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ABSTRACT

Residential and commercial buildings energy consumption is a significant source of greenhouse gas emissions in developed countries, accounting for about one-third of global energy related CO_2 emissions, compared with similar amounts for the other major sectors of transportation and industrial. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) identifies buildings as the sector with the largest potential for reduced greenhouse gas emissions over the next 20 years. In the United States in 1997, heating, ventilating, air conditioning, and refrigeration (HVACR) equipment accounted for about two-thirds of residential buildings energy consumption, and one-third of commercial buildings energy consumption. Increased efficiency of HVAC equipment can certainly save energy and reduce greenhouse gas emissions; however, there is a limit to the amount of savings from considering only HVAC equipment energy efficiency. .

Based on HVAC system energy efficiency limits, we must work with a wide group of buildings industry groups (architects, designers, construction, operators, service) to achieve a larger portion of the potential CO_2 emission reductions. This implies an integrated approach with all parts of the buildings sector working together. Examples are presented of how such an approach can lead to larger emission reductions, with monetary savings beyond implementation costs. These examples include building designs to reduce HVAC equipment load requirements, reduced lighting energy, and monitoring systems to detect HVAC equipment performance deterioration.

INTRODUCTION

Global warming science assessments show a sound basis for concern over the potential influence of human activities on future climate, with CO_2 emissions from burning of fossil fuels being the primary contributor. The UN Framework Convention on Climate Change provides a demonstration of this concern by establishing a goal of "…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

Buildings energy consumption is a significant source of greenhouse gas emissions, amounting to 36% of total emissions in 1995 in developed countries, with 21% from residential buildings and 15% from commercial buildings (1). On a primary energy basis, buildings in developed countries consumed 39.8% of total energy in 1995, with the distribution being 23.6 % residential and 16.2 % commercial (1). In the United States in 1997, heating (including water heating) ventilation, air conditioning and refrigeration (HVACR) accounted for 68% of residential buildings energy consumption and 34% of commercial buildings energy consumption (2). Lighting consumed 6% of residential building energy, and 25% of commercial building energy (2). See Figures 1 and 2. One route to decreased buildings energy consumption and decreased greenhouse gas emissions is obviously through increased HVAC and lighting energy efficiency. This route will be evaluated, followed by a broader integrated systems approach using initial building design to reduce HVAC equipment load requirements, monitoring systems to optimize building performance, and fault detection and diagnostic methods to detect and inform of HVAC equipment problems and performance deterioration.

HEATING AND COOLING SYSTEM EFFICIENCIES

Space heating consumes 35% of U.S. residential energy use (2), and two heating methods (heat pumps and gas/oil furnaces) will be considered to describe the range of product energy efficiencies available. Heat pump (heating) efficiency rating is indicated by HSPF (Heating Seasonal Performance Factor) which is the ratio of seasonal heating output divided by the seasonal power consumption. The U.S. DOE minimum requirement is an HSPF of 6.8, with the EPA/DOE Energy Star qualification value of at least 7.6 (3), representing a 10.5% decrease in energy consumption. Heat pumps with HSPF ratings up to 9.75 are available (3), representing a 30% decrease in energy consumption.

Gas and oil fired furnace efficiency rating is termed AFUE (Annual Fuel Utilization Efficiency) which is the heat transferred to the conditioned space divided by the fuel energy supplied. The U.S. DOE minimum requirement is 78% AFUE (4), with the EPA/DOE Energy Star qualification value of 90% or more. The 90% AFUE model represents a 13% decrease in energy consumption. The best available is 97% AFUE (4), which represents a 20% decrease in energy consumption.

Residential space cooling consumes 8% of U.S. residential energy use (2). Residential split system air conditioners are rated by SEER (Seasonal Energy Efficiency Ratio) which is the ratio of seasonal cooling output divided by the seasonal power consumption. The U.S. DOE minimum requirement is SEER of 10.0 (5), with the EPA/DOE Energy Star qualification value of at least 12.0, representing a 17% decrease in energy consumption. Split system air conditioners are available with SEER values up to 18 (5), but most of the high efficiency units are in the range of 12-16. A unit with 14 SEER represents a 29% decrease in energy consumption, and a unit with 18 SEER represents a 45% decrease in energy consumption as compared with the 10 SEER unit.

