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Residential and commercial[1] buildings

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1 The category of non-residential buildings is referred to by different names in the literature, including commercial, tertiary, public, office, and municipal. In this chapter we consider all non-domestic residential buildings under the "commercial" sector.

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EXECUTIVE SUMMARY

In 2004, emissions from the buildings sector including through electricity use were about 8.6 $GtCO_2$, 0.1 $GtCO_2$-eq N_2O, 0.4 $GtCO_2$-eq CH_4 and 1.5 $GtCO_2$-eq halocarbons (including CFCs and HCFCs). Using an accounting system that attributes CO_2 emissions to electricity supply rather than buildings end-uses, the direct energy-related carbon dioxide emissions of the building sector are about 3 Gt/yr.

For the buildings sector the literature uses a variety of baselines. Therefore a baseline was derived for this sector based on the literature, resulting in emissions between the B2 and A1B SRES scenarios, with 11.1 Gt of emissions of CO_2 in 2020 and 14.3 $GtCO_2$ in 2030 (including electricity emissions but omitting halocarbons, which could conceivably be substantially phased out by 2030).

Measures to reduce greenhouse gas (GHG) emissions from buildings fall into one of three categories: reducing energy consumption and embodied energy in buildings, switching to low-carbon fuels including a higher share of renewable energy, or controlling the emissions of non-CO_2 GHG gases.[2] This chapter devotes most attention to improving energy efficiency in new and existing buildings, which encompasses the most diverse, largest and most cost-effective mitigation opportunities in buildings.

The key conclusion of the chapter is that substantial reductions in CO_2 emissions from energy use in buildings can be achieved over the coming years using mature technologies for energy efficiency that already exist widely and that have been successfully used *(high agreement, much evidence)*. A significant portion of these savings can be achieved in ways that reduce life-cycle costs, thus providing reductions in CO_2 emissions that have a net benefit rather than cost. However, due to the long lifetime of buildings and their equipment, as well as the strong and numerous market barriers prevailing in this sector, many buildings do not apply these basic technologies to the level life-cycle cost minimisation would warrant *(high agreement, much evidence)*.

Our survey of the literature (80 studies) indicates that there is a global potential to reduce approximately 29% of the projected baseline emissions by 2020 cost-effectively in the residential and commercial sectors, the highest among all sectors studied in this report *(high agreement, much evidence)*. Additionally at least 3% of baseline emissions can be avoided at costs up to 20 US$/$tCO_2$ and 4% more if costs up to 100 US$/$tCO_2$ are considered. However, due to the large opportunities at low-costs, the high-cost potential has been assessed to a limited extent, and thus this figure is an underestimate *(high agreement, much evidence)*.

Using the global baseline CO_2 emission projections for buildings, these estimates represent a reduction of approximately 3.2, 3.6 and 4.0 $GtCO_2$/yr in 2020, at zero, 20 US$/$tCO_2$ and 100 US$/$tCO_2$ respectively. Our extrapolation of the potentials to the year 2030 suggests that, globally, about 4.5, 5.0 and 5.6 $GtCO_2$ at negative cost, <20 US$ and <100 US$/$tCO_2$-eq respectively, can be reduced (approximately 30, 35 and 40% of the projected baseline emissions) *(medium agreement, limited evidence)*. These numbers are associated with significantly lower levels of certainty than the 2020 ones due to very limited research available for 2030.

While occupant behaviour, culture and consumer choice and use of technologies are also major determinants of energy use in buildings and play a fundamental role in determining CO_2 emissions *(high agreement, limited evidence)*, the potential reduction through non-technological options is rarely assessed and the potential leverage of policies over these is poorly understood. Due to the limited number of demand-side end-use efficiency options considered by the studies, the omission of non-technological options and the often significant co-benefits, as well as the exclusion of advanced integrated highly efficiency buildings, the real potential is likely to be higher *(high agreement, limited evidence)*.

There is a broad array of accessible and cost-effective technologies and know-how that have not as yet been widely adopted, which can abate GHG emissions in buildings to a significant extent. These include passive solar design, high-efficiency lighting and appliances[3], highly efficient ventilation and cooling systems, solar water heaters, insulation materials and techniques, high-reflectivity building materials and multiple glazing. The largest savings in energy use (75% or higher) occur for new buildings, through designing and operating buildings as complete systems. Realizing these savings requires an integrated design process involving architects, engineers, contractors and clients, with full consideration of opportunities for passively reducing building energy demands. Over the whole building stock the largest portion of carbon savings by 2030 is in retrofitting existing buildings and replacing energy-using equipment due to the slow turnover of the stock *(high agreement, much evidence)*.

Implementing carbon mitigation options in buildings is associated with a wide range of co-benefits. While financial assessment has been limited, it is estimated that their overall value may be higher than those of the energy savings benefits *(medium agreement, limited evidence)*. Economic co-benefits include the creation of jobs and business opportunities, increased economic competitiveness and energy security. Other co-benefits include social welfare benefits for low-income households, increased access to energy services, improved indoor and outdoor air quality, as well as increased comfort,

2 Fuel switching is largely the province of Chapter 4, energy supply.
3 By appliances, we mean all electricity-using devices, with the exception of equipment used for heating, cooling and lighting.

health and quality of life. In developing countries, safe and high-efficiency cooking devices and high-efficiency electric lighting would not only abate substantial GHG emissions, but would reduce mortality and morbidity due to indoor air pollution by millions of cases worldwide annually *(high agreement, medium evidence)*.

There are, however, substantial market barriers that need to be overcome and a faster pace of well-enforced policies and programmes pursued for energy efficiency and de-carbonisation to achieve the indicated high negative and low-cost mitigation potential. These barriers include high costs of gathering reliable information on energy efficiency measures, lack of proper incentives (e.g., between landlords who would pay for efficiency and tenants who realize the benefits), limitations in access to financing, subsidies on energy prices, as well as the fragmentation of the building industry and the design process into many professions, trades, work stages and industries. These barriers are especially strong and diverse in the residential and commercial sectors; therefore, overcoming them is only possible through a diverse portfolio of policy instruments *(high agreement, medium evidence)*.

Energy efficiency and utilisation of renewable energy in buildings offer a large portfolio of options where synergies between sustainable development and GHG abatement exist. The most relevant of these for the least developed countries are safe and efficient cooking stoves that, while cutting GHG emissions, significantly, reduce mortality and morbidity by reducing indoor air pollution. Such devices also reduce the workload for women and children and decrease the demands placed on scarce natural resources. Reduced energy payments resulting from energy-efficiency and utilisation of building-level renewable energy resources improve social welfare and enhance access to energy services.

A variety of government policies have been demonstrated to be successful in many countries in reducing energy-related CO_2 emissions in buildings *(high agreement, much evidence)*. Among these are continuously updated appliance standards and building energy codes and labelling, energy pricing measures and financial incentives, utility demand-side management programmes, public sector energy leadership programmes including procurement policies, education and training initiatives and the promotion of energy service companies. The greatest challenge is the development of effective strategies for retrofitting existing buildings due to their slow turnover. Since climate change literacy, awareness of technological, cultural and behavioural choices are important preconditions to fully operating policies, applying these policy approaches needs to go hand in hand with programmes that increase consumer access to information and awareness and knowledge through education.

To sum up, while buildings offer the largest share of cost-effective opportunities for GHG mitigation among the sectors examined in this report, achieving a lower carbon future will require very significant efforts to enhance programmes and policies for energy efficiency in buildings and low-carbon energy sources well beyond what is happening today.

6.1 Introduction

Measures to reduce greenhouse gas (GHG) emissions from buildings fall into one of three categories: reducing energy consumption[4] and embodied energy in buildings, switching to low-carbon fuels including a higher share of renewable energy, or controlling the emissions of non-CO_2 GHG gases. Renewable and low-carbon energy can be supplied to buildings or generated on-site by distributed generation technologies. Steps to de-carbonise electricity generation can eliminate a substantial share of present emissions in buildings. Chapter 4 describes the options for centralized renewable energy generation, while this chapter covers building-level options for low-carbon electricity generation on-site. This chapter devotes most attention to energy efficiency in new and existing buildings, as fuel switching is largely covered elsewhere in this report (Chapter 4). Non-CO_2 GHGs are treated in depth in the IPCC special report on safeguarding the ozone layer and the climate system (IPCC/TEAP, 2005), but some of the most significant issues related to buildings are discussed in this chapter as well.

A very large number of technologies that are commercially available and tested in practice can substantially reduce energy use while providing the same services and often substantial co-benefits. After a review of recent trends in building energy use followed by a description of scenarios of energy use and associated GHG emissions, this chapter provides an overview of the various possibilities in buildings to reduce GHG emissions. Next, a selection of these technologies and practices is illustrated by a few examples, demonstrating the plethora of opportunities to achieve GHG emission reductions as significant as 70–80%. This is followed by a discussion of co-benefits from reducing GHG emissions from buildings, and a review of studies that have estimated the magnitude and costs of potential GHG reductions worldwide.

In spite of the availability of these high-efficiency technologies and practices, energy use in buildings continues to be much higher than necessary. There are many reasons for this energy waste in buildings. The chapter continues with identifying the key barriers that prevent rational decision-making in energy-related choices affecting energy use in buildings. Countries throughout the world have applied a variety of policies in order to deal with these market imperfections. The following sections offer an insight into the experiences with the various policy instruments applied in buildings to cut GHG emissions worldwide. The past five years have shown increasing application of these policies in many countries in Europe and growing interest in several key developing and transition economies. In spite of this fact, global CO_2 emissions resulting from energy use in buildings have increased at an average of 2.7% per year in the past five years for which data is available (1999–2004). The substantial barriers that need to be overcome and the relatively slow pace of policies and programmes for energy efficiency will provide major challenges to rapid achievement of low-emission buildings.

6.2 Trends in buildings sector emissions

In 2004, direct emissions from the buildings sector (excluding the emissions from electricity use) were about 3 $GtCO_2$, 0.4 $GtCO_2$-eq CH_4, 0.1 $GtCO_2$-eq N_2O and 1.5 $GtCO_2$-eq halocarbons (including CFCs and HCFCs). As mitigation in this sector includes a lot of measures aimed at electricity saving it is useful to compare the mitigation potential with carbon dioxide emissions, including those through the use of electricity. When including the emissions from electricity use, energy-related carbon dioxide emissions were 8.6 Gt/yr (Price *et al.*, 2006), or almost a quarter of the global total carbon dioxide emissions as reported in Chapter 1. IEA estimates a somewhat higher fraction of carbon dioxide emissions due to buildings.

