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# Reducing energy use in the buildings sector: measures, costs, and examples

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**Abstract** This paper reviews the literature concerning the energy savings that can be achieved through optimized building shape and form, improved building envelopes, improved efficiencies of individual energy-using devices, alternative energy using systems in buildings, and through enlightened occupant behavior and operation of building systems. Cost information is also provided. Both new buildings and retrofits are discussed. Energy-relevant characteristics of the building envelope include window-to-wall ratios, insulation levels of the walls and roof, thermal resistance and solar heat gain coefficient of windows, degree of air tightness to prevent unwanted exchange of air between the inside and outside, and presence or absence of operable windows that connect to pathways for passive ventilation. Provision of a high-performance envelope is the single most important factor in the design of low-energy buildings, not only because it reduces the heating and cooling loads that the mechanical system must satisfy but also because it permits alternative (and low-energy) systems for meeting the reduced loads. In many cases, equipment with significantly greater efficiency than is currently used is available. However, the savings available through better and alternative energy-using systems (such as alternative heating, ventilation, cooling, and lighting systems) are generally much larger than the savings that can be achieved by using more efficient devices (such as boilers, fans, chillers, and lamps). Because improved building envelopes and improved building systems reduce the need for mechanical heating and cooling equipment, buildings with dramatically lower energy use (50–75% savings) often entail no greater construction cost than conventional design while yielding significant annual energy-cost savings.

**Keywords** Buildings · Energy use · Energy efficiency · Renovations

## Introduction

The chapter on energy use in buildings of Working Group III of the Fourth Assessment Report (AR4) of the IPCC (Levine et al. 2007) outlines the broad strategies for reducing energy use in buildings, identifies the major technologies and systems that can be used to reduce energy use, and extensively discusses the policies that can be taken to realize the large energy-savings potential in the buildings sector. However, space permitted only a limited discussion of costs and of quantitative examples of the savings potential for new buildings and in renovations. This

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paper reviews the main strategies for reducing energy use in new and existing buildings and presents additional quantitative examples of the savings that have been achieved in real buildings based, in part, on information that has been published since the text of Levine et al. (2007) was finalized. This paper is complemented by Ürge-Vorsatz et al. (2009), which elaborates upon the policy discussion of Levine et al. (2007).

The report of AR4 Working Group I (Solomon et al. 2007) confirms that the eventual global mean warming for a doubling of the atmospheric carbon dioxide ($CO_2$) concentration, or its radiative equivalent, is highly likely to fall between 2°C and 4°C, while the report (Parry et al. 2007) of AR4 Working Group II (and the summary provided by Parry et al. 2008) makes it quite clear that serious widespread negative impacts are likely with only 2–3°C global mean warming relative to preindustrial times. From this, it follows that greenhouse gas concentrations equivalent to a doubling of preindustrial atmospheric $CO_2$ are dangerous, and that even the current $CO_2$ concentrations can be regarded as dangerous interference in the climatic system (see Harvey (2007a, b) for a more thorough analysis). From this, it follows that emissions of $CO_2$ need to be reduced with the utmost urgency. Given limits on how fast and to what extent carbon-free energy sources can be deployed, it is vital that significant absolute reductions in energy demand be achieved over the coming decades.

A key conclusion of this paper is that reductions in the energy intensity (annual energy use per unit of floor area) of new buildings by a factor of 3–4 relative to current local practice can be achieved and that reductions in the energy intensity of existing buildings by factors of 2–3 can be achieved through comprehensive renovations. The following sections provide an overview of how this can be done, while much more detailed information can be found in Harvey (2006). The final section of this paper presents scenarios to illustrate the consequences for absolute energy use by buildings and for average building energy intensities through to 2050 of various magnitudes and rates of reduction in the energy intensity of new and renovated buildings, in combination with different assumptions concerning the growth in total floor area between now and 2050.

## The importance of a systems approach to building design

The energy use of buildings depends to a significant extent on how the various energy-using devices (pumps, motors, fans, heaters, chillers, and so on) are put together as systems, rather than depending on the efficiencies of the individual devices. The savings opportunities at the system level are generally many times what can be achieved at the device level, and these system-level savings can often be achieved at a net investment-cost savings.

The systems approach requires an Integrated Design Process (IDP), in which the building performance is optimized through an iterative process that involves all members of the design team from the beginning. However, the conventional process of designing a building is a largely linear process, in which the architect makes a number of design decisions with little or no consideration of their energy implications and then passes on the design to the engineers, who are supposed to make the building habitable through mechanical systems. The design of mechanical systems is also largely a linear process with, in some cases, system components specified without yet having all of the information needed in order to design an efficient system (given the constraints imposed by the architect; Lewis 2004). This is not to say that there is no integration or teamwork in the traditional design process but rather that the integration is not normally directed toward minimizing total energy use through an iterative modification of a number of alternative initial designs and concepts so as to optimize the design as a whole.

The steps in the most basic IDP are:

- to consider *building orientation*, *form*, *and thermal mass*
- to specify a *high-performance building envelope*
- to maximize *passive* heating, cooling, ventilation, and daylighting
- to install efficient *systems* to meet remaining loads
- to ensure that individual energy-using *devices* are as efficient as possible and properly sized
- to ensure the systems and devices are *properly commissioned*

By focusing on building form and a high-performance envelope, heating, and cooling loads are minimized, daylighting opportunities are maximized, and mechanical systems can be greatly downsized. This generates cost savings that can offset the additional cost of a high-performance envelope and the additional cost of installing premium (high efficiency) equipment throughout the building. These steps alone can usually achieve energy savings on the order of 35–50% for a new commercial building, compared to standard practice, while utilization of more advanced or less conventional approaches has often achieved savings on the order of 50–80%. In the next section, the key envelope measures, techniques for utilizing passive solar energy, and alternative system-level designs are outlined.

## Reducing heating and cooling loads

At the early design stages, key decisions—usually made by the architect—can greatly influence the subsequent opportunities to reduce building energy use. These include building form, orientation, self-shading, height-to-floor-area ratio, window-to-wall area ratios, insulation levels and window properties, use of thermal mass within the building, and decisions affecting the opportunities for and effectiveness of passive ventilation and cooling. Many elements of traditional building designs in both developed and developing countries were effective in reducing heating and cooling loads, but have been discarded in modern designs.

### High-performance thermal envelopes combined with passive heating

The term thermal envelope refers to the shell of the building as a barrier to the transfer of heat between the inside and outside of the building. The effectiveness of the thermal envelope depends on (1) the insulation levels in the walls, ceiling, and other building parts; (2) the thermal properties of windows and doors; and (3) the rate of uncontrolled exchange of inside and outside air which, in turn, depends in part on the air tightness of the envelope.

A high-performance thermal envelope can reduce heat losses to the point where a large fraction of the remaining heat loss can be offset by internal heat gain (from people, lighting, appliances) and passive solar heat gain, with the heating system required only for the residual. For example, the European *Passive House Standard* requires a heating energy use of no more than 15 kWh/m$^2$/year, but this is typically achieved by reducing the heat loss to about 45 kWh/m$^2$/year, with one third of the heat loss offset by internal heat gains and one third offset by passive solar heat gains. By comparison, the maximum permitted heating load for new residential buildings in Germany was 65–100 kWh/m$^2$/year under the 1995 regulations, while the average heating requirement of existing buildings is estimated to be 220 kWh/m$^2$/year in Germany and 250–400 kWh/m$^2$/year in Eastern Europe (Krapmeier and Drössler 2001; Gauzin-Müller 2002). Thus, the Passive House standard represents a reduction in heating requirements by up to a factor of 25 compared to typical existing buildings. More generally, a number of advanced houses have been built in various cold-climate countries around the world that use only 10–25% of the heating energy of houses built according to the local national building code (Badescu and Sicre 2003; Hamada et al. 2003; Hastings 2004).

In countries with mild winters but still requiring heating (including many developing countries), modest (and therefore less costly) amounts of insulation can readily reduce heating requirements by a factor of 2 or more, as well as substantially reducing indoor summer temperatures, thereby improving comfort (in the absence of air conditioning) or reducing summer cooling energy use (Taylor et al. 2000; Florides et al. 2002; Safarzadeh and Bahadori 2005).

### Reducing the cooling load

Reducing the cooling load requires (1) orienting a building to minimize the wall area facing east or west (which are the directions most difficult to shade from the sun); (2) clustering buildings to provide some degree of self shading (as in many traditional communities in hot climates); (3) providing fixed or adjustable shading; (4) using highly reflective building materials; (5) increasing insulation; (6) using windows that transmit a relatively small fraction (as little at 25%) of the total (visible + invisible) incident solar energy while permitting a larger fraction of the visible radiation to enter for daylighting purposes; (7) utilizing thermal mass to minimize daytime interior temperature peaks; (8) utilizing nighttime ventilation to remove daytime heat; and (9) minimizing internal heat gains by using efficient lighting and appliances. The combination of external insulation, thermal mass, and night ventilation is particularly effective in hot-dry climates, as placing the insulation on the outside exposes the thermal mass to cool night air while minimizing the inward penetration of daytime heat into the thermal mass. These measures, alone or in combination, can typically reduce cooling loads by 50% or more (in many cases eliminating the need for mechanical cooling altogether). Low thermal mass and an open design with plenty of cross ventilation is normally recommended in hot humid climates, although Tenorio (2007) finds that in humid tropical areas of Brazil, thermal mass combined with night ventilation and selective use of air conditioning can reduce cooling energy use in a two-storey house by up to 80% compared to a fully air-conditioned house.