U.S. commercial building energy consumption for space heating is 13% of total commercial energy use, and space cooling is 7% of total commercial energy use (2). Furnace efficiency values can be used to approximate the potential reduction in heating energy consumption. For cooling, the Federal Energy Management Program website provides information on water-cooled electric chillers of 500 tons (1760 kW) capacity at 2,000 equivalent full-loads hours per year. The base model has a full-load efficiency (kW/ton) of 0.68 (6), while their cost effective recommended chiller has an efficiency of 0.56. The best available chiller has an efficiency of 0.47 (6). These two higher efficiency chillers represent reductions in energy consumption of 18% and 31%.

Summarizing the above data on potential energy savings utilizing highest efficiency heating and cooling systems (as compared with current U.S. DOE minimum requirements), residential and commercial heating energy consumption could be reduced by 20-30%, residential cooling energy consumption by 30-45%, and commercial cooling energy consumption by 30%. Replacement of current building stock of older, even less efficient equipment would result in larger savings. No cost-benefit analyses were made for the highest efficiency systems. As will be described in following sections, even greater energy savings can be achieved by taking an integrated building and systems approach to reduction of energy consumption.

INTEGRATED BUILDING AND SYSTEMS DESIGN

Greater energy savings are possible if buildings are designed for reduced heating, cooling, and lighting loads. This has been recognized and pointed out by many organizations, one example being Green Development Services formed by Rocky Mountain Institute in 1991 to enable buildings professionals to "integrate energy-efficient and environmentally responsive design into specific projects" (7). In *A Primer on Sustainable Building* (7), the authors state: "…..it's straightforward to design a building that can be cooled cheaply and efficiently. The key is whole-system engineering aimed at minimizing the need for mechanical cooling. This can be achieved by reducing unwanted heat gain, harnessing natural ventilation and cooling techniques, expanding occupants comfort envelope, and properly sizing and controlling air conditioners and other cooling equipment…….. Many of the same design measures that make a green building easier to cool also make it easier to heat. The basic strategy for space heating is first to minimize heating losses through the building shell. Second, capture as much of the sun's heat as possible. Finally, meet the remaining heating load with an efficient furnace, boiler, heat pump, wood stove, or other heater." They also state that building lighting energy can be reduced by 75% or more by taking a similar systems approach and using natural and energy-efficient lighting.

Governmental, academic, business, and environmental groups/organizations around the world have recognized the need to reduce buildings energy consumption, and are endorsing the integrated buildings and systems approach. A listing of such organizations can be found on the World Energy Efficiency Association website, www.weea.org/, and a few representative groups and organizations are listed following:

- American Society of Heating, Refrigerating, and Air-Conditioning Engineers — Atlanta, GA
- U.S. DOE Energy Efficiency and Renewable Energy Network — Washington, DC
- U.S. EPA ENERGY STAR programs — Washington, DC
- European Commission – Directorate General for Energy and Transport — Brussels, Belgium
- International Energy Agency — Paris, France
- CANMET Energy Technology Centre, Natural Resources Canada — Ottawa, Canada
- Japan Ministry of International Trade and Industry
    - New Energy Development Organization — Tokyo, Japan
    - Research Institute of Innovative Technology for the Earth — Kyoto, Japan

BUILDING ENERGY SIMULATION AND DESIGN TOOLS

The United States government has supported development of building energy simulation programs since about 1970, with the most widely used programs being designated as BLAST and DOE-2 (8). The BLAST program (Building Loads Analysis and System Thermodynamics) was an outgrowth of an earlier program written to predict thermal performance of a building: National Bureau of Standards Load Determination (NBSLD) program. BLAST has been sponsored by the U.S. Department of Defense (DOD), and DOE-2 has been sponsored by the Department of Energy (DOE). Both programs simulate energy flows throughout buildings, with years of successful applications in designing more energy efficient buildings throughout the world. Due to sections of the computer coding of both programs being over 20 years old, the DOE began development support of a new building energy simulation program in 1996, with the program to be named EnergyPlus. Version 1.0 of EnergyPlus was released in April 2001, and a description of EnergyPlus is provided in reference (9). It is expected that adoption of EnergyPlus will be gradual, as time will be required for users to learn and develop confidence in modeling results, plus user interfaces must be developed.