Figure 6.1 shows the estimated emissions of CO_2 from energy use in buildings from two different perspectives. The bar at the left represents emissions of CO_2 from all energy end-uses in buildings. The bar at the right represents only those emissions from direct combustion of fossil fuels. Because the electricity can be derived from fuels with lower carbon content than current fuels, CO_2 emissions from electricity use in buildings can also be altered on the supply side.

Carbon dioxide emissions, including through the use of electricity in buildings, grew from 1971 to 2004 at an annual rate of 2%, – about equal to the overall growth rate

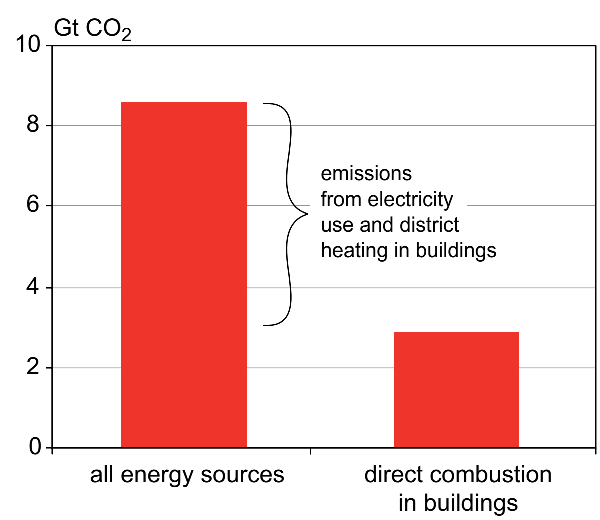

Figure 6.1: *Carbon dioxide emissions from energy, 2004*

Sources: IEA, 2006e and Price et al. 2006.

4 This counts all forms of energy use in buildings, including electricity.

of CO_2 emissions from all uses of energy. CO_2 emissions for commercial buildings grew at 2.5% per year and at 1.7% per year for residential buildings during this period. The largest regional increases in CO_2 emissions (including through the use of electricity) for commercial buildings were from developing Asia (30%), North America (29%) and OECD Pacific (18%). The largest regional increase in CO_2 emissions for residential buildings was from Developing Asia accounting for 42% and Middle East/North Africa with 19%.

During the past seven years since the IPCC Third Assessment Report (TAR, IPCC, 2001), CO_2 emissions (including through the use of electricity) in residential buildings have increased at a much slower rate than the 30-year trend (annual rate of 0.1% versus trend of 1.4%) and emissions associated with commercial buildings have grown at a faster rate (3.0% per year in last five years) than the 30-year trend (2.2%) (Price *et al.*, 2006).

Non-CO_2 emissions (largely halocarbons, CFCs, and HCFCs, covered under the Montreal Protocol and HFCs) from cooling and refrigeration contribute more than 15% of the 8.6 $GtCO_2$ emissions associated with buildings. About 1.5 $GtCO_2$-eq of halocarbon (HFCs, CFCs and HCFCs) emissions, or 60% of the total halocarbon emissions was due to refrigerants and blowing agents for use in buildings (refrigerators, air conditioners and insulation) in 2002. Emissions due to these uses are projected to remain about constant until 2015 and decline if effective policies are pursued (IPCC/TEAP, 2005).

6.3 Scenarios of carbon emissions resulting from energy use in buildings

Figure 6.2 shows the results for the buildings sector of disaggregating two of the emissions scenarios produced for the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000), Scenarios A1B and B2, into ten world regions (Price *et al.*, 2006). These scenarios show a range of projected buildings related CO_2 emissions (including through the use of electricity): from 8.6 $GtCO_2$ emissions in 2004 to 11.4 and 15.6 $GtCO_2$ emissions in 2030 (B2 and A1B respectively), representing an approximately 30% share of total CO_2 emissions in both scenarios. In Scenario B2, which has lower economic growth, especially in

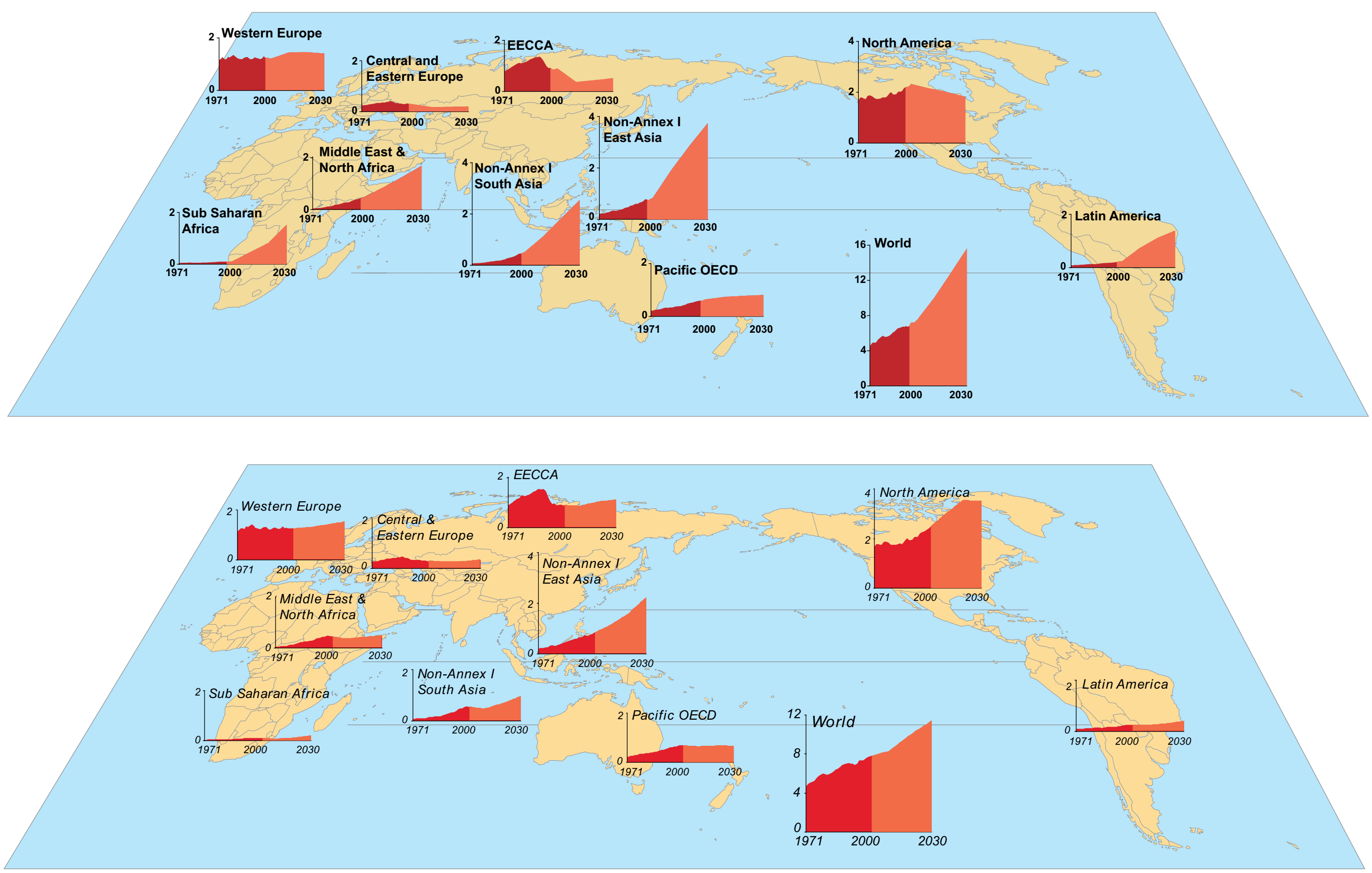

Figure 6.2: *CO_2 emissions including through the use of electricity: A1B (top) and B2 (bottom) IPCC (SRES) scenarios*

Note: Dark red – historic emissions 1971–2000 based on Price *et al.* (2006) modifications of IEA data. Light red – projections 2001–2030 data based on Price *et al.* (2006) disaggregation of SRES data; 2000–2010 data adjusted to actual 2000 carbon dioxide emissions. EECCA = Countries of Eastern Europe, the Caucasus and Central Asia.

the developing world (except China), two regions account for the largest portion of increased CO_2 emissions from 2004 to 2030: North America and Developing Asia. In Scenario A1B (which shows rapid economic growth, especially in developing nations), all of the increase in CO_2 emissions occurs in the developing world: Developing Asia, Middle East/North Africa, Latin America and sub-Saharan Africa, in that order. Overall, average annual CO_2 emissions growth is 1.5% in Scenario B2 and 2.4% in Scenario A1B over the 26-year period.

For the purpose of estimating the CO_2 mitigation potential in buildings, a baseline was derived based on the review of several studies. This baseline represents an aggregation of national and regional baselines reported in the studies (see Box 6.1). The building sector baseline derived and used in this chapter shows emissions between the B2 and A1B (SRES) scenarios, with 11.1 Gt of CO_2-eq emissions in 2020 and 14.3 Gt in 2030 (including electricity emissions).

6.4 GHG mitigation options in buildings and equipment

There is an extensive array of technologies that can be used to abate GHG emissions in new and existing residential and commercial buildings. Prior to discussing options for reducing specific end-uses of energy in buildings it is useful to present an overview of energy end-uses in the residential and commercial sectors, where such information is available and to review some principles of energy-efficient design and operation that are broadly applicable. Figure 6.3 presents a breakdown of energy end-use in the residential and commercial sector for the United States and China. The single largest user of energy in residential buildings in both regions is space heating, followed by water heating (China) and other uses – primarily electric appliances (USA). The order of the next largest uses are reversed in China and the United States, suggesting that electric appliances will increase in use over time in China. The end-uses in commercial buildings are much less similar between China and the United States. For China, heating is by far the largest end-use. For the United States, the largest end-use is other (plug loads involving office equipment and small appliances).

Water heating is the second end-use in China; it is not significant in commercial buildings in the United States. Lighting and cooling are similarly important as the third and fourth largest user in both countries.