## Passive and low-energy cooling techniques

Having reduced the thermal load through the above measures, usually by a factor of 2 or more, a number of purely passive cooling techniques (requiring no mechanical energy input) are available. Other techniques involve small inputs of mechanical energy to enhance what are largely passive cooling processes. The major passive and passive or low-energy cooling techniques are discussed below.

### Passive ventilation

Passive ventilation reduces the need for mechanical cooling by directly removing warm air when the incoming air is cooler than the outgoing air, reducing the perceived temperature due to the cooling effect of air motion and increasing the acceptable temperature through psychological adaptation when the occupants have control of operable windows. With regard to the latter, when the outdoor temperature is 30°C, the average preferred temperature in naturally ventilated buildings is 27°C, compared to 25°C in mechanically ventilated buildings (de Dear and Brager 2002).

Passive ventilation requires a driving force, and an adequate number of openings, to produce airflow. It can be induced through pressure differences arising from inside–outside temperature differences or from wind. Design features, both traditional and modern, that create thermal driving forces and/or utilize wind effects include courtyards, atria, wind towers, solar chimneys, and operable windows (Holford and Hunt 2003; Hawkes and Forster 2002). Passive ventilation not only reduces energy use, but can improve air quality (if the outdoor air is not overly polluted) and gives people what they generally want (a connection to the outside).

In buildings with good thermal mass exposed to the interior air, passive ventilation can continue right through the night, sometimes more vigorously than during the day due to the greater temperature difference between the internal and external air. Nighttime ventilation, in turn, serves to reduce the cooling load by making use of cool ambient air to remove heat.

### Evaporative cooling

Evaporation of water cools the remaining liquid water and air that comes into contact with it. The coldest temperature that can be achieved through evaporation is called the *wetbulb* temperature and depends on the initial temperature and humidity (the higher the initial humidity, the less evaporation and cooling that can occur). The wetbulb temperature is sufficiently low (≤20°C) in most of the world most of the time for cooling purposes (see Harvey 2006, Tables 6.7 and 6.8). There are two methods of evaporatively cooling the air supplied to buildings. In a direct evaporative cooler, water evaporates directly into the air stream to be cooled. In an *indirect* evaporative cooler, water evaporates into and cools a secondary air stream, which cools the supply air through a heat exchanger without adding moisture. By appropriately combining direct and indirect systems, evaporative cooling can provide comfortable temperature–humidity combinations most of the time in most parts of the world.

Evaporative cooling is most effective in dry regions, but water may be a limiting factor in such regions. However, arid regions tend to have a large diurnal temperature range, so thermal mass with external insulation and night ventilation can be used instead. Evaporative cooling is not effective in humid climates, but it can be extended to such climates through the use of desiccants (described below).

### Desiccant dehumidification

Desiccant dehumidification and cooling involves using a material (desiccant) that removes moisture from air and is regenerated using heat. Solid desiccants are a commercially available technology, while liquid desiccants are nearing commercialization. By over-drying the air, there is then room for adding moisture back to the air as a byproduct of evaporative cooling. Desiccants provide an efficient means of air conditioning using solar thermal energy or waste heat. A 30–50% savings in the primary energy use for cooling and dehumidification is possible in large centralized systems, with first-costs comparable to those of multi-zone rooftop air conditioners (Harvey 2006, Sections 6.6.4 and 7.4.11). A 50–75% savings is possible if waste or solar heat can be used to regenerate the desiccant, although costs will be greater due to the need for solar thermal collectors.

### Earth-pipe cooling

Ventilation air can be precooled by drawing outside air through a buried air duct. This is referred to as earth-pipe cooling. Good performance depends on the climate having a substantial annual temperature range so that the ground temperature (which will be close to the mean annual temperature) is comparatively cool. The ratio of the cooling obtained to fan energy required to move air through the earth pipe (analogous to the coefficient of performance (COP) of a heat pump or air conditioner) in experimental studies ranges from a low as about 5 in Italy (Solaini et al. 1998) and 8 in India during the pre-monsoon hot period (Thanu et al. 2001) to 30–50 in Germany (Eicker et al. 2006). Up to a 70% reduction in the cooling load in the northern US is possible with earth-pipe cooling (Lee and Strand 2008). By combining earth pipe cooling with solar chimneys or measures to exploit wind suction, both cooling and ventilation can be passively driven, with only occasional need for backup fans, an example being a school in Norway (Schild and Blom 2002)

## Heating and cooling equipment

### Furnaces and boilers

Commercial buildings, multiunit residences, and many single-family residences (especially in Europe) use boilers, which produce steam or hot water that is circulated, generally through radiators. Efficiencies (ratio of heat delivered to fuel use) range from 80% to 95%, not including distribution losses. Modern residential furnaces, which are used primarily in North America and produce warm air that is circulated through ducts, have efficiencies ranging from 78% to 96% (again, not including distribution system losses). Old equipment tends to have an efficiency in the range of 60–70%, so new equipment can provide a substantial savings. Space heating and hot water for consumptive use (e.g., showers) can be supplied with heat from small wall-hung boilers with an efficiency in excess of 90%.

### Heat pumps

A heat pump transfers heat from cold to warm (against the macro-temperature gradient) although at each point in the system, heat flow is from warm to cold. It relies on the fact that a liquid cools when it evaporates, and the cooling effect is greater the lower the pressure of evaporation, while a gas releases latent heat as it condenses and is warmed to a greater temperature the greater the pressure. A heat pump can transfer heat from outside to inside (during winter) and from inside to outside (during summer). An air conditioner is a heat pump that operates in only one direction. The efficiency of cooling equipment is indicated by its COP—the ratio of heat energy transferred to energy input.

The difference between the source temperature (from which heat is drawn) and the sink temperature (to which heat is added) is referred to as the temperature lift. By drawing heat from the warmest possible source temperature (such as the ground or exhaust air rather than cold outside air) and distributing the heat at the lowest possible temperature (as in radiant floors or ceilings) during heating mode, the temperature lift can be minimized and the COP increased. Similarly, during cooling mode, the temperature lift is minimized and COP maximized if coldness is distributed at the warmest possible temperature and the heat rejected at the lowest possible temperature. Figure 1 shows the variation in the COP of a heat pump in heating mode and in cooling mode for various evaporator–temperature combinations. There can easily be a factor of two differences in the COP for best- and worst-case systems.

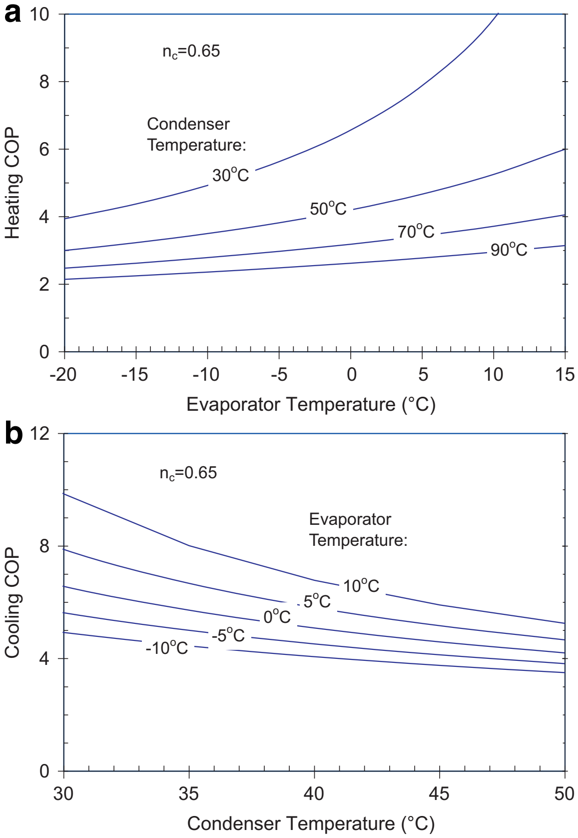

**Fig. 1** Variation in the COP of a heat pump in heating mode and in cooling mode for various evaporator–temperature combinations, assuming a Carnot efficiency (ratio of actual to ideal COP) of 0.64. Source, Harvey (2006)

If the heat pump COP is 3.0 and the efficiency in producing and delivering the electricity is only 33% (both being typical situations), then one unit of energy to the power plant supplies one unit of heat to the building—about the same as for a high efficiency furnace or boiler. However, if the COP can be pushed higher, and as more efficient fossil fuel electricity generation comes on line, there will be a net savings in source energy. If the building is well insulated and has thermal mass exposed to the interior, the heat pump could be used preferentially when intermittent carbon-free electricity sources (such as wind) are available in surplus, with temperatures freely drifting at other times. In this way, heat pumps can use carbon-free electricity and, by serving as a flexible electricity load, can facilitate a greater overall use of intermittent renewable energy sources for electricity.

### Air conditioners and chillers

Air conditioners used for houses, apartments, and small commercial buildings have a nominal COP ranging from 2.2 to 3.8 in North America and Europe, depending on operating conditions, whereas mini-split systems in Japan have COPs of up to 6.2. Chillers are larger cooling devices that produce chilled water (rather than cooled air) for use in large residential and commercial buildings. Chiller COP generally increases with size, with the largest and most efficient electric chillers having a COP of up to 8 under full-load operation and even higher under part-load operation. This is a factor of 3 better than typical air conditioners. Although additional energy is used in chiller-based systems for circulating chilled water and for operating a cooling tower, significant energy savings are still possible through the choice of the most efficient cooling equipment in combination with efficient auxiliary systems.