ENERGY-10 is a less complex building energy simulation program, targeted to buildings of less than 10,000 ft^2 (929 m^2), as more than 75% of all nonresidential buildings are less than this size. It was conceived at the National Renewable Energy laboratory (NREL, Doug Balcomb, reference 10), and programming was a cooperative effort of personnel from NREL, Lawrence Berkeley National Laboratory (LBNL), and the Berkeley Solar Group (BSG). ENERGY-10 uses the "whole-building or integrated design approach (which) emphasizes the need to take many different design aspects into account, as opposed to traditional design where only a few aspects are considered and optimized" (11). With relatively simple input of geographic location, total floor space, intended building use, number of stories, and type of heating, ventilation, and air conditioning system, ENERGY-10 creates output of two basic building designs. The first being a building using standard design procedures, and the second being a lower energy building using a combination of twelve strategies to reduce energy consumption. From this starting point, variable parameters can be adjusted to study effects on energy consumption of changes in building construction materials, lighting, air and duct leakage, and heating/cooling system efficiencies. ENERGY-10 was used during initial design reviews for the Chesapeake Bay Foundation Philip Merrill Environmental Center (12), providing input on strategies and systems to reduce building energy consumption. This building received the first platinum rating from the United States Green Building Council Leadership in Environmental Engineering Design (LEED) program (13).

CASE HISTORIES OF WHOLE BUILDING INTEGRATED APPROACH

National Renewable Energy Laboratory Buildings in Golden, Colorado

Two governmental agency buildings were designed in the early 1990s using the whole building approach (14). These were the Solar Energy Research Facility (SERF) and the Thermal Test Facility (TTF), located in Golden, Colorado, being part of the U. S. DOE National Renewable Energy Laboratory. The SERF building was completed in 1993, with size of 115,200 ft^2 (10,800 m^2). Several building energy simulation programs were used during the initial planning and design process to estimate energy savings versus the U.S. Federal Energy Code 10CFR435, which is based on ASHRAE Standard 90.1 (Energy Standard for Buildings Except Low-Rise Residential Buildings). Energy savings features of SERF included North/South building positioning to maximize use of daylighting, energy efficient lights, high insulating value walls and roofs, window selection for appropriate solar heat gain and thermal properties, heat recovery for vented and incoming air, and direct/indirect evaporative cooling with a water chiller back-up cooling system. SERF building performance measurements show a 45% reduction in energy costs compared to ASHRAE Standard 90.1 requirements. The three major savings categories were lighting (67%), heating (39%), and cooling (47%). The TTF building of 10,000 ft^2 (929 m^2) was built in 1996 with the same whole building design approach, achieving an energy savings of 63% versus the U.S. Federal Energy Code 10CFR435.

"I Have a Dream House" in Atlanta, Georgia

This 1,565 ft^2 (145 m^2) house was built in Atlanta, Georgia in 2001 through a cooperative effort of the U.S. DOE Building America Program, Southface Energy Institute, and EarthCraft House. The house was designed based on Building America's whole-house systems approach, which considers the house as a complete system instead of separate components. Walls, roof, and floors are structural insulated panels with high insulating value, and providing construction with a tightened building envelope. Other energy savings factors were thermal windows, sealed air ducts, gas furnace of 93% efficiency, and an air conditioner of 13 SEER. Construction costs were similar to a conventional home, yet tests show the house uses 55% less energy for cooling and heating than a comparable house in the Atlanta area (15).

Tokyo Gas Building in Yokohama, Japan

This building functions as offices and showroom, with floor space of 60,750 ft^2 (5,645m^2) over 5 stories. The design concept was to minimize environmental loads throughout the building lifetime. Electricity is produced by a gas engine cogeneration system, and waste heat from the system is used to operate a double effect absorption water chiller-heater. The building has extensive glass construction, with north-south building positioning and window design providing daylighting and passive solar effects. Windows on the south side of the building are of high transparency, low emissivity double glazing with high heat insulation properties. Light shelves are positioned to block sun rays during the summer, and allow to enter during the winter. Electricity requirement for lighting has been reduced to one third of the amount required for a comparable building. During mild seasons, automatic ventilation windows are opened and outside air enters the building. A building energy management system optimizes operation of the heating, ventilating, air conditioning, and lighting systems. The building energy consumption has been measured at 45% less than an office building of similar size and standard design (16).

