO_x emissions reductions.

Traffic light and streetlights

A high percentage of a municipality's electricity bill is comprised of energy for operating streetlights and traffic lights. Research has shown that retrofitting streetlights with high pressure sodium and metal halide lamps and traffic lights with light-emitting diodes (LEDs) saves a lot of energy. Installing these energy efficient technologies will not only save the municipality money on its electric bills, but will also reduce greenhouse gas emissions.

ESL has developed two methodologies to identify the energy and emissions savings from energy efficient technologies. The first is the

utility bill mode where pre- and post-retrofit utility bill data (electricity use) and daily weather data are used to run regression models to determine the actual energy savings. The regression models use ASHRAE's Inverse Model Toolkit to find statistical evidence that the retrofitting process is significantly reducing electricity use. The energy savings is then passed on to eGRID to determine the NO_x reductions.

ELS also employs a design mode methodology that calculates energy savings on a lamp-by-lamp basis. The user provides lamp type, lamp code, wattage, and number of lamps for both pre- and post-retrofit, then this data is used to calculate energy savings compared to the 1999 baseline year. This information is fed into eCALC to calculate emissions reductions in NO_x, SO_x, and CO_2.

Water supply and wastewater

The utility bill mode is the methodology utilized to calculate savings from retrofitting water supply and wastewater distribution systems. Energy efficient pumping systems are the main energy savings technology employed to date in water supply and wastewater distribution systems. Therefore, pre- and post-retrofit utility bill data (electricity use and gallons of water or waste water processed) and daily weather data are used in a dual-regression process to determine the energy savings. ESL utilizes ASHRAE's Inverse Model Toolkit and eGRID to quantify NO_x reductions.

Solar thermal and photovoltaic

Although the use of solar thermal and photovoltaic systems is growing rapidly, their annual energy production relative to energy created through fossil fuels is still negligible. However, having concrete data on the energy producing capabilities of thermal and photovoltaic systems is vital in order to promote the use of solar systems in both residential and commercial settings. ESL has integrated three tools, F-Chart, PV-FChart, and ASHRAE's Inverse Model Toolkit, to develop a comprehensive approach to calculating the potential energy savings from the installation of solar systems. The F-Chart and PV-F Chart are tools developed by the University of Wisconsin. The F-Chart calculates electricity savings from solar thermal systems, which produce heat using energy from the sun. The PV-F Chart calculates electricity savings from solar photovoltaic systems, which turn solar energy into electricity.

ESL systems have the capability to calculate energy savings from either high efficiency or average efficiency solar photovoltaic panels. The energy captured from solar photovoltaic panels is determined by location, orientation, and pitch. This data is used to calculate annual electricity and peak Ozone Season electricity production, taking into account the latitude of the county and the weather. The electricity savings are then input into eGRID to obtain a NO_x emissions reduction figure.

Energy savings calculations with solar thermal systems are restricted to domestic water heating and pool heating systems. Using the F-Chart, ESL is able to quantify the energy captured from these solar thermal systems. The energy generated is weather normalized using ASHRAE's Inverse Model Toolkit tool. This data is then used to calculate annual and peak day thermal output. Finally, this information is funneled through eCALC to obtain reduction in NO_x emissions.

Wind power generation

It is of no surprise that wind power is gaining momentum as a legitimate and reliable source of energy in the United States. First, the energy payback ratio—a figure that compares the amount of energy produced at a power plant to the amount of energy it takes to build, run, and decommission— is much higher for wind farms than for traditional fossil fuel power plants. Second, wind farms have the potential to generate a significant proportion of our energy demands.[12] According to Pacific Northwest Laboratory, the potential annual energy from wind power in the U.S. exceeds the current electricity generated by a factor of two.[13] Finally, generating energy from wind is a much more environmentally sustainable process than our current approach.

In 2008, approximately 1 percent, or 48 billion kWh, of United States electricity will be produced by wind power, which is enough electricity to fuel about 4.5 million average American households.[14] Although the electricity from wind power is still insignificant proportionally, it is important to highlight its environmental impact. Generating 48 billion kWh of energy from the conventional U.S. electrical fuel mix results in emitting 29 million tons of CO_2 into the atmosphere.[15] Reducing the level of CO_2 in the atmosphere will reduce the impacts of global warming.