## Heating, ventilation, and air conditioning systems

The term HVAC (heating, ventilation, and air conditioning) refers to the system that produces and delivers coldness and warmth as well as fresh air throughout a building.

### Principles of energy-efficient HVAC design

In the simplest HVAC systems, heating or cooling is provided by circulating a fixed amount of air at a sufficiently warm or cold temperature to maintain the desired room temperature. The rate at which air is circulated in this case is normally much greater than that needed for ventilation to remove contaminants, and is constant. During the cooling season, the air is supplied at the coldest temperature needed in any zone, and reheated as necessary just before entering other zones.

There are a number of changes in the design of HVAC systems that can achieve dramatic savings in the energy use for heating, cooling, and ventilation. These include,

- using variable-air volume systems with variable-speed fans so as to minimize simultaneous heating and cooling of air and to reduce fan energy use

- using heat exchangers to recover heat or coldness from ventilation exhaust air and to supply it to the incoming fresh air
- separating the ventilation from the heating and cooling functions by using chilled or hot water for temperature control and circulating only the volume of air needed for ventilation
- implementing a demand-controlled ventilation system in which ventilation airflow changes with changing building occupancy
- separating cooling from dehumidification functions through the use of desiccant dehumidification, with the desiccant preferably regenerated with solar heat
- correctly sizing all components
- allowing the temperature maintained by the HVAC system to vary seasonally with outdoor conditions, as a large body of evidence indicates that the temperature and humidity set-points commonly encountered in air-conditioned buildings are significantly lower than necessary (de Dear and Brager 1998; Fountain et al. 1999).

Hydronic systems (in which water rather than air is circulated), especially floor radiant heating or cooling systems in residential buildings and chilled ceiling heating or cooling in commercial buildings, require less energy than forced air systems to distribute a given amount of heat, have low distribution heat losses, and do not induce infiltration of outside air (as in poorly balanced air distribution systems). They allow heating and cooling to be provided at temperatures closer to the desired room temperature, which increases the efficiency of heating and cooling devices.

In many buildings, heating and cooling is provided by circulating a volume of warm or cool air that is several times that required for ventilation purposes. To reduce the volume of outside air that needs to be conditioned, it is common to recirculate, say, 80% of the internal air on each circuit and replace only 20% with fresh outside air. This spreads contaminants throughout the building. If heating and cooling is largely supplied hydronically, the airflow can be set equal to that required for ventilation purposes alone but then, of necessity, must be completely replaced with fresh air after each circuit through the building. This forms a dedicated outdoor air supply system and, if combined with displacement ventilation (described below), allows ceiling heat gains (from lighting or rising thermal plumes and constituting up to 30% of the total cooling requirement) to be directly vented to the outside rather than having to be removed by the chillers before the air is recirculated. This is one of the many examples of system–level interactions that can lead to large energy savings (see Harvey 2008, for other such examples).

An optimal combination of the measures listed here can reduce the HVAC energy use by 30% to 75%. These savings are in addition to the savings arising from reducing heating and cooling loads. Further information on two particularly advantageous features of an efficient HVAC system—chilled-ceiling cooling and displacement ventilation—is given below.

### Radiant chilled-ceiling cooling

Chilled ceiling (CC) cooling refers to the circulation of chilled water either through panels mounted underneath the ceiling, or circulating through pipes inside a concrete ceiling. The entire ceiling is chilled in this way, creating a cooling effect largely through the reduction in emission of infrared radiation. CC cooling has been used in Europe since at least the mid 1970s. Significant energy savings arise because of the greater effectiveness of water than air in transporting heat and because the chilled water is supplied at 16°C to 20°C rather than at 5°C to 7°C. This not only allows a higher chiller COP when the chiller operates but also allows more frequent use of water-side free cooling, in which the chiller is bypassed altogether and evaporatively cooled water from a cooling tower is used directly for space cooling. Even in the absence of water-side free cooling, savings of 6–42% have been calculated for systems in various US cities compared to all-air systems (Stetiu and Feustel 1999).

### Displacement ventilation

Conventional ventilation relies on turbulent mixing to dilute room air with ventilation air. A superior system is *displacement ventilation* in which air is introduced at low speed through many diffusers in the floor or along the sides of a room and is warmed by internal heat sources (occupants, lights, plug-in equipment) as it rises to the top of the room, displacing the air already present. This allows cooling to be supplied at a warmer temperature (~18°C *vs.* ~13°C in a conventional mixing ventilation system) and permits smaller airflows. Savings of 40–60% in cooling energy use occur in US cities compared to a standard system (Sodec 1999; Mumma 2001; Bourassa et al. 2002; Howe et al. 2003).

### Control systems and commissioning

Building Energy Management Systems are control systems for individual buildings or groups of buildings that use computers and distributed microprocessors for monitoring, data storage, and communication (Levermore 2000). Building commissioning is a quality control process that begins with the early stages of design. It helps ensure that the design intent is clear and readily tested, that installation is subjected to on-site inspection, and that all systems are tested and functioning properly before the building is accepted. Savings typically range from 15% to 30% at a cost of 1–3% of the HVAC system and a payback time of 2 years or less (Claridge et al. 2001; Roth et al. 2003; Liu et al. 2003; Poulos 2007).

## Lighting

Strategies to reduce lighting energy use focus on (1) efficient lighting *systems*; (2) efficient lighting devices (ballasts, lamps, luminaires); and (3) optimal use of daylighting (taking into account additional cooling loads if excess daylight is supplied). An example of an efficient lighting system would be one with separate controls for different lighting zones and use of task or ambient lighting (relatively low background light levels where appropriate, supplemented with greater lighting when and where needed). Space limitations do not permit a substantial discussion of lighting energy use; an extensive review in Harvey (2006, Chapter 9) indicates that, in retrofits, a 30–50% savings in electricity use can be routinely achieved, while a savings of 70–75% is sometimes possible with considerable effort. Daylighting can provide 40–80% savings in lighting energy use in perimeter offices, 20–33% savings in combined lighting + cooling energy use, and up to 90% savings deep in rooms using fiber optics.

## Integrated energy savings

There are numerous examples of buildings of all types, and in all climate zones, that have achieved energy savings of 50% to 75% or more compared to the energy use of buildings built under current local practice.

### Advanced residential buildings

Hamada et al. (2003) summarize the characteristics and energy savings for 66 advanced houses in 17 countries. For the 28 houses where the savings in heating energy use is reported, the savings compared to the same house built according to conventional standards ranges from 23% to 98%, with eight houses achieving a savings of 75% or better.

Several hundred houses that meet the *Passive House Standard*—a house with an annual heating requirement of no more than 15 kWh/m$^2$/year irrespective of the climate and a total energy consumption of no more than 42 kWh/m$^2$/year—have been built in Europe. By comparison, the average heating load of new residential buildings is about 60–100 kWh/m$^2$/year in Switzerland and Germany but about 220 kWh/m$^2$/year for the average of existing buildings in Germany and 250–400 kWh/m$^2$/year in Central and Eastern Europe. Thus, Passive Houses represent a reduction in heating energy use by a factor of 4–5 compared to new buildings and by a factor of 10–25 compared to the average of existing buildings. Technical details, measured performance, design issues, and occupant response to Passive Houses in various countries can be found in Krapmeier and Drössler (2001), Feist et al. (2005), Schnieders and Hermelink (2006), and Hastings and Wall (2007a, b), with full technical reports available at www.cepheus.de.

Parker et al. (1998) shows how a handful of very simple measures (attic radiant barriers; wider and shorter return-air ducts; use of the most efficient air conditioners with variable speed drives; use of solar hot water heaters; efficient refrigerators, lighting, and pool pumps) can reduce total energy use by 40–45% in single-family houses in Florida compared to conventional practices. These savings are achieved while still retaining black asphalt shingle roofs that produce roof surface temperatures of up to 82°C! Holton (2002), Gamble et al. (2004), and Rudd et al.

(2004) have shown how a series of modest insulation and window improvements can lead to energy savings of 30–75% in a wide variety of US climates. In all three studies, alterations in building form to facilitate passive solar heating, use of thermal mass combined with night ventilation to meet cooling requirements (where applicable), or use of features such as earth-pipe cooling, evaporative coolers, or exhaust-air heat pumps are not considered. Thus, the full potential is considerably greater. Demirbilek et al. (2000) find, through computer simulation, that a variety of simple and modest measures can reduce heating energy requirements by 60% compared to conventional designs for two-storey single-family houses in Ankara, Turkey.

### Commercial buildings

Table 1 gives documented examples of new commercial buildings in North America, Europe, and Asia that achieved a minimum of a 50% reduction in overall energy use compared to current conventional practice. Several surveys indicate that these are not unrepresentative examples, but rather, that energy savings of 50–75% can be routinely achieved in new commercial buildings through maximal implementation of the measures reviewed in this paper.

First, the National Renewable Energy Laboratory in the US extracted the key energy-related parameters from a sample of 5,375 buildings in the 1999 *Commercial Buildings Energy Consumption Survey*, and then used energy models to simulate their energy performance (Torcellini and Crawley 2006). The results of this exercise are as follows,

- average energy use as built is 266 kWh/m$^2$/year
- average energy use if complying with the ASHRAE 90.1-2004 standard is 157 kWh/m$^2$/year, a savings of 41%
- average energy use would be 92 kWh/m$^2$/year with improved electrical lighting, daylight, overhangs for shading, and elongation of the buildings along an east–west axis (applicable only to new buildings; a savings of 65%)

With implementation of technological improvements expected to be available in the future, the gross energy use is so small that PV panels can generate more energy than the buildings consume, so that the buildings would serve as a net source of energy.