Houses without Heating Systems – Lindas, Sweden

Twenty houses without traditional heating systems have been built in Sweden under a project named Cost Efficient Passive Houses as European Standards (CEPHEUS), which is within the THEREMIE Programme of the European Commission. Main support for the project is through the Swedish Council for Building Research: FORMAS. Energy savings features are high levels of airtightness and insulation, low emissivity triple glazing windows, passive solar design, and ventilation system with 85% heat recovery. Remaining requirements for heating are by heat from occupants, appliances, and lighting. Solar collectors meet about half of hot water heating requirement, with an electric heater providing the remainder. Total house energy consumption in a normal year is estimated to be 5,400 kWh. With the house floor space of 120 m^2, the energy consumption is 45 kWh/ m^2, which is 75% lower than energy consumption of new buildings meeting current European standards. Total building costs are normal, with costs for extra energy-savings features offset by no need for a traditional heating system (17).

Low Fuel Consumption Apartment Building Renovation – Ludwigshafen, Germany

A 1930s apartment building has been renovated using a combination of new technologies to reduce energy consumption. There are nine apartments with total living space of 7,535 ft^2 (700m^2). Insulation was applied to the building exterior, with the insulation being rigid polystyrene foam containing flakes of graphite that reflect heat radiation and thereby lower conductive heat transfer. Larger windows permit more natural lighting and passive use of solar heating; windows are triple glazed to reduce heat loss. An air exchange system enables recovery of 85% of heat from leaving air. An indoor wall coating contains microencapsulated wax as a phase change material, in effect providing more thermal mass to the walls to reduce temperature changes. Building energy consumption is expressed in terms of liters of heating oil per square meter per year: The renovated apartments consume 3 liters/year/m^2, which is to be compared with 20 liters/year/m^2 in a comparable unmodernized building, a energy reduction of 85%. New building construction in Germany must conform to year 2000 regulations of 7 liters/year/m^2, so the renovated building value of 3 liters/year/m^2 is 55% lower than most recent building requirements (18,19).

INTEGRATED BUILDING MONITORING AND CONTROL SYSTEMS

After design and construction of buildings with high energy efficiency, additional steps are required to maintain building operation at peak efficiency. The first is building commissioning, which is a complete testing of control systems to verify design-based operation, and establish a baseline of performance. The importance of this has been recognized by the International Energy Agency in establishing Annex 40 on *Commissioning of Building HVAC Systems for Improving Energy Efficiency*. A representative article on building commissioning is by Kohl (20).

The increasing complexity of building control systems requires methods of fault detection and diagnostics (FDD) to identify performance deterioration and/or improperly operating equipment. Examples might be heat exchanger fouling, excessive compressor vibration, air handling unit damper inoperable, or refrigerant leakage. The International Energy Agency has completed Annex 34 on FDD titled: *Computer Aided Evaluation of HVAC Performance: the Practical Application of FDD Techniques* *in Real Buildings* (21). Information developed during the study showed some building HVAC energy efficiency decreases of 20-30% without system performance monitoring, fault detection, and corrective maintenance. Examples of FDD methods are reported by Chen and Braun (22) for a rooftop air conditioner, and by House, Vaezi-Nejad, and Whitcomb for air handling units (23).

Building monitoring and control must integrate many building systems such as HVAC and lighting energy management, FDD, fire, security, and utility connections. With this wide range of functions, it is inevitable that control systems from several different manufacturers will be installed, and must have some type of common data communication protocol for proper integrated operation. An ASHRAE project committee was formed in 1987 to investigate the need for such a standard protocol, and after eight years of industry member effort, published ASHRAE Standard 135-1995, BACnet® - *A Data Communication Protocol for Building Automation and Control Networks*. This is the only open, consensus-developed standard in the building controls industry (24). It has been accepted as the standard data communication protocol in Japan and Korea, is at the pre-standard level in CEN TC247 (European Standardization Technical Committee), and is now in the International Standards Organization process (ISO TC205) for consideration as an ISO standard.