The single largest use of energy in residential buildings in both regions is for space heating, followed by water heating. Space heating is also the single largest use of energy in commercial

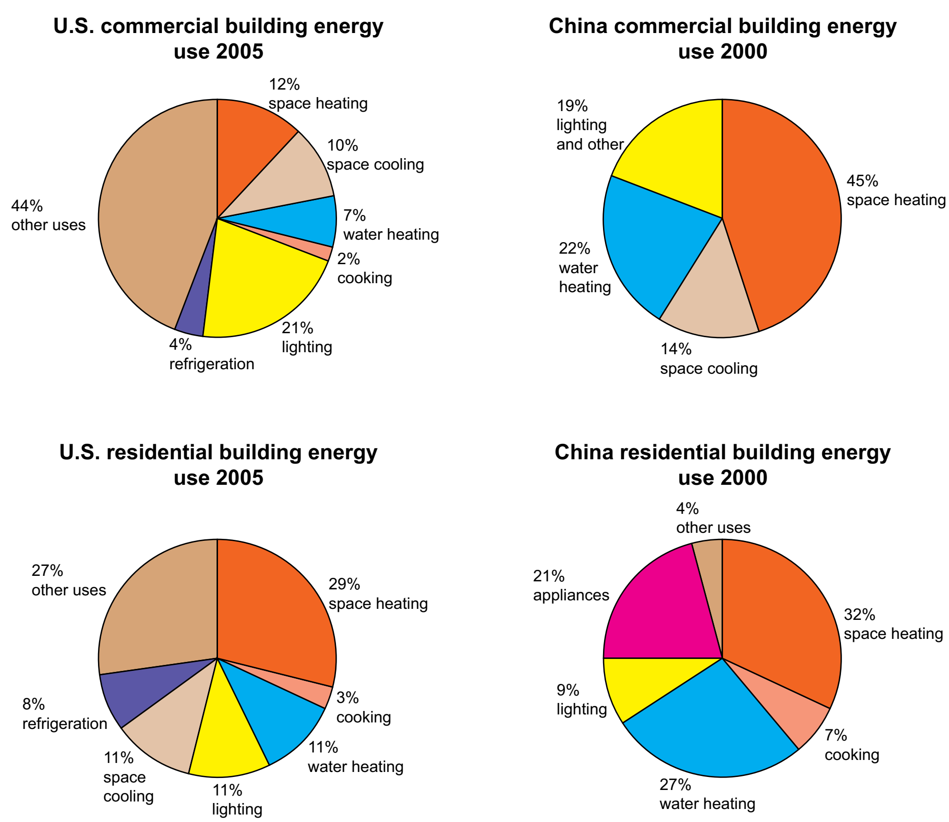

Figure 6.3: *Breakdown of residential and commercial sector energy use in United States (2005) and China (2000).*

Sources: EIA, 2006 and Zhou, 2007.

buildings in the EU, accounting for up to 2/3 of total energy use and is undoubtedly dominant in the cold regions of China and in the Former Soviet Union. Lighting is sometimes the largest single use of electricity in commercial buildings, although in hot climates, air conditioning tends to be the single largest use of electricity.

6.4.1 Overview of energy efficiency principles

Design strategies for energy-efficient buildings include reducing loads, selecting systems that make the most effective use of ambient energy sources and heat sinks and using efficient equipment and effective control strategies. An integrated design approach is required to ensure that the architectural elements and the engineering systems work effectively together.

6.4.1.1 Reduce heating, cooling and lighting loads

A simple strategy for reducing heating and cooling loads is to isolate the building from the environment by using high levels of insulation, optimizing the glazing area and minimizing the infiltration of outside air. This approach is most appropriate for cold, overcast climates. A more effective strategy in most other climates is to use the building envelope as a filter, selectively accepting or rejecting solar radiation and outside air, depending on the need for heating, cooling, ventilation and lighting at that time and using the heat capacity of the building structure to shift thermal loads on a time scale of hours to days.

6.4.1.2 Utilize active solar energy and other environmental heat sources and sinks

Active solar energy systems can provide electricity generation, hot water and space conditioning. The ground, ground water, aquifers and open bodies of water, and less so air, can be used selectively as heat sources or sinks, either directly or by using heat pumps. Space cooling methods that dissipate heat directly to natural heat sinks without the use of refrigeration cycles (evaporative cooling, radiative cooling to the night sky, earth-pipe cooling) can be used.

6.4.1.3 Increase efficiency of appliances, heating and cooling equipment and ventilation

The efficiency of equipment in buildings continues to increase in most industrialized and many developing countries, as it has over the past quarter-century. Increasing the efficiency – and where possible reducing the number and size – of appliances, lighting and other equipment within conditioned spaces reduces energy consumption directly and also reduces cooling loads but increases heating loads, although usually by lesser amounts and possibly for different fuel types.

6.4.1.4 Implement commissioning and improve operations and maintenance

The actual performance of a building depends as much on the quality of construction as on the quality of the design itself. Building commissioning is a quality control process that includes design review, functional testing of energy-consuming systems and components, and clear documentation for the owner and operators. Actual building energy performance also depends critically on how well the building is operated and maintained. Continuous performance monitoring, automated diagnostics and improved operator training are complementary approaches to improving the operation of commercial buildings in particular.

6.4.1.5 Change behaviour

The energy use of a building also depends on the behaviour and decisions of occupants and owners. Classic studies at Princeton University showed energy use variations of more than a factor of two between houses that were identical but had different occupants (Socolow, 1978). Levermore (1985) found a variation of 40% gas consumption and 54% electricity consumption in nine identical children's homes in a small area of London. When those in charge of the homes knew that their consumption was being monitored, the electricity consumption fell. Behaviour of the occupants of non-residential buildings also has a substantial impact on energy use, especially when the lighting, heating and ventilation are controlled manually (Ueno *et al.*, 2006).

6.4.1.6 Utilize system approaches to building design

Evaluation of the opportunities to reduce energy use in buildings can be done at the level of individual energy-using *devices* or at the level of building 'systems' (including building energy management systems and human behaviour). Energy efficiency strategies focused on individual energy-using devices or design features are often limited to incremental improvements. Examining the building as an entire system can lead to entirely different design solutions. This can result in new buildings that use much less energy but are no more expensive than conventional buildings.

The systems approach in turn 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. The steps in the most basic IDP for a commercial building include (i) selecting a high-performance envelope and highly efficient equipment, properly sized; (ii) incorporating a building energy management system that optimises the equipment operation and human behaviour, and (iii) fully commissioning and maintaining the equipment (Todesco, 2004). These steps alone can usually achieve energy savings in 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 in the order of 50–80% (Harvey, 2006).

6.4.1.7 Consider building form, orientation and related attributes

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 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 have been effective in reducing heating and cooling loads. Urban design, including the clustering of buildings and mixing of different building types within a given area greatly affect the opportunities for and cost of district heating and cooling systems (Section 6.4.7) as well as transport energy demand and the shares of different transport modes (Chapter 5, Section 5.5.1).

6.4.1.8 Minimize halocarbon emissions

Many building components – notably air conditioning and refrigeration systems, foam products used for insulation and other purposes and fire protection systems – may emit greenhouse gases with relatively high global-warming potentials. These chemicals include chlorofluorocarbons, hydrochlorofluorocarbons, halons (bromine-containing fluorocarbons) and hydrofluorocarbons (HFCs). While the consumption of the first three is being eliminated through the Montreal Protocol and various national and regional regulations, their on-going emission is still the subject of strategies discussed in the IPCC special report (IPCC/TEAP, 2005). Meanwhile, the use and emissions of HFCs, mostly as replacements for the three ozone-depleting substances, are increasing worldwide.

For many air conditioning and refrigeration applications, the CO_2 emitted during the generation of electricity to power the equipment will typically vastly outweigh the equivalent emissions of the HFC refrigerant. Some exceptions to this general rule exist and two building-related emission sources – CFC chillers and HFC supermarket refrigeration systems – are discussed further. In addition to these applications, some emission mitigation from air conditioning and refrigeration systems is achievable through easy, low-cost options including education and training, proper design and installation, refrigerant leakage monitoring and responsible use and handling of refrigerants throughout the equipment lifecycle.

Like air conditioning and refrigeration systems, most foams and fire protection systems are designed to exhibit low leak rates, and therefore often only emit small portions of the total fluorocarbon under normal use conditions. Upon decommissioning of the building and removal and/or destruction of foam products and fire protection systems, however, large portions of the remaining fluorocarbon content may be released, particularly if no specific measures are adopted to prevent such release. This raises the need to ensure that proper end-of-life management protocols are followed to avoid these unnecessary emissions.

6.4.2 Thermal envelope

The term 'thermal envelope' refers to the shell of the building as a barrier to unwanted heat or mass transfer between the interior of the building and the outside conditions. The effectiveness of the thermal envelope depends on (i) the insulation levels in the walls, ceiling and ground or basement floor, including factors such as moisture condensation and thermal bridges that affect insulation performance; (ii) the thermal properties of windows and doors; and (iii) the rate of exchange of inside and outside air, which in turn depends on the air-tightness of the envelope and driving forces such as wind, inside-outside temperature differences and air pressure differences due to mechanical ventilation systems or warm/cool air distribution.

Improvements in the thermal envelope can reduce heating requirements by a factor of two to four compared to standard practice, at a few percent of the total cost of residential buildings, and at little to no net incremental cost in commercial buildings when downsizing of heating and cooling systems is accounted for (Demirbilek *et al.*, 2000; Hamada *et al.*, 2003; Hastings, 2004). A number of advanced houses have been built in various cold-climate countries around the world that use as little as 10% of the heating energy of houses built according to the local national building code (Badescu and Sicre, 2003; Hamada *et al.*, 2003; Hastings, 2004). Reducing the envelope and air exchange heat loss by a factor of two reduces the heating requirement by more than a factor of two because of solar gains and internal heat gains from equipment, occupants and lighting. 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 two 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).

6.4.2.1 Insulation

The choice of insulation material needs to maximize long-term thermal performance of the building element overall. As mentioned previously, this involves consideration of remaining thermal bridges and any water ingress, or other factor, which could result in deterioration of performance over time. For existing buildings, space may be at a premium and the most efficient insulation materials may be needed to minimize thicknesses required. Where upgrading of existing elements is essentially voluntary, minimization of cost and disturbance is equally important and a range of post-applied technologies can be considered, including cavity wall insulation, spray foams and rolled loft insulation. Only a few specific applications with effective control of end-of life emissions have been identified in which foams containing high GWP blowing agents will lead to lower overall climate impacts than hydrocarbon or CO_2 solutions. However, where this is the case, care should still be taken to optimize life-cycle management techniques in order to minimize blowing agent emissions (see 6.4.15).