Second, in the UK, energy consumption guidelines indicate that energy use for office buildings is typically about 300–330 kWh/m$^2$/year for standard mechanically ventilated buildings, 173–186 kWh/m$^2$/year with good practice (a savings of about 40–45%), and 127–145 kWh/m$^2$/year for naturally ventilated buildings with good practice (Walker et al. 2007)—a savings of 55–60%.

Third, Voss et al. (2007) present data on the measured energy use in 21 passively cooled commercial and educational buildings in Germany. The passive cooling techniques involve earth-to-air heat exchangers (nine cases), slab cooling directly connected to the ground via pipes in boreholes or connected to the groundwater (nine cases), and some form of night ventilation (16 cases), along with a limited window-to-wall ratio (0.27–0.43) and external sun shading. The buildings also have a high degree of insulation and many have triple-glazed windows. Nine of the buildings have total onsite energy use of 25–55 kWh/m$^2$/year and ten had 55–110 kWh/m$^2$/year energy use, compared to 175 kWh/m$^2$/year for conventional designs, so the savings is up to a factor of seven. Three buildings have a heating energy use less than 20 kWh/m$^2$/year and eight have a heating energy use of 20–40 kWh/m$^2$/year compared to a typical heating energy use of 125 kWh/m$^2$/year.

Large savings potentials (compared to recent practice) are not restricted to mid-latitude climates or to industrialized countries. As indicated in Table 1, simulation studies for typical office buildings in Malaysia and Beijing indicate a potential savings using simple techniques of about 65–70%, while the Torrent Pharmaceutical Research Centre in Ahmedabad, India achieved an electricity savings of 64% and a demonstration office building in Beijing achieved a savings of 60%.

## First-cost of deep energy savings in buildings

High performance residential buildings generally cost a few percent more than conventional residential buildings, whereas high-performance commercial and institutional buildings can sometimes cost slightly less. In the case of commercial buildings, there is a greater opportunity to offset the cost of a high-performance envelope with lower costs of mechanical systems, as mechanical systems are a greater fraction

**Table 1** Summary of exemplary (in terms of energy use) new commercial buildings where baseline and reference energy use have been published

| Building and location | Energy use | Energy savings | Reference for comparison of energy use | Key features | Reference |
|---|---|---|---|---|---|
| Canadian examples | | | | | |
| Green on the Grand (offices), Kitchener, Ontario | 81.2 kWh/m$^2$/year (design total) Natural Gas: 43.1 kWh/m$^2$/year Electricity: 38 kWh/m$^2$/year | 50.4% | ASHRAE 90.1-1989 | Double-stud manufactured wood-frame wall; fibreglass-frame, triple-glazed, double-low-e, argon- filled, insulating-spacer windows; reduced lighting power densities; radiant heating and cooling panels, DOAS w/ heat recovery, natural gas fired absorption chiller; outdoor pond replaces conventional cooling tower | C-2000 Internal Program Report[a] |
| Crestwood Corporate Centre Building No.8 | 62.6 kWh/m$^2$/year (design total) Natural Gas 14.2 kWh/m$^2$/year Electricity 48.4 kWh/m$^2$/year | 51.7% | ASHRAE 90.1-1989 | Tilt-up concrete walls with upgraded air tightness and insulation; thermally broken Al-framed DG low-e windows; reduced lighting power densities; high efficiency boiler and chiller; 4-pipe fan coil system w/ DOAS | C-2000 Internal Program Report[a,b] |
| MEC Retail Store Ottawa | 202.8 kW/m$^2$ annual (design) Natural Gas 110.3 kWh/m$^2$/year Electricity 92.5 kWh/m$^2$/year | 56% | MNECB | Upgraded wall and roof insulation, DG low-e argon-filled, warm edge spacer windows in clad wood or TB Al frames; TG low-e windows on north faces; roof monitors for daylighting and greatly reduced connected lighting power; high efficiency boiler, mid efficiency rooftop ventilation unit, ventilation heat recovery, upgraded chiller efficiency, $CO_2$ DCV, variable speed fan drives | CBIP Internal Technical Review Report[a,b] |
| SC3 Smith Carter Office, Winnipeg | 142.8 kW/m$^2$/year (design) Electricity 142.8 kWh/m$^2$/year | 55% | MNECB | Upgraded insulation in walls and roof; DG low-e argon-filled warm edge spacer windows in TB Al frames; daylighting w/ wireless digital and occupancy sensor controls; exterior solar shading, reduced connected lighting power, combination boiler and ground source heat pump w/ GSHP sized for cooling, DOAS w/ UFAD | CBIP Internal Technical Review Report[a] |
| MEC Retail Store Winnipeg | 101.5 ekW/m$^2$ annual (design) Natural Gas 41.9 kW/m$^2$ Electricity 59.6 kWh/m$^2$ | 56% | MNECB | Upgraded insulation in walls and roof, low fenestration-to-wall ratio, DG low-e argon-filled warm edge spacer windows in TB aluminum frames; daylighting w/ occupancy sensor controls and reduced connected lighting power; mid efficiency boiler, DOAS, radiant slab and panel heating with ground water cooling | C-2000 Internal Program Report[a] |
| Father Michael McGivney Secondary School | 148 kWh/m$^2$/year | 58% | 352 kWh/m$^2$/year | GSHP, heat pipe type heat recovery unit | Genest and Minea (2006) |

| | | | | | |
|---|---|---|---|---|---|
| MEC Retail Store, Montreal | 147.3 kW/m$^2$/year (design) 133 kW/m$^2$/year (actual 2004) | 68% | MNECB (466 kWh/m$^2$/year) | High-performance envelope, daylighting, GSHP, DOAS, radiant slab heating and cooling, earth coupled outside air tempering. | Genest and Minea (2006) |
| Centre for Interactive Research on Sustainability, Vancouver (proposed design) | 56 kWh/m$^2$/year without BiPV and solar thermal (47 kWh/m$^2$/year with solar) | 84% | Typical existing building (353 kWh/m$^2$/year) | High-performance envelope, adjustable atrium shading, hybrid ventilation, daylighting, VSDs, DCV, 90% heat recovery effectiveness | Hepting and Ehret (2005) |
| S examples | | | | | |
| NREL offices and labs, Golden, Colorado | | 45% and 63% (two buildings) | ASHRAE 90.1 | | Murphy (2002) |
| Environmental Center, Oberlin College, Ohio | 87 kWh/m$^2$/year[b]<br>60 kWh/m$^2$/year with recommended changes | 48%<br>64% | ASHRAE 90.1-2001 (169 kWh/m$^2$/year) | High-performance envelope, GSHP, daylighting | Pless et al. (2006) |
| Federal Courthouse, Denver | | 50% | ASHRAE 90.1-1989 | Triple glazing, modest insulation, sunshading, daylighting, T5 lamps, VAV displacement ventilation, direct and indirect evaporative cooling, VSD on all air handlers and pumps, BiPV | Mendler and Odell (2000) |
| Home improvement store, Silverthorne, Colorado | 124 kWm/m$^2$/year | 54% | ASHRAE 90.1-2001 (296 kWh/m$^2$/year) | Higher-performance envelope, hydronic radiant floor heating, reducing lighting load and daylighting, solar thermal collectors. | Torcellini et al. (2004a) |
| SC Johnson Wax Headquarters, Racine (WI) | <218 kWh/m$^2$/year total | 54%<br>69% | Ave new buildings<br>Existing SJC buildings | Daylighting with automatic controls, fixed and adjustable shading, demand-controlled desktop personal air supply | Mendler and Odell (2000) |
| Academic building, U. of Wisconsin, Green Bay | | 60% | Wisconsin energy code | Wall *U* value 0.16 W/m$^2$/K Roof *U* value 0.11 W/m$^2$/K Skylights with suspended reflectors and motorized blackout panels BiPV | Mendler and Odell (2000) |
| Center for Health and Healing at the Oregon Health and Science University, River Campus | | 60% | ASHRAE 90.1-1999 | Hybrid ventilation, solar preheating of ventilation air, heat recovery, radiant heating/cooling, demand-controlled displacement ventilation, PV modules as exterior shading, commissioning. | Interface Engineering (2005) |
| Zion National Park Visitor Centre | 85 kWh/m$^2$/year | 62% | Code-compliant building at 222 kWh/m2/year | Modestly better insulation and windows, high thermal mass, daylighting with controls, downdraft evaporative cooling | Long et al. (2006) |
| Cambria Office Building, Ebensburg, Pennsylvania | 124 kWh/m$^2$/year | 64% | Reference buildings at 322 kWh/m$^2$/year | High-performance envelope, Underfloor air distribution, heat recovery ventilators, GSHP, daylight and motion sensors | Torcellini et al. (2004b) |
| Federal Reserve Bank, Minneapolis | <134 kWh/m$^2$/year total 9.1 W/m$^2$ connected lighting load 7.0 W/m$^2$ average | 74% | ASHRAE 90.1 | Window *U* value 0.74 W/m$^2$/K Wall *U* value 0.2 W/m$^2$/K Conventional VAV HVAC | Mendler and Odell (2000) |