CONCLUSIONS

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) identifies buildings as the sector with the largest potential for reduced greenhouse gas emissions over the next 20 years. Residential and commercial buildings greenhouse gas emissions can be significantly reduced by an integrated approach to building design, systems, and operation. Considering United States buildings, the use of heating and cooling systems with near-maximum-available energy efficiencies can reduce heating energy consumption by 20-30%, and cooling energy consumption by 30-40% (as compared to the current minimum system efficiency requirements by the U.S. DOE). Greater energy savings and greenhouse gas reductions are possible if buildings are designed (or renovated) for reduced heating, cooling, and lighting loads, sometimes termed the integrated, whole-building approach. This approach has been demonstrated by six residential and commercial building case histories from the United States, Japan, Sweden, and Germany. By using a combination of energy savings features such as building positioning to maximize use of daylighting, energy efficient lighting, window selection for appropriate solar heat gain and thermal properties, improved insulation of walls, roofs, and floors, air-tight building envelope, sealed air distribution ducts, heat recovery for vented and incoming air, and efficient heating and cooling systems, the six case histories described reductions in buildings energy consumptions from 45% to 75%, with an average of 56%. For continued operation at the lower energy consumption values, building systems operation must be monitored with provisions for fault detection and diagnostics, followed by corrective maintenance.

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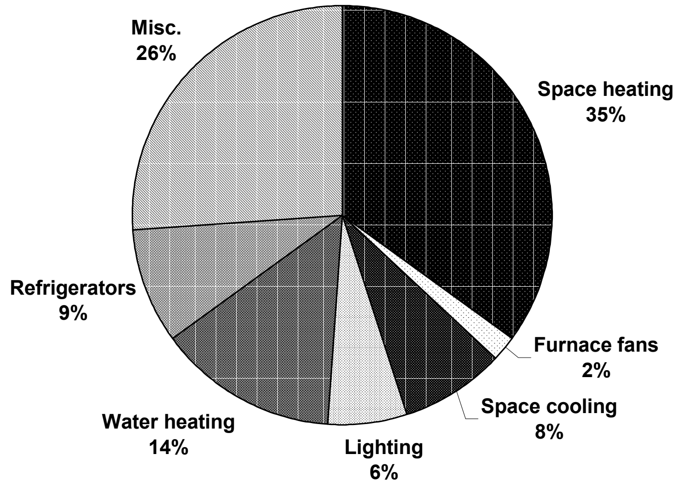

Figure 1. 1997 Primary Energy Consumption in U.S. Residential Buildings

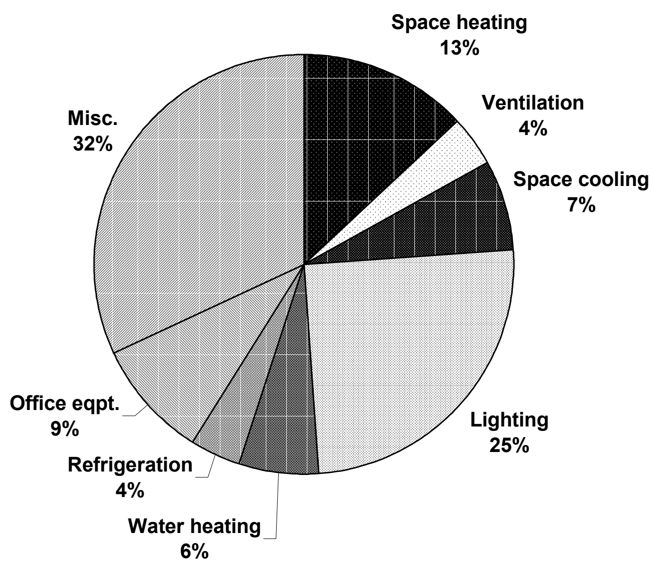

Figure 2. 1997 Primary Energy Consumption in U.S. Commercial Buildings