6.4.2.2 Windows

The thermal performance of windows has improved greatly through the use of multiple glazing layers, low-conductivity gases (argon in particular) between glazing layers, low-emissivity coatings on one or more glazing surfaces and use of framing materials (such as extruded fibreglass) with very low conductivity. Operable (openable) windows are available with heat flows that have only 25–35% of the heat loss of standard non-coated double-glazed (15 to 20% of single-glazed) windows. Glazing that reflects or absorbs a large fraction of the incident solar radiation reduces solar heat gain by up to 75%, thus reducing cooling loads. In spite of these technical improvements, the costs of glazing and windows has remained constant or even dropped in real terms (Jakob and Madlener, 2004). A major U.S. Department of Energy program is developing electrochromic and gasochromic windows which can dynamically respond to heating and cooling in different seasons.

6.4.2.3 Air leakage

In cold climates, uncontrolled exchange of air between the inside and outside of a building can be responsible for up to half of the total heat loss. In hot-humid climates, air leakage can be a significant source of indoor humidity. In residential construction, installation in walls of a continuous impermeable barrier, combined with other measures such as weather-stripping, can reduce rates of air leakage by a factor of five to ten compared to standard practice in most jurisdictions in North America, Europe and the cold-climate regions of Asia (Harvey, 2006).

In addition to leakage through the building envelope, recent research in the United States has demonstrated that leaks in ducts for distributing air for heating and cooling can increase heating and cooling energy requirements by 20–40% (Sherman and Jump, 1997; O'Neal *et al*., 2002; Francisco *et al.*, 2004). A technology in early commercial use in the United States seals leaks by spraying fine particles into ducts. The sticky particles collect at leakage sites and seal them permanently. This technology is cost-effective for many residential and commercial buildings; it achieves lower costs by avoiding the labour needed to replace or manually repair leaky ducts.

6.4.3 Heating systems

6.4.3.1 Passive solar heating

Passive solar heating can involve extensive sun-facing glazing, various wall- or roof-mounted solar air collectors, double-façade wall construction, airflow windows, thermally massive walls behind glazing and preheating or pre-cooling of ventilation air through buried pipes. Technical details concerning conventional and more advanced passive solar heating techniques, real-world examples and data on energy savings are provided in books by Hastings (1994), Hestnes *et al.* (2003) and Hastings (2004). Aggressive envelope measures combined with optimisation of passive solar heating opportunities, as exemplified by the European Passive House Standard, have achieved reductions in purchased heating energy by factors of five to thirty (i.e., achieving heating levels less than 15 kWh/m^2/yr even in moderately cold climates, compared to 220 and 250–400 kWh/m^2/yr for the average of existing buildings in Germany and Central/Eastern Europe, respectively (Krapmeier and Drössler, 2001; Gauzin-Müller, 2002; Kostengünstige Passivhäuser als europäische Standards, 2005).

6.4.3.2 Space heating systems

In the industrialized nations and in urban areas in developing countries (in cold winter climates), heating is generally provided by a district heating system or by an on-site furnace or boiler. In rural areas of developing countries, heating (when provided at all) is generally from direct burning of biomass. The following sections discuss opportunities to increase energy efficiency in these systems.

Heating systems used primarily in industrialized countries

Multi-unit residences and many single-family residences (especially in Europe) use boilers, which produce steam or hot water that is circulated, generally through radiators. Annual Fuel Utilization Efficiencies (AFUE) values range from 80% to 99% for the boiler, not including distribution losses. Modern residential forced-air furnaces, which are used primarily in North America, have AFUE values ranging from 78% to 97% (again, not including distribution system losses). Old equipment tends to have an efficiency in the range of 60–70%, so new equipment can provide substantial savings (GAMA (Gas Appliance Manufacturers Association), 2005). In both boilers and furnaces, efficiencies greater than about 88% require condensing operation, in which some of the water vapour in the exhaust is condensed in a separate heat exchanger. Condensing boilers are increasingly used in Western Europe due to regulation of new buildings, which require higher-efficiency systems.

Hydronic systems (in which water rather than air is circulated), especially floor radiant heating systems, are capable of greater energy efficiency than forced air systems because of the low energy required to distribute a given amount of heat, low distribution heat losses and absence of induced infiltration of outside air into the house due to poorly balanced air distribution systems (low-temperature systems also make it possible to use low-grade solar thermal energy).

Heat pumps use an energy input (almost always electricity) to transfer heat from a cold medium (the outside air or ground in the winter) to a warmer medium (the warm air or hot water used to distribute heat in a building). During hot weather, the heat pump can operate in reverse, thereby cooling the indoor space. In winter, drawing heat from a relatively warm source (such as the ground rather than the outside air) and distributing the heat at the lowest possible temperature can dramatically improve the heat pump efficiency. Use of the ground rather than the outside air as a heat source reduced measured energy use for heating by 50 to 60% in two US studies (Shonder *et al.*, 2000; Johnson, 2002). Due to the large energy losses (typically 60–65%) in generating electricity from fossil fuels, heat pumps are particularly advantageous for heating when they replace electric-resistance heating, but may not be preferable to direct use of fuels for heating. The ground can also serve as a low-temperature heat sink in summer, increasing the efficiency of air conditioning.

Coal and biomass burning stoves in rural areas of developing countries

Worldwide, about three billion people use solid fuels – biomass and, mainly in China, coal – in household stoves to meet their cooking, water heating and space heating needs. Most of these people live in rural areas with little or no access to commercial sources of fuel or electricity (WEC (World Energy Council and Food and Agriculture Organization), 1999). Statistical information on fuel use in cooking stoves is sketchy, so any estimates of energy use and associated GHG emissions are uncertain.[5] The global total for traditional biofuel use – a good proxy for energy use in household stoves – was about 32 EJ in 2002, compared to commercial energy use worldwide of 401 EJ (IEA, 2004c).

Worldwide, most household stoves use simple designs and local materials that are inefficient, highly polluting and contribute to the overuse of local resources. Studies of China and India have found that if only the Kyoto Protocol basket of GHGs is considered, biomass stoves appear to have lower emission factors than fossil-fuel alternatives (Smith *et al.*, 2000; Edwards *et al.*, 2004). If products of incomplete combustion (PICs) other than methane and N_2O are considered, however, then biomass stove-fuel combinations exhibit GHG emissions three to ten times higher than fossil-fuel alternatives, and in many cases even higher emissions than from stoves burning coal briquettes (Goldemberg *et al.*, 2000). Additional heating effects arise from black carbon emissions associated with wood-burning stoves. Programmes to develop and disseminate more-efficient biomass stoves have been very effective in China, less so in India and other countries (Barnes *et al.*, 1994; Goldemberg *et al.*, 2000; Sinton *et al.*, 2004). In the long term, stoves that use biogas or biomass-derived liquid fuels offer the greatest potential for significantly reducing the GHG (and black carbon) emissions associated with household use of biomass fuels.

6.4.4 Cooling and cooling loads

Cooling energy can be reduced by: 1) reducing the cooling load on a building, 2) using passive techniques to meet some or all of the load, and 3) improving the efficiency of cooling equipment and thermal distribution systems.

6.4.4.1 Reducing the cooling load

Reducing the cooling load depends on the building shape and orientation, the choice of building materials and a whole host of other decisions that are made in the early design stage by the architect and are highly sensitive to climate. In general, recently constructed buildings are no longer adapted to prevailing climate; the same building forms and designs are now seen in Stockholm, New York, Houston, Hong Kong, Singapore and Kuwait. However, the principles of design to reduce cooling load for any climate are well known. In most climates, they include: (i) orienting a building to minimize the wall area facing east or west; (ii) clustering buildings to provide some degree of self shading (as in many traditional communities in hot climates); (iii) using high-reflectivity building materials; (iv) increasing insulation; (v) providing fixed or adjustable shading; (vi) using selective glazing on windows with a low solar heat gain and a high daylight transmission factor and avoiding excessive window area (particularly on east- and west-facing walls); and (vii) utilizing thermal mass to minimize daytime interior temperature peaks. As well, internal heat loads from appliances and lighting can be reduced through the use of efficient equipment and controls.

Increasing the solar reflectivity of roofs and horizontal or near-horizontal surfaces around buildings and planting shade trees can yield dramatic energy savings. The benefits of trees arise both from direct shading and from cooling the ambient air. Rosenfeld *et al.* (1998) computed that a very large-scale, city-wide program of increasing roof and road albedo and planting trees in Los Angeles could yield a total savings in residential cooling energy of 50–60%, with a 24–33% reduction in peak air conditioning loads.

6.4.4.2 Passive and low-energy cooling techniques

Purely passive cooling techniques require no mechanical energy input, but can often be greatly enhanced through small amounts of energy to power fans or pumps. A detailed discussion of passive and low-energy cooling techniques can be found in

5 Estimates are available for China and India, collectively home to about one third of the world's population. Residential use of solid fuels in China, nearly all used in stoves, was about 9 EJ in 2002, or 18% of all energy use in the country (National Bureau of Statistics, 2004). The corresponding figures for India were 8 EJ and 36% (IEA, 2004c). In both cases, nearly all of this energy is in the form of biomass.

Harvey (2006) and Levermore (2000). Highlights are presented below:

Natural and night-time ventilation

Natural 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, providing night-time cooling of exposed thermal mass and increasing the acceptable temperature through psychological adaptation when the occupants have control of operable windows. 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).

Natural ventilation requires a driving force and an adequate number of openings, to produce airflow. Natural ventilation 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). In addition to being increasingly employed in commercial buildings in Europe, natural ventilation is starting to be used in multi-story commercial buildings in more temperate climates in North America (McConahey *et al.*, 2002). Natural ventilation can be supplemented with mechanical ventilation as needed.

In climates with a minimum diurnal temperature variation of 5°C to 7°C, natural or mechanically assisted night-time ventilation, in combination with exposed thermal mass, can be very effective in reducing daily temperature peaks and, in some cases, eliminating the need for cooling altogether. Simulations carried out in California indicate that night-time ventilation is sufficient to prevent peak indoor temperatures from exceeding 26°C over 43% of California in houses with an improved envelope and modestly greater thermal mass compared to standard practice (Springer *et al.*, 2000). For Beijing, da Graça et al. (2002) found that thermally and wind-driven night-time ventilation could eliminate the need for air conditioning of a six-unit apartment building during most of the summer if the high risk of condensation during the day due to moist outdoor air coming into contact with the night-cooled indoor surfaces could be reduced.

Evaporative cooling

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 conditions most of the time in most parts of the world.

Subject to availability of water, direct evaporative cooling can be used in arid areas; indirect evaporative cooling extends the region of applicability to somewhat more humid climates. A new indirect-direct evaporative cooler in the development phase indicated savings in annual cooling energy use of 92 to 95% for residences and 89 to 91% for a modular school classroom in simulations for a variety of California climate zones (DEG, 2004).