**Table 1** (continued)

| Building and location | Energy use | Energy savings | Reference for comparison of energy use | Key features | Reference |
|---|---|---|---|---|---|
|  | lighting load |  |  |  |  |
| Iowa Association of Municipalities office | 107 kWm/m$^2$/year simulated<br>88–91 measured | 65%<br>75% | Iowa building code | 19% window:wall ratio, high-performance envelope, daylighting, GSHP, enthalpy wheel for heat recovery. | McDougall et al. (2006) |
| Judson College Library, Illinois |  | 69% fans, 78% cooling | Mechanically ventilated building | Design study to illustrate effectiveness of hybrid ventilation in reducing cooling and fan energy use in a continental climate | Short and Lomas (2007) |
| Science Museum of Minnesota | 64 kWh/m$^2$/year gross, <0 kWh/m$^2$/net using PV arrays | 78% | 290 kWh/m$^2$/year for code-compliant building | Passive solar design, daylighting, GSHP for heating and cooling (with respective COPs of 3.1 and 3.7) | Steinbock et al. (2007) |
| Environmental Technology Centre, Sonoma State University, California |  | 80% | California Title 24 |  | Beeler (1998) |
| European examples |  |  |  |  |  |
| Brundtland Centre, Denmark | 50 kWh/m$^2$/year | 70% | Typical comparable building (170 kWh/m$^2$/year) |  | Prasad and Snow (2005) |
| Center for Sustainable Building, Kassel, Germany | 16.5 kWh/m$^2$/year heating<br>32–42 kWh/m$^2$/year total energy use | 73%<br>76–82% | 1995 German Building Code<br>Typical office building | Wall $U$ value 0.11 W/m$^2$/K, window $U$ value 0.8 W/m$^2$/K, radiant slab heating and cooling, ground heat exchanger (COP=23), hybrid ventilation, daylighting | Schmidt (2002) and Schmidt (personal communication 2006) |
| Debis Building, Potsdamer Platz, Berlin | 75 kWm/m$^2$/year total | 80% |  | Double-skin façade and passive ventilation | Grut (2003) |
| Ionica Building, UK | 64 kWm/m$^2$/year total | 46% | Good-practice air conditioned building | Hybrid ventilation | Hybvent website (hybvent.civil.auc.dk) |
| Solar Bau program, 10 buildings in Germany | 25–140 kWh/m$^2$/year primary energy excluding office equipment | 50–90% | Typical office buildings, 300–600 kWh/m$^2$/year primary energy | Mechanical night ventilation with exposed thermal mass or hydronic cooling integrated with groundwater, external shading, reduced glazing area, minimal internal heat gains, efficient lighting. | Wagner et al. (2004) |
| Solar Office, Doxford International Business Park, UK | 85 kWh/m$^2$/year | 80% | Typical new air-conditioned buildings in the UK (400 kWh/m$^2$/year) | Passive ventilation and cooling; BiPV functioning as partial shading devices. | Prasad and Snow (2005) |

| | | | | | |
|---|---|---|---|---|---|
| Elizabeth Fry Building and Zuckerman Building, University of East Anglia | 30–37 kWh/m$^2$/year heating<br>93–100 kWh/m$^2$/year total | | | High-performance envelope, concrete hollow-core ceiling slab with night-time ventilation, high air tightness | Cohen et al. (2007), Turner and Tovey (2006) |
| Asian examples | | | | | |
| Kier Building, South Korea | 68 kWm/m$^2$/year electricity,<br>18 kWm/m$^2$/year heat | | | Double-skin façade, ground coupled heat exchanger, solar thermal and PV. | Prasad and Snow (2005) |
| Liberty Tower, Meiji University, Japan | | 48% | Japanese building code | Hybrid ventilation | Hybvent website (hybvent.civil.auc.dk) |
| Tokyo Earth Port | 380 kWm/m$^2$/year primary energy | 45% | Typical office building in Japan | Hybrid ventilation | Baird (2001) |
| Torrent Pharmaceutical Research Centre in Ahmedabad, India | | 64% for electricity | Conventional modern building | Evaporative cooling and hybrid ventilation (passive downdraught cooling) | Ford et al. (1998) |
| Demonstration office in Beijing | 65 kWm/m$^2$/year electricity<br>78 kWm/m$^2$/year total | 60% | Similarly equipped office in Beijing with central air conditioning | Optimized building form and orientation, improved windows and chillers, reduced window area, simple daylighting scheme | Xu et al. (2007) |
| Ministry of Energy, Water & Communications Building, Putrajaya, Malaysia | 100 kWh/m$^2$/year total on-site energy use based on computer simulation | 64% | Conventional design (275 kWh/m$^2$/year) | Daylighting, insulation in walls and roof, energy efficient equipment, energy management, room temperature 24°C instead of 23°, tight building | Roy et al. (2005) |
| Shangai Eco-Building, National Construction Department | 48 kWh/m$^2$/year heating + cooling on-site energy use based on computer simulations | 69% | Conventional design (155 kWh/m$^2$/year) | Window shading devices, advanced glazing, highly insulated envelope, natural ventilation | Zhen et al. (2005) |

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[a] Available from Stephen Pope, Natural Resources Canada

[b] Gross energy use, excluding contribution from PV

*COP* coefficient of performance, *DCV* demand-controlled ventilation, *DG* double-glazed, *DOAS* dedicated outdoor air supply, *GSHP* ground-source heat pump, *TB* thermally-broken, *TG* triple-glazed, *UFAD* underfloor air distribution, *VAV* variable air volume, *VSD* variable-speed drive of the overall cost in the case of commercial buildings. For both commercial and residential buildings, the cost of achieving a given energy performance will be lower in new buildings than in existing buildings, and the achievable energy performance is much better for new buildings (as certain design decisions cannot be reversed). Thus, failure to rapidly implement vastly better building performance requirements in building codes represents a significant lost opportunity.

### Cost of deep savings in residential buildings

Increasing the amount of insulation entails greater insulation costs and hence greater annual mortgage costs but reduced heating costs. Figure 2 shows the tradeoff between these two for residential buildings in Canada. There is a very broad minimum in the total cost, and total costs at insulation levels substantially greater than currently required are substantially less that at required insulation levels. Absolute costs are different in other countries, but the broad features of the cost curves highlighted here are still applicable.

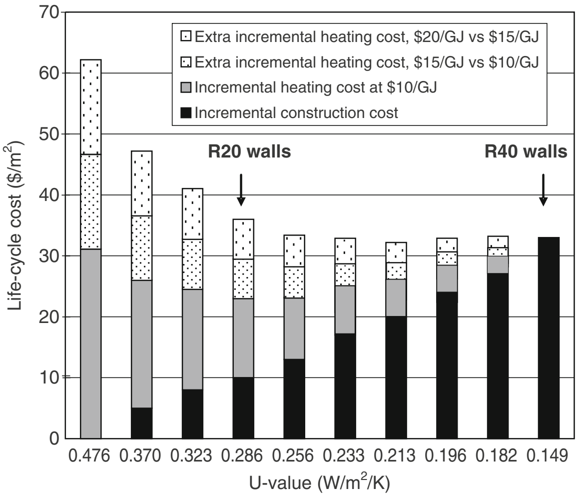

**Fig. 2** Comparison of incremental lifecycle costs of walls in Canada with increasing amounts of insulation (successively smaller *U* values). The lowest part of each bar is the incremental construction cost relative to the least-insulated wall, the second part of each bar is the incremental heating cost relative to the best-insulated wall for a heating fuel cost of $10/GJ, the third part of each bar is the additional incremental heating cost if the heating fuel costs $15/GJ instead of $10/GJ, and the top part of each bar is the additional incremental heating cost if the heating fuel costs $20/GJ instead of $15/GJ. Incremental heating costs and/or construction financing costs were computed assuming HDD= 5000 K-day, 6%/year interest, 3%/year energy-cost inflation, and financing over a 30-year period. Not included in this cost comparison are the reduction in cooling energy use and the downsizing of heating and cooling equipment that occurs with higher-performance thermal envelopes. Source: Harvey (2006)

Window performance can be chosen so as to permit elimination of perimeter heating on the coldest winter days, down to temperatures of −40°C while serving as a net heat source over the course of the heating season (due to passive solar gains exceeding heat losses). The elimination of perimeter heating in turn reduces costs and amplifies the savings in heating energy use by shifting the warmest temperatures away from the window area (Harvey and Siddall 2008). Figure 3 shows the window heat loss-coefficient (*U* value) below which perimeter heating units can be eliminated, as a function of the coldest anticipated outdoor temperature.

Figure 4 shows the progressive decline in the cost of the additional investment required to meet the Passive House standard (which requires 4–8 times less heating energy use than in conventional new housing) in central Europe. Through learning, costs have fallen to the point where the incremental cost can be justified based on 2005 energy prices and interest rates. Schnieders and Hermelink (2006) report that the additional cost averaged over 13 Passive House projects in Germany, Sweden, Austria, and Switzerland is 8% of the cost of a standard house but that when amortized over 25 years at 4% interest and divided by the saved energy, the cost of saved energy averages 6.2 eurocents/kWh (the range is 1.1–11 eurocents/kWh). This is somewhat more than the present cost of natural gas to residential consumers in most European countries, which ranges from 2–8 cents/kWh (IEA 2004). Audenaert et al. (2008) estimate extra costs of 4% for low-energy houses and 16% for Passive Houses in Belgium (having energy savings of 35% and 72% relative to current standard houses in Belgium).