ESL has developed a system that utilizes eGRID and eCALC to determine emissions reduction due to electricity generated from wind energy providers in Texas's Electricity Reliability Council of Texas (ERCOT) region. The eGRID system is specific to wind power generation because it incorporates electricity and pollution data from utility companies in the ERCOT region. Energy and NO_x savings are calculated on an annual and peak-day basis.

Conclusion

Recently policymakers, architects, engineers, and other disciplines involved in the building process have been quick to endorse renewable energy sources and energy efficient policies. Examples include the incorporation of energy conservation techniques into building design and construction through codifying green building practices into the International Energy Conservation Code and ASHRAE codes, and the implementation of State Implementation Plan credits to provide businesses with a financial incentive to conserve energy via renewable energy sources such as solar panels and wind energy. However, with all this progress there has been a lack of data to support the effectiveness of energy efficiency and renewable energy policies and programs.

Filling this gap, ESL, in collaboration with the Texas Commission on Environmental Quality and the EPA, has developed methodologies to quantify energy savings and the resulting reductions in NO_x emissions from changes to building codes in single-, multi-family and commercial buildings. ESL has also developed similar simulations to capture the energy and NO_x emissions savings from various renewable energy sources, including solar thermal, solar photovoltaic, wind energy, and high-pressure sodium, metal halide and LED lights. ESL's simulation models interface with user-friendly web-based applications and are therefore accessible to builders, designers, engineers, architects, policymakers and the public at large.

ESL's quantification methodologies provide multiple benefits. First, the simulation models provide concrete data on the unit energy and NO_x emissions savings from which business can obtain SIP credits. Rewarding businesses financially for conserving energy will provide the necessary incentives for them to increase efforts to save energy. Second, designers

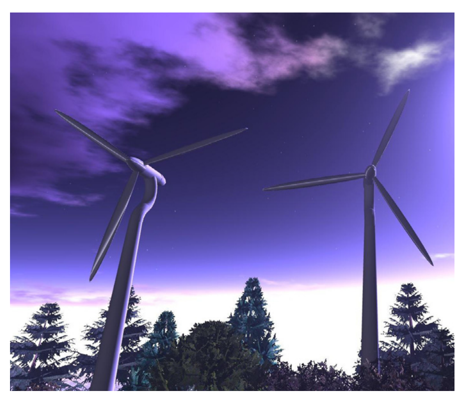

Figure 5: Wind Power

and builders will gain a better understanding of the factors that provide the greatest energy efficiencies. For example, builders will learn what HVAC systems produce the lowest energy output for specific climates. Lastly, it provides policymakers a method of quantifying the reduction in emissions due to a systematic change in building codes and the use of renewable energy sources. Therefore, the data produced by the simulation models will create a link between policymakers and the professionals affected by energy efficient polices and installation of renewable energy sources. This link is critical to the process of continually improving energy conservation techniques.

ESL has developed a robust system to quantify energy savings and their resulting reduction in NO_x emissions. However, it is important that other organizations and governments continue to build on ESL's advancements and create systems to quantify other air pollutants. For example, methodologies for quantifying CO_2 reductions must be a priority considering that it is the biggest contributor to global warming.

Notes

1. Energy Information Administration. "International Total Primary Energy Consumption and Energy Intensity." http://www.eia.doe.gov/emeu/international/energyconsumption.htm

2. The World Fact Book. "European Union." Central Intelligence Agency. https://www.cia.gov/library/publications/the-world-factbook/print/ee.htm

3. The World Fact Book. "United States." Central Intelligence Agency. https://www.cia.gov/library/publications/the-world-factbook/print/us.html

4. National Renewable Energy Laboratory. "Buildings Research." http://www.nrel.gov/buildings/

5. Office of Air Quality Planning & Standards, "Ground Level Ozone." U.S. Environmental Protection Agency. http://www.epa.gov/air/ozonepollution/