Other passive cooling techniques

Underground earth-pipe cooling consists of cooling ventilation air by drawing outside air through a buried air duct. Good performance depends on the climate having a substantial annual temperature range. 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. The energy used for dehumidification can be reduced by 30 to 50% compared to a conventional overcooling/reheat scheme (50 to 75% savings of conventional sources if solar energy is used to regenerate the desiccant) (Fischer *et al.*, 2002; Niu *et al.*, 2002). In hot-humid climates, desiccant systems can be combined with indirect evaporative cooling, providing an alternative to refrigeration-based air conditioning systems (Belding and Delmas, 1997).

6.4.4.3 Air conditioners and vapour-compression chillers

Air conditioners used for houses, apartments and small commercial buildings have a nominal COP (cooling power divided by fan and compressor power, a direct measure of efficiency) ranging from 2.2 to 3.8 in North America and Europe, depending on operating conditions. More efficient mini-split systems are available in Japan, ranging from 4.5 to 6.2 COP for a 2.8 kW cooling capacity unit. Chillers are larger cooling devices that produce chilled water (rather than cooled air) for use in larger commercial buildings. COP generally increases with size, with the largest and most efficient centrifugal chillers having a COP of up to 7.9 under full-load operation and even higher under part-load operation. Although additional energy is used in chiller-based systems for ventilation, circulating chilled water and operating a cooling tower, significant energy savings are possible through the choice of the most efficient cooling equipment in combination with efficient auxiliary systems (see Section 6.4.5.1 for principles).

Air conditioners – from small room-sized units to large building chillers – generally employ a halocarbon refrigerant in a vapour-compression cycle. Although the units are designed to exhibit low refrigerant emission rates, leaks do occur and additional emissions associated with the installation, service and disposal of this equipment can be significant. The emissions will vary widely from one installation to the next and depend greatly on the practices employed at the site. In some cases, the GWP-weighted lifetime emissions of the refrigerant will outweigh the CO_2 emissions associated with the electricity, highlighting the need to consider refrigerant type and handling as well as energy efficiency when making decisions on the purchase, operation, maintenance and replacement of these systems.

Until recently, the penetration of air conditioning in developing countries has been relatively low, typically only used in large office buildings, hotels and high-income homes. That is quickly changing however, with individual apartment and home air conditioning becoming more common in developing countries, reaching even greater levels in developed countries. This is evident in the production trends of typical room-to-house sized units, which increased 26% (35.8 to 45.4 million units) from 1998 to 2001 (IPCC/TEAP, 2005).

6.4.5 Heating, ventilation and air conditioning (HVAC) systems

The term HVAC is generally used in reference to commercial buildings. HVAC systems include filtration and, where required by the climate, humidification and dehumidification as well as heating and cooling. However, energy-efficient houses in climates with seasonal heating are almost airtight, so mechanical ventilation has to be provided (during seasons when windows will be closed), often in combination with the heating and/or cooling system, as in commercial buildings.

6.4.5.1 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. 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 (i) using variable-air volume systems so as to minimize simultaneous heating and cooling of air; (ii) using heat exchangers to recover heat or coldness from ventilation exhaust air; (iii) minimizing fan and pump energy consumption by controlling rotation speed; (iv) 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; (v) separating cooling from dehumidification functions through the use of desiccant dehumidification; (vi) implementing a demand-controlled ventilation system in which ventilation airflow changes with changing building occupancy which alone can save 20 to 30% of total HVAC energy use (Brandemuehl and Braun, 1999); (vii) correctly sizing all components; and (viii) allowing the temperature maintained by the HVAC system to vary seasonally with outdoor conditions (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), while computer simulations by Jaboyedoff *et al.* (2004) and by Jakob *et al*. (2006) indicate that increasing the thermostat by 2°C to 4°C will reduce annual cooling energy use by more than a factor of three for a typical office building in Zurich, and by a factor of two to three if the thermostat setting is increased from 23°C to 27°C for night-time air conditioning of bedrooms in apartments in Hong Kong (Lin and Deng, 2004).

Additional savings can be obtained in 'mixed-mode' buildings, in which natural ventilation is used whenever possible, making use of the extended comfort range associated with operable windows, and mechanical cooling is used only when necessary during periods of very warm weather or high building occupancy.

6.4.5.2 Alternative HVAC systems in commercial buildings

The following paragraphs describe two alternatives to conventional HVAC systems in commercial buildings that together can reduce the HVAC system energy use by 30 to 75%. These savings are in addition to the savings arising from reducing heating and cooling loads.

Radiant chilled-ceiling cooling
A room may be cooled by chilling a large fraction of the ceiling by circulating water through pipes or lightweight panels. Chilled ceiling (CC) cooling has been used in Europe since at least the mid-1970s. In Germany during the 1990s, 10% of retrofitted buildings used CC cooling (Behne, 1999). 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 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 water from the cooling tower is used directly for space cooling**.** For example, a cooling tower alone could directly meet the cooling requirements 97% of the time in Dublin, Ireland and 67% of the time in Milan, Italy if the chilled water is supplied at 18°C (Costelloe and Finn, 2003).

Displacement ventilation
Conventional ventilation relies on turbulent mixing to dilute room air with ventilation air. A superior system is 'displacement ventilation' (DV) 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. The thermodynamic advantage of displacement ventilation is that the supply air temperature is significantly higher for the same comfort conditions (about 18^{o}C compared with about 13^{o}C in a conventional mixing ventilation system). It also permits significantly smaller airflow.

DV was first applied in northern Europe; by 1989 it had captured 50% of the Scandinavian market for new industrial buildings and 25% for new office buildings (Zhivov and

Rymkevich, 1998). The building industry in North America has been much slower to adopt DV; by the end of the 1990s fewer than 5% of new buildings used under-floor air distribution systems (Lehrer and Bauman, 2003). Overall, DV can reduce energy use for cooling and ventilation by 30 to 60%, depending on the climate (Bourassa *et al.*, 2002; Howe *et al.*, 2003).

6.4.6 Building energy management systems (BEMS)

BEMSs are control systems for individual buildings or groups of buildings that use computers and distributed microprocessors for monitoring, data storage and communication (Levermore, 2000). The BEMS can be centrally located and communicate over telephone or Internet links with remote buildings having 'outstations' so that one energy manager can manage many buildings remotely. With energy meters and temperature, occupancy and lighting sensors connected to a BEMS, faults can be detected manually or using automated fault detection software (Katipamula *et al.*, 1999), which helps avoid energy waste (Burch *et al.*, 1990). With the advent of inexpensive, wireless sensors and advances in information technology, extensive monitoring via the Internet is possible.

Estimates of BEMS energy savings vary considerably: up to 27% (Birtles and John, 1984); between 5% and 40% (Hyvarinen, 1991; Brandemuehl and Bradford, 1999; Brandemuehl and Braun, 1999; Levermore, 2000); up to 20% in space heating energy consumption and 10% for lighting and ventilation; and 5% to 20% overall (Roth *et al.*, 2005).

6.4.6.1 Commissioning

Proper commissioning of the energy systems in a commercial building is a key to efficient operation (Koran, 1994; Kjellman *et al.*, 1996; IEA, 2005; Roth *et al.*, 2005). Building commissioning is a quality control process that begins with the early stages of design. Commissioning 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. A systems manual is prepared to document the owner's requirements, the design intent (including as-built drawings), equipment performance specifications and control sequences.

Recent results of building commissioning in the USA showed energy savings of up to 38% in cooling and/or 62% in heating and an average higher than 30% (Claridge *et al.*, 2003). A study by Mills *et al*. (2005) reviewed data from 224 US buildings that had been commissioned or retro-commissioned. The study found that the costs of commissioning new buildings were typically outweighed by construction cost savings due to fewer change orders and that retro-commissioning produced median energy savings of 15% with a median payback period of 8.5 months. It is very difficult to assess the energy benefits of commissioning new buildings due to the lack of a baseline.

6.4.6.2 Operation, maintenance and performance benchmarking

Once a building has been commissioned, there is a need to maintain its operating efficiency. A variety of methods to monitor and evaluate performance and diagnose problems are currently under development (Brambley *et al.*, 2005). Post-occupancy evaluation (POE) is a useful complement to ongoing monitoring of equipment and is also useful for ensuring that the building operates efficiently. A UK study of recently constructed buildings found that the use of POE identified widespread energy wastage (Bordass *et al.*, 2001a; Bordass *et al*., 2001b).

Cogeneration and District Heating/Cooling

Buildings are usually part of a larger community. If the heating, cooling and electricity needs of a larger collection of buildings can be linked together in an integrated system without major distribution losses, then significant savings in primary energy use are possible – beyond what can be achieved by optimising the design of a single building. Community-scale energy systems also offer significant new opportunities for the use of renewable energy. Key elements of an integrated system can include: 1) district heating networks for the collection of waste or surplus heat and solar thermal energy from dispersed sources and its delivery to where it is needed; 2) district cooling networks for the delivery of chilled water for cooling individual buildings; 3) central production of steam and/or hot water in combination with the generation of electricity (cogeneration) and central production of cold water; 4) production of electricity through photovoltaic panels mounted on or integrated into the building fabric; 5) diurnal storage of heat and coldness produced during off-peak hours or using excess wind-generated electricity; and 6) seasonal underground storage of summer heat and winter coldness.

District heating (DH) is widely used in regions with large fractions of multi-family buildings, providing as much as 60% of heating and hot water energy needs for 70% of the families in Eastern European countries and Russia (OECD/IEA, 2004). While district heating can have major environmental benefits over other sources of heat, including lower specific GHG emissions, systems in these countries suffer from the legacies of past mismanagement and are often obsolete, inefficient and expensive to operate (Lampietti and Meyer, 2003, Ürge-Vorsatz *et al.,* 2006). Making DH more efficient could save 350 million tonnes of CO_2 emissions in these countries annually, accompanied by significant social, economic and political benefits (OECD/IEA, 2004).

The greatest potential improvement in the efficiency of district heating systems is to convert them to cogeneration systems that involve the simultaneous production of electricity and useful heat. For cogeneration to provide an improvement in efficiency, a use has to be found for the waste heat. Centralized production of heat in a district heat system can be more efficient than on-site boilers or furnaces even in the absence of cogeneration and in spite of distribution losses, if a district-heating network is used with heat pumps to upgrade and distribute heat from scattered sources. Examples include waste heat from sewage in Tokyo (Yoshikawa, 1997) and Gothenberg, Sweden (Balmér, 1997) and low-grade geothermal heat in Tianjin, China, that is left over after higher-temperature heat has been used for heating and hot water purposes (Zhao *et al.*, 2003). Waste heat from incineration has been used, particularly in northern Europe.