An analysis of the cost of reducing energy use in single-family houses in the US indicates that total financial costs (annual mortgage costs plus energy costs) are minimized at an energy savings of only 40% (Anderson et al. 2006), but this analysis did not consider the savings arising from elimination of perimeter heating units when high-performance windows are specified nor did it consider simple measures such as overhangs for shading to reduce cooling loads.

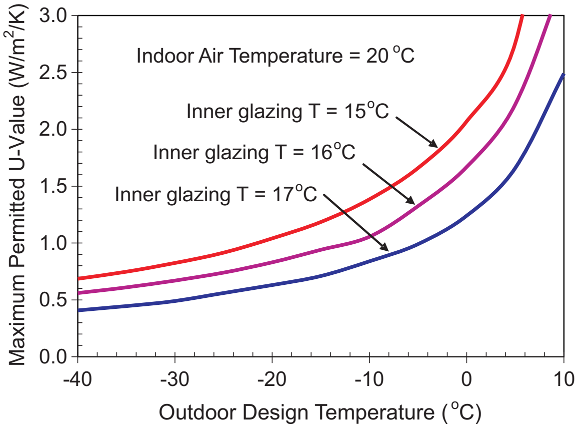

**Fig. 3** Window *U* value below which perimeter heating is not needed as a function of the minimum expected winter outdoor temperature and of the minimum permitted temperature of the innermost glazing surface. Source, Harvey and Siddall (2008)

## Cost of deep savings in commercial buildings

As an example of the savings in first-cost that is possible for commercial buildings with advanced, energy-efficient designs, Table 2 gives a breakdown of capital costs for commercial buildings in Vancouver, Canada, having conventional windows (double-glazed, air-filled, low-e) and a conventional heating/cooling system, and for buildings with moderately high-performance windows (triple-glazed, low-e, argon-filled) and radiant-slab heating and cooling. The high-performance building is 9% less expensive to build than a comparable conventional building, while using about half the energy.

Another example of a building with large energy savings costing less than if built according to code is provided by one of the first buildings built on the new Oregon Health and Science University, River Campus in 2006. This 16-storey building is expected to achieve an energy savings of 60% relative to ASHRAE 90.1-1999 through such measures as hybrid ventilation using the stack effect in stairwells, solar preheating of office ventilation air, heat recovery on laboratory ventilation, radiant heating or cooling, demand-controlled displacement ventilation, PV modules as exterior shading, accurate equipment sizing, and commissioning. Incremental costs or upfront savings are given in Table 3. Cost savings due to downsizing of the mechanical systems permitted by the efficiency measures exceeded the cost of the efficiency measures. A further credit arises from the space saved due to more efficient and downsized mechanical systems. The net result is a construction cost savings of about $3.5 million out of an original budget of $145.4 million (a 2.4% savings) and operating cost savings of $600,000/year.

In other cases, highly efficient buildings have cost more, but the time required to pay back the additional cost with energy-cost savings has been short. As an example, the recently completed science building at

**Fig. 4** Learning curve showing the progressive decrease in the incremental cost of meeting the Passive House standard for the central unit of row houses. Source, Feist (2005)

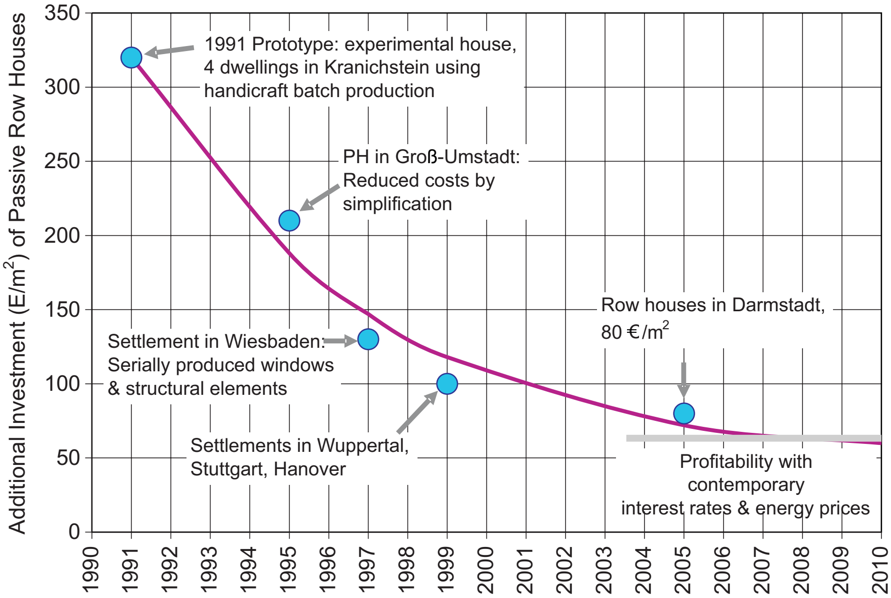

**Table 2** Comparison of component costs for a building with a conventional VAV mechanical system and conventional (double-glazed, low-e) windows with those for a building with radiant slab heating and cooling and high-performance (triple-glazed, low-e, argon-filled) windows, assuming a 50% glazing area/wall area ratio

| Building component | Conventional building | High-performance building |
|---|---|---|
| Glazing | $140/m$^2$ | $190/m$^2$ |
| Mechanical System | $220/m$^2$ | $140/m$^2$ |
| Electrical System | $160/m$^2$ | $150/m$^2$ |
| Tenant finishings | $100/m$^2$ | $70/m$^2$ |
| Floor-to-floor height | 4.0 m | 3.5 m |
| Total | $620/m$^2$ | $550/m$^2$ |
| Energy use | 180 kWh/m$^2$/year | 100 kWh/m$^2$/year |

Costs are in 2001 Canadian dollars for the Vancouver market in 2001, are given per m$^2$ of floor area, and are based on fully costed and built examples over a 3-year period. Source, Geoff McDonell (Omicron Consulting, Vancouver), personal communication, December 2004, and McDonell (2003).

Concordia University, Montreal, with offices, classrooms, and 250 fume hoods, achieved a 45% reduction in energy use relative to ASHRAE 90.1-1999 at an incremental cost of 2.3% ($1,356,000 out of $59,500,000) while yielding an annual energy cost savings of $854,000, for a payback time of 19 months (Lemire and Charneux 2005).

Table 4 provides information on the incremental cost and energy savings for 32 buildings in the USA that met various levels of the Leadership in Energy and Environmental Design (LEED) standard. The energy savings are broken into reductions in gross energy demand, and reductions in net energy demand including on-site generation (by, for example, PV modules), which tends to be expensive. The cost premium is the total cost premium required to meet the various LEED standards and so includes the cost of non-energy features as well. Nevertheless, average costs are less than 2% of the cost of the reference building and are smaller on average for buildings with 50% savings in net energy use than for buildings with 30% savings.

**Table 3** Economics of the new Oregon Health and Science University building

| Item | Cost |
|---|---|
| Total project cost | $145.4 million |
| Energy efficiency features | $975,000 |
| PV system | $500,000 |
| Solar thermal system | $386,000 |
| Commissioning | $150,000 |
| Total | $2,011,000 |
| Savings in mechanical systems | $3,500,000 |
| Value of saved space | $2,000,000 |
| Net cost | −$3,489,000 |
| Estimated annual operating cost savings | $600,000 |

Source, Interface Engineering (2005)

Measured performance information on ten buildings in the German *SolarBau* program where at least 1 year of data were available by 2003 is given in Wagner et al. (2004). Five of the ten buildings achieved the 100 kWh/m$^2$/year primary energy target (compared to 300–600 kWh/m$^2$/year for conventional designs), but no building used more than 140 kWh/m$^2$/year of primary energy.[1] Additional costs are reported to be comparable to the difference in cost between alternative standards for interior finishing.

In addition to energy-cost savings, high performance buildings—especially buildings with daylighting, task lighting, and natural ventilation that can be controlled by the occupants—have difficult-to-quantify but important additional savings. These include improved worker productivity, improved retention of workers, and improved competitiveness in hiring skilled workers.

## Energy savings through retrofits of existing commercial and residential buildings and associated costs

To achieve significant reductions in overall energy use by buildings, considerable effort will need to be directed at existing buildings due to the fact that most

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[1] Primary energy in the case of electricity is the energy used by the power plant and is about three times the energy content of the electricity used by the building.

**Table 4** Energy savings relative to ASHRAE 90.1-1999 and cost premium for buildings meeting various levels of the LEED standard in the USA

| LEED level | Sample size | % Energy savings, based on | | Cost premium (%) |
|---|---|---|---|---|
| | | Gross energy use | Net energy use | |
| Certified | 8 | 18 | 28 | 0.66 |
| Silver | 18 | 30 | 30 | 2.11 |
| Gold | 6 | 37 | 48 | 1.82 |

Source, Kats et al. (2003)

of the buildings that will exist in 2030 and even in 2050 in some countries already exist today. However, even long-lived buildings require periodic major renovations (and certainly at least once between now and 2050), which provide opportunities for achieving deep (50–75%) reductions in energy use.

### Commercial buildings

Measures that can be taken to reduce energy use in existing commercial buildings include upgrades to the thermal envelope (such as reduction in air leakage, or complete replacement of curtain walls), replacement of heating and cooling equipment, reconfiguration of HVAC systems, implementation of better control systems, lighting improvements, and implementation of measures to reduce the use of hot water. The quantitative savings from specific measures depends on the preexisting characteristics, climate, internal heat loads, and occupancy pattern for the particular building in question. However, large (50–70% or more) savings in energy use have been achieved through retrofits of commercial buildings throughout the world.