6-11. Office of Air Quality Planning & Standards, "Health and Environmental Impacts of NO_x." U.S. Environmental Protection Agency. http://www.epa.gov/air/urbanair/nox/hlth.html

12-15. American Wind Energy Association. "Wind Energy Fast Facts." http://www.awea.org/newsroom/pdf/Fast_Facts.pdf

Figures

Figure 1: http://flickr.com/photos/hometowninvasion/ 289704683/

Figure 2: http://flickr.com/photos/senor_codo/352250460/

Figure 3: Environmental Protection Agency

Figure 4: http://www.solardecathlon.org/images/photo_gallery_2007/photo_gallery_georgia-lg.jpg

Figure 5: http://flickr.com/photos/torley/2609162335/

References

Energy Systems Laboratory, http://esl.eslwin.tamu.edu/docs/documents/

Office of Air Quality Planning & Standards, "Six Common Air Pollutants: Nitrogen Oxide." U.S. Environmental Protection Agency. http://www.epa.gov/air/urbanair/nox

Biography

Dr. Jeffrey S. Haberl, P.E., is a Professor of Architecture at Texas A&M University and an ASHRAE and IPMVP Fellow. Dr. Haberl's educational background includes B.S., M.S., and Ph.D. degrees from the University of Colorado at Boulder and post-doctoral research at Princeton University's Center for Energy and Environmental Studies. Dr. Haberl came to Texas A&M in 1989 and has dedicated nearly 3 decades performing building energy research at Texas A&M University, Princeton University, the University of Colorado, Rockwell International, the Colorado State Office of Energy Conservation, the City of Boulder, and the USDOE Administrative Services.

His work emphasizes statistical building energy modeling, methods for diagnosing operational problems, operator feedback using comparisons of predicted and actual energy use, artificial intelligence, advanced energy usage graphics, prescreening calculations for improving commercial energy audits, public-domain M&V algorithms, computerized solar shading procedures, and procedures for calculating air pollution savings from energy efficiency and renewable energy projects (i.e., SO_x, NOx, CO_2, PM and Hg).

He is a Co-PI of the Laboratory's Senate Bill 5 program (with Dr. Charles Culp, and Mr. Bahman Yazdani), where he provides technical leadership for the code compliance calculator and emissions calculations from energy efficiency and renewable energy; a Co-PI for the USEPA's new National Center of Excellence on Displaced Emissions Reductions (CEDER) (with Dr. Charles Culp and Mr. Bahman Yazdani), which was established in the Spring of 2007 to help the EPA transfer the Texas emissions reductions calculation procedures to other states; a Co-PI for the Laboratory's Continuous Commissioning® program for improving energy efficiency in existing buildings; and he is the Co-PI of Texas A&M's 2007 Solar Decathlon Effort (with Pliny Fisk – PI).

He was the Principal Investigator for the Computer Support and Improved Energy Audit of the Texas LoanSTAR project from 1990 to 2002, a $98.6 million revolving loan for the state of Texas that was the first large-scale project in the United States to continuously measure and report energy savings in over 160 building energy conservation retrofits, and he has served as the Chair for 14 MS and 10 PhD students.

Dr. Haberl is a Registered Engineer in the State of Texas, has authored or co-authored 73 publications, 128 conference proceedings, 193 reports and holds numerous U.S. patents. He has been Handbook chairman of ASHRAE TC 1.5 (Computer Applications) and has contributed to the ASHRAE Handbook Chapters #49 and #60. He helped develop Standard 140 and Guideline 14, and has participated on numerous ASHRAE Research Projects (827, 865, 1004, 1017, 1050, 1092 and 1093).

He received a Boulder County Energy Conservation Award, two USDOE innovative research awards for work performed at the University of Colorado, a USDOE special citation for his work at the Forrestal and Germantown complexes, a 1990 GSA Design Award, a 1992 National Endowment of the Arts Federal Design Award for his work at the Forrestal building, and an ASHRAE Distinguished Service Award.