Chilled water supplied to a district-cooling network can be produced through trigeneration (the simultaneous production of electricity, heat and chilled water), or it can be produced through a centralized chilling plant independent of power generation. District cooling provides an alternative to separate chillers and cooling towers in multi-unit residential buildings that would otherwise use inefficient small air conditioners. In spite of the added costs of pipes and heat exchangers in district heating and cooling networks, the total capital cost can be less than the total cost of heating and cooling units in individual buildings, (Harvey, 2006, Chapter 15). Adequate control systems are critical to the energy-efficient operation of both district cooling and central (building-level) cooling systems.

District heating and cooling systems, especially when combined with some form of thermal energy storage, make it more economically and technically feasible to use renewable sources of energy for heating and cooling. Solar-assisted district heating systems with storage can be designed such that solar energy provides 30 to 95% of total annual heating and hot water requirements under German conditions (Lindenberger *et al.*, 2000). Sweden has been able to switch a large fraction of its building heating energy requirements to biomass energy (plantation forestry) for its district heating systems (Swedish Energy Agency, 2004).

6.4.7 Active collection and transformation of solar energy

Buildings can serve as collectors and transformers of solar energy, meeting a large fraction of their energy needs on a sustainable basis with minimal reliance on connection to energy grids, although for some climates this may only apply during the summer. As previously discussed, solar energy can be used for daylighting, for passive heating and as one of the driving forces for natural ventilation, which can often provide much or all of the required cooling. By combining a high-performance thermal envelope with efficient systems and devices, 50–75% of the heating and cooling energy needs of buildings as constructed under normal practice can either be eliminated or satisfied through passive solar design. Electricity loads, especially in commercial buildings, can be drastically reduced to a level that allows building-integrated photovoltaic panels (BiPV) to meet much of the remaining electrical demand during daytime hours. Photovoltaic panels can be supplemented by other forms of active solar energy, such as solar thermal collectors for hot water, space heating, absorption space cooling and dehumidification.

6.4.7.1 Building-integrated PV (BiPV)

The principles governing photovoltaic (PV) power generation and the prospects for centralized PV production of electricity are discussed in Chapter 4, Section 4.3.3.6. Building-integrated PV (BiPV) consists of PV modules that function as part of the building envelope (curtain walls, roof panels or shingles, shading devices, skylights). BiPV systems are sometimes installed in new 'showcase' buildings even before the systems are generally cost-effective. These early applications will increase the rate at which the cost of BiPVs comes down and the technical performance improves. A recent report presents data on the cost of PV modules and the installed-cost of PV systems in IEA countries (IEA, 2003b). Electricity costs from BiPV at present are in the range of 0.30–0.40 US$/kWh in good locations, but can drop considerably with mass production of PV modules (Payne *et al.*, 2001).

Gutschner *et al.* (2001) have estimated the potential for power production from BiPV in IEA member countries. Estimates of the percentage of present total national electricity demand that could be provided by BiPV range from about 15% (Japan) to almost 60% (USA).

6.4.7.2 Solar thermal energy for heating and hot water

Most solar thermal collectors used in buildings are either flat-plate or evacuated-tube collectors.[6] Integrated PV/thermal collectors (in which the PV panel serves as the outer part of a thermal solar collector) are also commercially available (Bazilian *et al.*, 2001; IEA, 2002). 'Combisystems' are solar systems that provide both space and water heating. Depending on the size of panels and storage tanks, and the building thermal envelope performance, 10 to 60% of the combined hot water and heating demand can be met by solar thermal systems at central and northern European locations. Costs of solar heat have been 0.09–0.13 €/kWh for large domestic hot water systems and 0.40–0.50 €/kWh for combisystems with diurnal storage (Peuser *et al.*, 2002).

Worldwide, over 132 million m^2 of solar collector surface for space heating and hot water were in place by the end of 2003. China accounts for almost 40% of the total (51.4 million m^2), followed by Japan (12.7 million m^2) and Turkey (9.5 million m^2) (Weiss *et al.*, 2005).

6 See Peuser *et al.* (2002) and Andén (2003) for technical information.

6.4.8 Domestic hot water

Options to reduce fossil or electrical energy used to produce hot water include (i) use of water saving fixtures, more water-efficient washing machines, cold-water washing and (if used at all) more water-efficient dishwashers (50% typical savings); (ii) use of more efficient and better insulated water heaters or integrated space and hot-water heaters (10–20% savings); (iii) use of tankless (condensing or non-condensing) water heaters, located close to the points of use, to eliminate standby and greatly reduce distribution heat losses (up to 30% savings, depending on the magnitude of standby and distribution losses with centralized tanks); (v) recovery of heat from warm waste water; (vi) use of air-source or exhaust-air heat pumps; and (vii) use of solar thermal water heaters (providing 50–90% of annual hot-water needs, depending on climate). The integrated effect of all of these measures can frequently reach a 90% savings. Heat pumps using CO_2 as a working fluid are an attractive alternative to electric-resistance hot water heaters, with a COP of up to 4.2–4.9 (Saikawa *et al.*, 2001; Yanagihara, 2006).

6.4.9 Lighting systems

Lighting energy use can be reduced by 75 to 90% compared to conventional practice through (i) use of daylighting with occupancy and daylight sensors to dim and switch off electric lighting; (ii) use of the most efficient lighting devices available; and (iii) use of such measures as ambient/task lighting.

6.4.9.1 High efficiency electric lighting

Presently 1.9 $GtCO_2$ are emitted by electric lighting worldwide, equivalent to 70% of the emissions from light passenger vehicles (IEA, 2006b). Continuous improvements in the efficacy[7] of electric lighting devices have occurred during the past decades and can be expected to continue. Advances in lamps have been accompanied by improvements in occupancy sensors and reductions in cost (Garg and Bansal, 2000; McCowan *et al.*, 2002). A reduction in residential lighting energy use of a factor of four to five can be achieved compared to incandescent/halogen lighting.

For lighting systems providing ambient (general space) lighting in commercial buildings, the energy required can be reduced by 50% or more compared to old fluorescent systems through use of efficient lamps (ballasts and reflectors, occupancy sensors, individual or zone switches on lights and lighter colour finishes and furnishings. A further 40 to 80% of the remaining energy use can be saved in perimeter zones through daylighting (Rubinstein and Johnson, 1998; Bodart and Herde, 2002). A simple strategy to further reduce energy use is to provide a relatively low background lighting level, with local levels of greater illumination at individual workstations. This strategy is referred to as 'task/ambient lighting' and is popular in Europe. Not only can this alone cut lighting energy use in half, but it provides a greater degree of individual control over personal lighting levels and can reduce uncomfortable levels of glare and high contrast.

About one third of the world's population depends on fuel-based lighting (such as kerosene, paraffin or diesel), contributing to the major health burden from indoor air pollution in developing countries. While these devices provide only 1% of global lighting, they are responsible for 20% of the lighting-related CO_2 emissions and consume 3% of the world's oil supply. A CFL or LED is about 1000 times more efficient than a kerosene lamp (Mills, 2005). Efforts are underway to promote replacement of kerosene lamps with LEDs in India. Recent advances in light-emitting diode (LED) technology have significantly improved the cost-effectiveness, longevity and overall viability of stand-alone PV-powered task lighting (IEA, 2006b).

6.4.10 Daylighting

Daylighting systems involve the use of natural lighting for the perimeter areas of a building. Such systems have light sensors and actuators to control artificial lighting. Opportunities for daylighting are strongly influenced by architectural decisions early in the design process, such as building form; the provision of inner atria, skylights and clerestories (glazed vertical steps in the roof); and the size, shape and position of windows. IEA (2000) provides a comprehensive sourcebook of conventional and less conventional techniques and technologies for daylighting.

A number of recent studies indicate savings in lighting energy use of 40 to 80% in the daylighted perimeter zones of office buildings (Rubinstein and Johnson, 1998; Jennings *et al.*, 2000; Bodart and Herde, 2002; Reinhart, 2002; Atif and Galasiu, 2003; Li and Lam, 2003). The management of solar heat gain along with daylighting to reduce electric lighting also leads to a reduction in cooling loads. Lee *et al.* (1998) measured savings for an automated Venetian blind system integrated with office lighting controls, finding that lighting energy savings averaged 35% in winter and ranged from 40 to 75% in summer. Monitored reductions in summer cooling loads were 5 to 25% for a southeast-facing office in Oakland, California building, with even larger reductions in peak cooling loads. Ullah and Lefebvre (2000) reported measured savings of 13 to 32% for cooling plus ventilation energy using automatic blinds in a building in Singapore.

An impediment to more widespread use of daylighting is the linear, sequential nature of the design process. Based on a survey of 18 lighting professionals in the USA, Turnbull

7 This is the ratio of light output in lumens to input power in watts.

and Loisos (2000) found that, rather than involving lighting consultants from the very beginning, architects typically make a number of irreversible decisions at an early stage of the design that adversely impact daylighting, 'then' pass on their work to the lighting consultants and electrical engineers to do the lighting design. As a result, the lighting system becomes, *de facto*, strictly an electrical design.

6.4.11 Household appliances, consumer electronics and office equipment

Energy use by household appliances, office equipment and consumer electronics, from now on referred to as 'appliances', is an important fraction of total electricity use in both households and workplaces (Kawamoto *et al*., 2001; Roth *et al.*, 2002). This equipment is more than 40% of total residential primary energy demand in 11 large OECD nations[8] (IEA, 2004f). The largest growth in electricity demand has been in miscellaneous equipment (home electronics, entertainment, communications, office equipment and small kitchen equipment), which has been evident in all industrialized countries since the early 1980s. Such miscellaneous equipment now accounts for 70% of all residential appliance electricity use in the 11 large OECD nations (IEA, 2004f). Appliances in some developing countries constitute a smaller fraction of residential energy demand. However, the rapid increase in their saturation in many dynamically developing countries such as China, especially in urban areas, demonstrates the expected rise in importance of appliances in the developing world as economies grow (Lawrence Berkeley National Laboratory, 2004).

On a primary energy basis appliances undoubtedly represent a larger portion of total energy use for residential than for commercial buildings. In the United States, for example, they account for almost 55% of total energy consumption in commercial buildings. Miscellaneous equipment and lighting combined account for more than half of total energy consumption in commercial buildings in the United States and Japan (Koomey *et al.*, 2001; Murakami *et al.*, 2006).