Some examples from the literature of savings achieved through relatively simple measures are:

- A projected savings of 30% of total energy use in 80 office buildings in Toronto through lighting upgrades alone (Larsson 2001);
- A realized savings of 40% in heating + cooling + ventilation energy use in a Texas office building through conversion of the ventilation system from one with constant airflow to one with variable air flow (Liu and Claridge 1999);
- A realized savings of 40% of heating energy use through the retrofit of an 1865 two-storey office building in Athens, where low energy was achieved through some passive technologies that required the cooperation of the occupants (Balaras (2001)
- A projected savings of more than 50% of heating and cooling energy for restaurants in cities throughout the USA by simply optimizing the ventilation system (Fisher et al. 1999)
- A projected 51% savings in cooling + ventilation energy use in an institutional building complex in Singapore through simple upgrades to the existing system (Sekhar and Phua 2003)
- A realized savings of 74% in cooling energy use in a one-storey commercial building in Florida through duct sealing, chiller upgrade, and fan controls (Withers and Cummings 1998)
- Realized savings of 50–70% in heating energy use through retrofits of schools in Europe and Australia (described in the March 1997 issue of the *CADDET Energy Efficiency Newsletter*, published by the International Energy Agency)
- Realized fan, cooling, and heating energy savings of 59%, 63%, and 90%, respectively, in buildings at a university in Texas, roughly half due to a standard retrofit and half due to adjustment of the control-system settings (which were typical for North America) to optimal settings (Claridge et al. 2001)
- Average realized savings of 68% in natural gas use after conversion of ten US schools from non-condensing boilers producing low-pressure steam to condensing boilers producing low-temperature hot water, and an average savings of 49% after conversion of ten other US schools from high- to low-temperature hot water and from non-condensing to condensing boilers (Durkin 2006)
- Projected savings of 30–60% in cooling loads in an existing Los Angeles office building simply by operating the existing HVAC system in a manner

so as to make maximum use of night cooling opportunities (Armstrong et al. 2006)

- Projected savings of 48% from a typical 1980s office building in Turkey through simple upgrades to mechanical systems and replacing existing windows with low-e windows having shading devices, with an overall economic payback time of about 6 years (Çakmanus 2007)
- Projected savings of 36–77% through retrofits of a variety of office types in a variety of European climates, with payback times generally in the 1–30-year range (Hestnes and Kofoed 1997, 2002; Dascalaki and Santamouris 2002)

It should be emphasized that comprehensive retrofits of buildings are generally done for many reasons in addition to reducing energy costs. Thus, measures that are extensive enough to significantly reduce energy use may not pay for themselves in terms of energy cost savings alone, but this does not mean that they should not be carried out.

A significant potential area for reduced energy use in existing buildings is through replacement of existing curtain walls or upgrades of existing insulation and windows. Given the current frenzy constructing nearly all-glass buildings but not even using high-performance glazing, replacing existing glazing systems and curtain walls will be an essential future activity if deep reductions in heating and cooling energy use are to be achieved. Recently, the curtain walls were replaced on the 24-storey 1952 Unilever building (Lever House) in Manhattan (see http://www.som.com/content.cfm/lever_house_curtain_wall_replacement), so there seems to be no major technical problems in undertaking complete curtain wall replacements on high-rise office buildings.

In the case of brick or cement façades, one option is to construct a second glazed façade over the first—creating a double-skin façade—which opens up opportunities for passive ventilation and reduced cooling loads through the provision of adjustable external shading devices. This has often been done in Europe. A North American example of the construction of a second façade over the original façade is provided by the Telus headquarters building in Vancouver. In this case, the second façade was constructed as part of measures to increase the earthquake resistance of the building. Construction of a second façade can also be undertaken as a measure to preserve original facades that are deteriorating due to moisture problems related to defects in the original construction.

## Residential buildings

Energy use of residential buildings can be reduced through upgrading of windows, adding internal insulation to walls during renovations, adding external insulation to walls, adding insulation to roofs at the time that roofs need to be replaced, and through measures to reduce uncontrolled exchange of inside and outside air. Some documented examples of comprehensive retrofit measures and the energy savings are:

- sealing of ductwork alone in US houses saving an average of 15–20% of annual heating and air conditioning energy use (Francisco et al. 1998)
- a retrofit of 4,003 homes in Louisiana, including the switch from natural gas to a ground source heat pump for space and water heating, thereby eliminating natural gas use and still decreasing electricity use by one third (Hughes and Shonder 1998)
- upgrade of multiunit housing in Germany using, among other measures, External Insulation and Finishing Systems to achieve a factor of 8 reduction in heating energy use (see www.3lh.de)
- an envelope upgrade of an apartment block in Switzerland reduce the heating requirement by almost factor of 3 (Humm 2000)
- reduction of heating energy use in retrofits of houses in the York region (UK) by 35% through air sealing and modest insulation upgrades and a projected 70% savings with more extensive measures (Bell and Lowe 2000)
- comprehensive retrofit of old apartment block in Zurich, including replacement of roof, achieving an 88% savings in heating energy use measured over a 2-year period (Viridén et al. 2003)

In apartment buildings with balconies, the balcony slabs are a conduit for heat loss. Glazing the balconies so that they serve to preheat ventilation air, and integrating the balcony with the ventilation system of the apartments, can turn a thermal liability into an asset. Transpired solar air collectors over vertically extensive equatorward-facing walls are another solar option, as well as transparent solar insulation, construction of a second (glass) façade over the original façade, and installation of conventional solar-air thermal collectors. Savings of 60–70% in old (per-1950) buildings and 30–40% in new (1970 or later) buildings in Europe have been obtained in these ways (Boonstra et al. 1997; Haller et al. 1997; Voss 2000).

Studies for the European Mineral Wool Manufacturers Association by the Dutch consulting firm Ecofys indicate that the energy consumption in old buildings in western Europe (EU-15) can be reduced by more than 50% with no additional cost over a 30-year lifetime, and by up to 75% in new countries of the EU-27 (Petersdorff et al. 2005a, b).

A number of single-family and multiunit residential buildings have been upgraded to the Passive Standard in Europe. In the case of an old detached house (documented at www.hausderzukunft.at/results.html/id3955), the renovation reduced the heating energy use from 280 to 14.6 kWh/m$^2$/year at 16% greater cost than a conventional renovation, but the impact of the extra cost on mortgage payments is less than the energy cost savings. In the case of a 50-unit residential building (documented at www.hausderzukunft.at/results.html/id3951), heating energy use was reduced from 179 to 13.3 kWh/m$^2$/year at 27% greater renovation cost.

## Construction of a generic scenario for future energy use and energy intensity

The energy use for a given building sector with a given fuel in a given region at a given time in the future will depend on:

- the fraction of the existing floor space that has been renovated by the given time
- the difference between the energy intensity before and after renovation
- the fraction of the existing floor space that has been replaced by the given time
- the difference between the energy intensity of the old and replacement floor space
- the net addition of new floor space each year between the present and the year in question
- the energy intensity of the new floor space added each year

Older buildings on average are more energy intensive than more recent buildings. In Canada, for example, new commercial buildings on average have an energy intensity about 16% less than the stock average, while the most energy-intensive buildings (those built in the 1960s) have an energy intensity about 16% greater than the stock average. Let $\Delta E$ be the deviation in the energy intensity of new buildings from the stock average. $\Delta E$=0.16 for total average energy use applied to all buildings across Canada but would be different in other countries and for different building types within any given country or region.

To illustrate the challenges in achieving large absolute reductions in the total energy use by building stock, even as far in the future as 2050, the following accounting procedure was used to calculate the variation in total building use and in the average energy intensity from 2005 to 2050 relative to the values in 2005,

- the entire building stock is divided into 45 equal cohorts of size $f_{\text{start}}$ ($f_{\text{start}}$ is given as a fraction of the floor area in 2005, so $f_{\text{start}}=1/45$);
- the initial energy intensity $E_{\text{start}}$ of each cohort relative to the average initial energy intensity is assumed to vary across the cohorts from $1+\Delta E$ to $1-\Delta E$, with an equal fraction of the building stock in energy-intensity intervals of equal width
- the cohorts are replaced or renovated in order of decreasing energy intensity (so in 2006, some portion of the most energy-intensive cohort is renovated and some portion is replaced, while in 2007 the second most energy-intensive cohort is renovated or replaced, and so on)
- the portions of the total building stock that are renovated and replaced by 2050 are $F_{\text{reno}}$ and $F_{\text{replaced}}$, respectively, so the floor areas renovated or replaced in a given year (as a fraction of the total floor area in 2005) are $f_{\text{reno}}=F_{\text{reno}}/45$ and $f_{\text{replaced}}=F_{\text{replace}}/45$, respectively (if $F_{\text{reno}}+F_{\text{replaced}}=1.0$, then $f_{\text{reno}}+f_{\text{replaced}}=f_{\text{start}}$)
- in addition, the building floor area, as a fraction of the initial floor area, is assumed to grow by some specified amount between 2005 and 2050
- the energy intensity of a new building, or of a renovated building after the renovation, depends on the year in which it is built or renovated, and does not change once built or renovated

- the energy intensity of successive cohorts of new buildings decreases over time from $E_{\text{new-0}}$ to $E_{\text{new-f}}$, and the energy intensity of renovated buildings decreases over time from $E_{\text{reno-0}}$ to $E_{\text{reno-f}}$ (all these energy intensities are relative to the initial stock average)
- the initial energy intensities $E_{\text{new-0}}$ and $E_{\text{reno-0}}$ persist until year $I_1$, then decrease linearly to their final values by year $I_2$, and are held constant thereafter.

Thus, the total energy use of the building stock in year $n$, $E(n)$, relative to energy use in 2005, is given by

$$E(n)=\sum_{i=1}^{n}\left\{\begin{array}{l}\left(f_{\text{repl}}(i)+f_{\text{new}(i)}\right)E_{\text{new}}(i)+f_{\text{reno}}(i)E_{\text{reno}}(i)\\ +f_{\text{remain}}(i)E_{\text{start}}(i)\end{array}\right\}+\sum_{i=n+1}^{45}f_{\text{start}}(i)E_{\text{start}}(i) \tag{1}$$

where $n$ is the number of years since 2005 (and so runs from 1 to 45), $E_{\text{new}}(i)$ is the energy intensity of new buildings built in year $i$ ($E_{\text{new}}(i)$ runs from $E_{\text{new-0}}$ to $E_{\text{new-}f}$, as explained above), $E_{\text{start}}(i)$ is the energy intensity prior to renovation of buildings renovated in year $i$ ($E_{\text{start}}(1)=1.0+\Delta E$ and $E_{\text{start}}(45)=1.0-\Delta E$), $E_{\text{reno}}(i)$ is the energy intensity after renovation of buildings that are renovated in year $i$ ($E_{\text{reno}}(i)$ runs from $E_{\text{reno-0}}$ to $E_{\text{reno-}f}$), and $f_{\text{remain}}(i)=1.0-f_{\text{repl}}(i)-f_{\text{reno}}(i)$. It is assumed that the most recently built existing buildings (those built in 2005) have an energy intensity equal to $1.0-\Delta E$, and it is also assumed that new buildings in 2006 (and up to year $I_1$) have the same energy intensity. Thus, we set $E_{\text{new-0}}=1.0-\Delta E$.

Figure 5 shows the variation in the average energy intensity and in total energy use by the building stock, relative to the average and total in 2005, for low (25% growth) and high (100% growth) scenarios of floor area, for $\Delta E=0.16$, and for the following technology cases:

- Moderate
  The energy intensity of new and renovated buildings decreases from 84% of the 2005 stock average in 2010 to 42% in 2050 (i.e., a factor of 2 reduction compared to average current practice for new buildings).
- Deep
  The energy intensity of new buildings decreases from 84% of the 2005 stock average in 2010 to 21% in 2050 (i.e., a factor of four reduction compared to average current practice for new buildings), while the energy intensity of renovated buildings decreases from 84% of the 2005 stock average in 2010 to 33% in 2050.
- Deep and fast
  Same as Deep, except that the intensity levels achieved by 2005 in Deep are achieved by 2020 instead

As can be seen from Fig. 5a, the combination of a doubling in floor area and even a factor of four reduction in the energy intensity of new buildings and a factor of three reduction in the energy intensity of renovated buildings, gradually achieved by 2050, is not sufficient to prevent absolute energy use from increasing (albeit by only 22% before declining slightly). This is because many existing buildings have been renovated and many new buildings constructed before most of the eventual reductions in energy intensity are achieved. Conversely, if the assumed final energy intensities are reached by 2020, then a 25% reduction in absolute energy use by 2050 occurs. For countries where only a 25% further increase in total floor area occurs, absolute energy use by buildings can be reduced by almost a factor of two with deep and fast reductions in the energy intensities of new and renovated buildings.

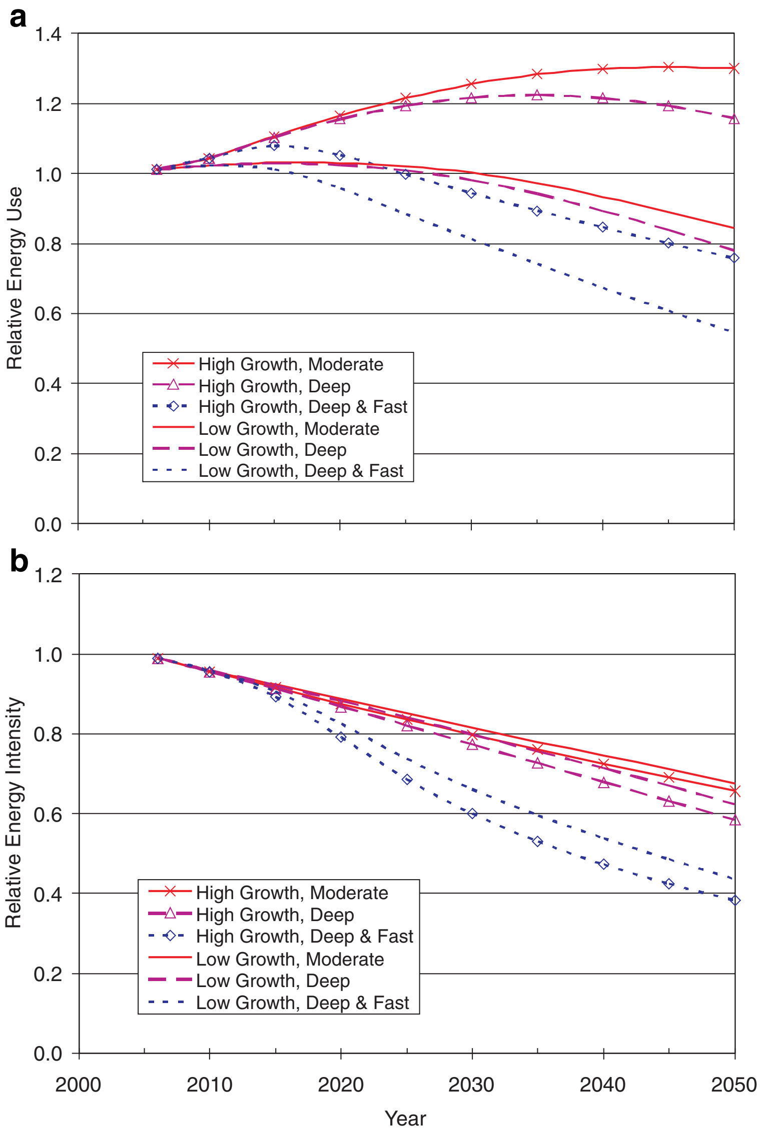
Figure 5b shows the variation in average energy intensity (relative to 2005) for the above scenarios. Average energy intensity is smaller for the scenario with high growth in floor area because a larger fraction of the future building floor area is relatively new (and, therefore, has lower than average energy intensity) when there is greater growth in the total floor area.

The results presented here are merely illustrative but serve to underline the importance of rapidly reducing the energy intensity of new and renovated buildings in order to achieve modest (25%) to substantial (50%) reductions in absolute energy use from the buildings sector.

## Implications for $CO_2$ emissions

We have not explicitly considered the impacts of energy efficiency measures on $CO_2$ emissions. The

**Fig. 5** Variation in the average energy intensity and in total energy use by the building stock, relative to the average and total in 2005, for scenarios of low (25%) and high (100%) growth in the total building floor area by 2050, and for moderate or deep and slow or fast reductions in the energy intensity of new and renovated buildings, as computed using Eq. 1. See text for details



reduction in relative $CO_2$ emissions depends on (1) the relative importance of fuels and electricity as end-use energy in the buildings sector; (2) the relative changes in demand for electricity and for fuels (including any shift between fuels and electricity as overall end use demand decreases); and (3) the mix of energy sources used to supply electricity on the margin (that is, supplying the next increment of increased or decreased electricity use). The sources of electricity on the margin (and the efficiency of marginal fossil fuel sources) often vary with time of day and season, so the timing of electricity savings as well as the magnitude will affect the resulting change in $CO_2$ emissions. Conversely, any measures that increase flexibility in electricity demand (such as higher performance envelopes or thermal energy storage) may permit shifting electricity demand to times when only non-fossil energy sources supply the grid, thereby permitting $CO_2$ emission reductions, or more permit greater use of variable non-fossil electricity sources (such as wind energy). Thus, relative $CO_2$ emission could, with well-designed packages of efficiency measures, be larger than the relative savings in electricity demand.

## Concluding comments

Significant savings in energy use in new buildings of all types and in all climate zones, compared to current practice, are possible using existing technologies. For commercial buildings, a 25% reduction should be easily achievable by most design firms; a 50% reduction requires a higher degree of skill during the design process but normally does not require unconventional systems; a 75% reduction normally requires unconventional systems (such as displacement ventilation and chilled-ceiling cooling in commercial buildings) and an enlightening occupant behavior but, has been achieved in many buildings around the world. In residential buildings, heating loads can be largely eliminated with high levels of insulation, high-performance windows, and construction of a close to airtight envelope with mechanical ventilation and heat recovery. Passive techniques can greatly reduce cooling requirements in both commercial and residential buildings. The main obstacles to achieving these high energy savings in new buildings is the lack of knowledge and motivation within the design profession. Extensive training programs in the integrated design process and in the techniques for reducing hearting, cooling, ventilation, and lighting loads in buildings as well as training of all the trades involved in building construction are urgently required, even with a significant strengthening of building codes. Given the long lifetimes of the building stock and the urgency of the global warming problem (see Risbey 2008), an appropriate target would be to achieve a factor of 3–4 reduction in the energy intensity of new buildings by 2020 and programs to achieve (on average) a factor of 2–3 reduction in the energy intensity of existing buildings whenever significant renovations are carried out.

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