The most efficient appliances require a factor of two to five less energy than the least efficient appliances available today. For example, in the USA, the best horizontal-axis clothes-washing machines use less than half the energy of the best vertical-axis machines (FEMP, 2002), while refrigerator/freezer units meeting the current US standard (478 kWh/yr) require about 25% of the energy used by refrigerator/freezers sold in the USA in the late 1970s (about 1800 kWh/yr) and about 50% of energy used in the late 1980s. Available refrigerator/freezers of standard US size use less than 400 kWh/yr (Brown *et al.*, 1998). However, this is still in excess of the average energy use by (generally smaller) refrigerators in Sweden, the Netherlands, Germany and Italy in the late 1990s (IEA, 2004f).

Standby and low power mode use by consumer electronics (i.e., energy used when the machine is turned off) in a typical household in many countries often exceeds the energy used by a refrigerator/freezer unit that meets the latest US standards, that is often more than 500 kWh/yr, (Bertoldi *et al.*, 2002). The growing proliferation of electronic equipment such as set-top boxes for televisions, a wide variety of office equipment (in homes as well as offices) and sundry portable devices with attendant battery chargers – combined with inefficient power supplies (Calwell and Reeder, 2002) and highly inefficient circuit designs that draw unnecessary power in the resting or standby modes – have caused this equipment to be responsible for a large fraction of the electricity demand growth in both residential and commercial buildings in many nations. Efforts are underway especially at the International Energy Agency and several countries (e.g., Korea, Australia, Japan and China) to reduce standby energy use by a factor of two to three (Ross and Meier, 2002; Fung *et al.*, 2003). Electricity use by office equipment may not yet be large compared to electricity use by the HVAC system, but (as noted) it is growing rapidly and is already an important source of internal heat gain in offices and some other commercial buildings. The biggest savings opportunities are: 1) improved power supply efficiency in both active and low-power modes, 2) redesigned computer chips that reduce electricity use in low-power mode, and 3) repeated reminders to users to turn equipment off during non-working hours.

The cooking stove, already referred to in Section 6.4.3.2 for heating, is a major energy-using appliance in developing countries. However, there is particular concern about emissions of products of incomplete combustion described in that section. Two-and-a-half billion people in developing countries depend on biomass, such as wood, dung, charcoal and agricultural residues, to meet their cooking energy needs (IEA, 2006e). Options available to reduce domestic cooking energy needs include: 1) improved efficiency of biomass stoves; 2) improved access to clean cooking fuels, both liquid and gaseous; 3) access to electricity and low-wattage and low-cost appliances for low income households; 4) non-electric options such as solar cookers; 5) efficient gas stoves; and 6) small electric cooking equipment such as microwaves, electric kettles or electric frying pans. Improved biomass stoves can save from 10 to 50% of biomass consumption for the same cooking service (REN21 (Renewable Energy Policy Network), 2005) at the same time reducing indoor air pollution by up to one-half. Although the overall impact on emissions from fuel switching can be either positive or negative, improved modern fuels and greater conversion efficiency would result in emission reductions from all fuels (IEA, 2006e).

8 Australia, Denmark, Finland, France, Germany, Italy, Japan, Norway, Sweden, the United Kingdom, and the United States.

6.4.12 Supermarket refrigeration systems

Mitigation options for food-sales and service buildings, especially supermarkets and hypermarkets extend beyond the energy savings mitigation options reviewed so far (e.g., high efficiency electric lighting, daylighting, etc.). Because these buildings often employ large quantities of HFC refrigerants in extensive and often leaky systems, a significant share of total GHG emissions are due to the release of the refrigerant. In all, emissions of the refrigerant can be greater than the emissions due to the system energy use (IPCC/TEAP, 2005).

Two basic mitigation options are reviewed in IPCC/TEAP report: leak reduction and alternative system design. Refrigerant leakage rates are estimated to be around 30% of banked system charge. Leakage rates can be reduced by system design for tightness, maintenance procedures for early detection and repairs of leakage, personnel training, system leakage record keeping and end-of-life recovery of refrigerant. Alternative system design involves for example, applying direct systems using alternative refrigerants, better containment, distributed systems, indirect systems or cascade systems. It was found that up to 60% lower LCCP values can be obtained by alternative system design (IPCC/TEAP, 2005).

6.4.13 Energy savings through retrofits

There is a large stock of existing and inefficient buildings, most of which will still be here in 2025 and even 2050. Our long-term ability to reduce energy use depends critically on the extent to which energy use in these buildings can be reduced when they are renovated. The equipment inside a building, such as the furnace or boiler, water heater, appliances, air conditioner (where present) and lighting is completely replaced over time periods ranging from every few years to every 20–30 years. The building shell – walls, roof, windows and doors – lasts much longer. There are two opportunities to reduce heating and cooling energy use by improving the building envelope: (i) at any time prior to a major renovation, based on simple measures that pay for themselves through reduced energy costs and potential financial support or incentives; and (ii) when renovations are going to be made for other (non-energy) reasons, including replacement of windows and roofs.

6.4.13.1 Conventional retrofits of residential buildings

Cost-effective measures that can be undertaken without a major renovation of residential buildings include: sealing points of air leakage around baseboards, electrical outlets and fixtures, plumbing, the clothes dryer vent, door joists and window joists; weather stripping of windows and doors; and adding insulation in attics, to walls or wall cavities. A Canadian study found that the cost-effective energy savings potential ranges from 25–30% for houses built before the 1940s, to about 12% for houses built in the 1990s (Parker *et al.*, 2000). In a carefully documented retrofit of four representative houses in the York region of the UK, installation of new window and wooden door frames, sealing of suspended timber ground floors and repair of cracks in plaster reduced the rate of air leakage by a factor of 2.5–3.0 (Bell and Lowe, 2000). This, combined with improved insulation, doors and windows, reduced the heating energy required by an average of 35%. Bell and Lowe (2000) believe that a reduction of 50% could be achieved at modest cost using well-proven (early 1980s) technologies, with a further 30–40% reduction through additional measures.

Studies summarized by Francisco *et al.* (1998) indicate that air-sealing retrofits alone can save an average of 15–20% of annual heating and air conditioning energy use in US houses. Additional energy savings would arise by insulating pipework and ductwork, particularly in unconditioned spaces. Rosenfeld (1999) refers to an 'AeroSeal' technique (see Sec. 6.4.2.2) that he estimates is already saving three billion US$/yr in energy costs in the USA. Without proper sealing, homes in the USA lose, on average, about one-quarter of the heating and cooling energy through duct leaks in unconditioned spaces – attics, crawl spaces, basements.

In a retrofit of 4003 homes in Louisiana, the heating, cooling and water heating systems were replaced with a ground-source heat pump system. Other measures were installation of attic insulation and use of compact fluorescent lighting and water saving showerheads. Space and hot water heating previously provided by natural gas was supplied instead by electricity (through the heat pump), but total electricity use still decreased by one third (Hughes and Shonder, 1998).

External Insulation and Finishing Systems (EIFSs) provide an excellent opportunity for upgrading the insulation and improving the air-tightness of single- and multi-unit residential buildings, as well as institutional and commercial buildings. This is because of the wide range of external finishes that can be applied, ranging from stone-like to a finish resembling aged plaster. A German company manufacturing some of the components used in EIFSs undertook a major renovation of some of its own 1930s multi-unit residential buildings. The EIFSs in combination with other measures achieved a factor of eight measured reduction in heating energy use (see www.3lh.de). An envelope upgrade of an apartment block in Switzerland reduced the heating requirement by a factor of two, while replacing an oil-fired boiler at 85% seasonal average efficiency with an electric heat pump having a seasonal average COP of 3.2 led to a further large decrease in energy use. The total primary energy requirement decreased by about 75% (Humm, 2000).

6.4.13.2 Conventional retrofits of institutional and commercial buildings

There are numerous published studies showing that energy savings of 50 to 75% can be achieved in commercial buildings through aggressive implementation of integrated sets of measures. These savings can often be justified in terms of the energy-cost savings alone, although in other cases full justification requires consideration of a variety of less tangible benefits. In the early 1990s, a utility in California sponsored a 10 million US$ demonstration of advanced retrofits. In six of seven retrofit projects, an energy savings of 50% was obtained; in the seventh project, a 45% energy savings was achieved. For Rosenfeld (1999), the most interesting result was not that an alert, motivated team could achieve savings of 50% with conventional technology, but that it was very hard to find a team competent enough to achieve these results.

Other, recent examples that are documented in the published literature include:

- A realized savings of 40% in heating, plus cooling, plus ventilation energy use in a Texas office building through conversion of the ventilation system from one with constant 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-story office building in Athens, where low-energy was achieved through some passive technologies that required the cooperation of the occupants (Balaras, 2001);
- A realized savings of 74% in cooling energy use in a one-story 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 (CADDET, 1997);
- Realized fan, cooling and heating energy savings of 59, 63 and 90% respectively in buildings at a university in Texas; roughly half due to 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).

6.4.13.3 Solar retrofits of residential, institutional and commercial buildings

Solar retrofit performed in Europe under the IEA Solar and Cooling Program achieved savings in space heating of 25–80% (Harvey, 2006, Chapter 14). The retrofit examples described above, while achieving dramatic (35–75%) energy savings, rely on making incremental improvements to the existing building components and systems. More radical measures involve re-configuring the building so that it can make direct use of solar energy for heating, cooling and ventilation. The now-completed Task 20 of the IEA's *Solar Heating and Cooling (SHC)* implementing agreement was devoted to solar retrofitting techniques.

Solar renovation measures that have been used are installation of roof- or façade-integrated solar air collectors; roof-mounted or integrated solar DHW heating; transpired solar air collectors, advanced glazing of balconies, external transparent insulation; and construction of a second-skin façade over the original façade. Case studies are presented in Boonstra and Thijssen (1997), Haller *et al.* (1997) and Voss (2000a), Voss (2000b) and are summarized in Harvey (2006), Chapter 14).

6.4.14 Trade-offs between embodied energy and operating energy

The embodied energy in building materials needs to be considered along with operating energy in order to reduce total lifecycle energy use by buildings. The replacement of materials that require significant amounts of energy to produce (such as concrete and steel) with materials requiring small amounts of energy to produce (such as wood products) will reduce the amount of energy embodied in buildings. Whether this reduces energy use on a lifecycle basis, however, depends on the effect of materials choice on the energy requirements for heating and cooling over the lifetime of the building and whether the materials are recycled at the end of their life (Börjesson and Gustavsson, 2000; Lenzen and Treloar, 2002). For typical standards of building construction, the embodied energy is equivalent to only a few years of operating energy, although there are cases in which the embodied energy can be much higher (Lippke *et al.*, 2004). Thus, over a 50-year time span, reducing the operating energy is normally more important than reducing the embodied energy. However, for traditional buildings in developing countries, the embodied energy can be large compared to the operating energy, as the latter is quite low.

In most circumstances, the choice that minimizes operating energy use also minimizes total lifecycle energy use. In some cases, the high embodied energy in high-performance building envelope elements (such as krypton-filled double- or triple-glazed windows) can be largely offset from savings in the embodied energy of heating and/or cooling equipment (Harvey, 2006, Chapter 3), so a truly holistic approach is needed in analysing the lifecycle energy use of buildings.

6.4.15 Trade-offs involving energy-related emissions and halocarbon emissions

Emissions of halocarbons from building cooling and refrigeration equipment, heat pumps and foam insulation amount to 1.5 $GtCO_2$-eq at present, compared to 8.6 $GtCO_2$ from buildings (including through the use of electricity) (IPCC/TEAP, 2005). Emissions due to these uses are projected only to 2015 and are constant or decline in this period. Halocarbon emissions are thus an important consideration. Issues pertaining to stratospheric ozone and climate are comprehensively reviewed in the recent IPCC/TEAP report (IPCC/TEAP, 2005).

Halocarbons (CFCs, HCFCs and HFCs) are involved as a working fluid in refrigeration equipment (refrigerators, freezers and cold storage facilities for food), heating and cooling of buildings (heat pumps, air conditioners and chillers) and as an blowing agent used in foam insulation for refrigerators, pipes and buildings. All three groups are greenhouse gases. The GWP of HCFCs is generally lower than CFCs. The GWP of HFCs is also generally lower than that of the CFCs, but generally slightly higher than that of the HCFCs. The consumption (production plus imports, minus exports, minus destruction) of CFCs except for critical uses (e.g., medical devices) stopped in 1996 in developed countries, while developing countries have been given to 2010 to eliminate consumption. HCFCs are being phased out, also for reasons of ozone depletion, but will not be completely phased out of production until 2030 in developed countries and 2040 in developing countries. Nevertheless, projected emissions of HCFCs and HFCs (and ongoing emissions from CFC banks) are sufficiently high that scenarios of halocarbon emissions related to buildings in 2015 show almost the same emissions as in 2002 (about 1.5 $GtCO_2$-eq. emissions). For the coming decade or longer, the bank of CFCs in the stock of cooling equipment and foams is so large that particular attention needs to be given to recovering these CFCs.

Lifetime emissions of refrigerants from cooling equipment, expressed as CO_2-eq per unit of cooling, have fallen significantly during the past 30 years. Leakage rates are generally in the order of 3%, but rates as high as 10–15% occur. By 2010, it is expected that HFCs will be the only halocarbon refrigerant to be used in air conditioners and heat pumps manufactured in developed countries. Non-halocarbon refrigerants can entail similar efficiency benefits if the heat pump is fully optimised. Thus, both the performance of the heat pump and the impact of halocarbon emissions need to be considered in evaluating the climatic impact of alternative choices for refrigerants.

The climatic impact of air conditioners and most chillers is generally dominated by the energy used to power them. For leakage of HFC refrigerants at rates of 1 to 6%/yr (IPCC/TEAP, 2005) (best practice is about 0.5%/yr) and recovery of 85% of the refrigerant (compared to 70–100% in typical practice) at the end of a 15-year life, refrigerant leakage accounts for only 1 to 5% of the total impact on climate of the cooling equipment to up to 20%, without end-of-life recovery, of the total impact (derived from (IPCC/TEAP, 2005). This demonstrates the importance of end-of-life recovery, which is highly uncertain for HFCs at present. However, for CFC chillers, the high GWP of the refrigerant and the typical high leakage of older CFC-based designs cause the refrigerant to be a significant factor in overall emissions. This demonstrates that emphasis needs to be put on the replacement of CFC chillers in both developed and developing countries for which hydrocarbons are now widely used in EU countries.

The energy/HFC relationship for air conditioners does not hold for most large built-up refrigeration systems, such as those found in supermarkets and hypermarkets. Roughly half of the total equivalent emissions from these systems result from the refrigerant, in case an HFC blend is used. Various designs explored in IPCC/TEAP report (IPCC/TEAP, 2005) indicate that direct refrigerant emissions can drop from 40–60% of the total emissions in a typical system to 15% for improved systems. The value is 0% for systems using hydrocarbon or ammonia refrigerants. Although some designs may incur a slight increase in energy use, total (energy + refrigerant) emissions are nonetheless significantly reduced.

For foam insulation blown with halocarbons, the benefit of reduced heating energy use can outweigh the effect of leakage of blowing agent when insulating buildings that were previously either poorly insulated or uninsulated (Ashford *et al.*, 2005). However, for high levels of insulation, the opposite becomes true (Harvey, 2007) without end-of-life recovery of the blowing agent. In general terms, the use of methods such as Life Cycle Climate Performance (LCCP) is essential in evaluating the most appropriate course of action in each situation.

6.4.16 Summary of mitigation options in buildings

The key conclusion of section 6.4 is that substantial reductions in CO_2 emissions from energy use in buildings can be achieved over the coming years using existing, mature technologies for energy efficiency that already exist widely and that have been successfully used (*high agreement, much evidence*). There is also a broad array of widely accessible and cost-effective technologies and know-how that can abate GHG emissions in buildings to a significant extent that has not as yet been widely adopted.

Table 6.1 summarizes selected key technological opportunities in buildings for GHG abatement in five world regions based on three criteria. Twenty-one typical technologies were selected from those described in section 6.4. As economic and climatic conditions in regions largely determine the applicability and importance of technologies, countries were divided into three economic classes and two climatic types. The three criteria include the maturity of the technology, cost/effectiveness and appropriateness. Appropriateness includes climatic, technological and cultural applicability. For example, direct evaporative cooling is ranked as highly appropriate in dry and warm climates but it is not appropriate in humid and warm climates. The assessment of some technologies depends on other factors, too. For instance, the heat pump system depends on the energy source and whether it is applied to heating or cooling. In these cases, variable evaluation is indicated in the table.

Table 6.1: *Applicability of energy efficiency technologies in different regions. Selected are illustrative technologies, with an emphasis on advanced systems, the rating of which is different between countries*

Energy efficiency or emission reduction technology	Developing countries						OECD						Economies in transition, Continental			Reference
	Cold climate			Warm climate			Cold climate			Warm climate						
	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	
Structural insulation panels	⬤	⬤	⬤	●	●	•	⬤	●	●	●	●	●	●	⬤	⬤	6.4.2.1
Multiple glazing layers	⬤	⬤	⬤	⬤	●	•[1] ●[2]	~	⬤	⬤	⬤	⬤	●	⬤	⬤	⬤	6.4.2.2
Passive solar heating	⬤	●	●	⬤	●	•	⬤	●	⬤	⬤	●	●	⬤	●	⬤	6.4.3.1
Heat pumps	●[3]	•	•	● ⬤[4]	•[5] ●[6]	•[7] ●[8]	⬤[9]	●	●	~[10] ⬤[11]	●[12] ⬤[13]	●[14] ⬤[15]	⬤[16]	●	●	6.4.3.3 6.4.8
Biomass derived liquid fuel stove	⬤	●	⬤	●	•	•	~	●	⬤	~	●	•	~	⬤	⬤	6.4.3.2
High-reflectivity bldg. materials	•	•	•	●	⬤	●	⬤	●	●	~	●	⬤	⬤	●	●	6.4.4.1
Thermal mass to minimize daytime interior temperature peaks	~	⬤	●	~	⬤	•[17] ⬤[18]	~	⬤	●	~	⬤	•[19] ⬤[20]	~	⬤	⬤	6.4.2
Direct evaporative cooler	•	•	•	~	⬤	•[21] ⬤[22]	•	•	•	~	⬤	•[23] ⬤[24]	•	•	•	6.4.4.2
Solar thermal water heater	~	⬤	⬤	⬤	⬤	⬤	~	⬤	⬤	~	⬤	⬤	~	⬤	⬤	6.4.8
Cogeneration	⬤	●	●	●	•	•	~	●	⬤	~	●	●	⬤	●	⬤	6.4.6
District heating & cooling system	⬤	●	●	•	•	•	~	●	⬤	⬤	●	●	⬤	●	⬤	6.4.6
PV	⬤	●	●	•	•	•	~	●	⬤	⬤	●	●	⬤	●	●	6.4.7.1
Air to air heat exchanger	⬤	●	⬤	⬤	●	⬤	⬤	⬤	⬤	⬤	⬤	⬤	⬤	●	⬤	6.4.5.1
High efficiency lightning (FL)	~	●	⬤	~	●	⬤	μ	•	⬤	μ	•	⬤	⬤	●	⬤	6.4.10
High efficiency lightning (LED)	~	•	⬤	~	•	⬤	•	•	⬤	•	•	⬤	•	●	⬤	6.4.10
HC-based domestic refridgerator	●	●	⬤	●	●	⬤	~	⬤	⬤	⬤	●	•[25] ⬤[26]	⬤	●	⬤	6.4.11
HC or CO_2 air conditioners	•	~	μ	•	~	μ	•	●	●	•	•	μ[27] ●[28]	•	~	●	6.4.4.3
Advance supermarket technologies	•	⬤	⬤	•	⬤	⬤	~	⬤	⬤	●	⬤	⬤	●	⬤	⬤	6.4.12

Table 6.1: *Applicability of energy efficiency technologies in different regions. Selected are illustrative technologies, with an emphasis on advanced systems, the rating of which is different between countries*

Energy efficiency or emission reduction technology	Developing countries						OECD						Economies in transition, Continental			Reference
	Cold climate			Warm climate			Cold climate			Warm climate						
	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	Technology stage	Cost/ effectiveness	Appropri-ateness	
Variable speed drives for pumps and fans	~	●	●	~	●	●	~	●	●	~	●	●	~	●	●	6.4.4.2
Advanced control system based on BEMS	⬤	●	●	⬤	●	●	⬤	●	●	⬤	●	●	⬤	●	●	6.4.6

Notes:
[1] For heat block type; [2] For Low-E; [3] Limited to ground heat source etc.; [4] For air conditioning; [5] For hot water; [6] For cooling; [7] For hot water; [8] For cooling; [9] Limited to ground heat source, etc.; [10] For cooling; [11] For hot water; [12] For hot water; [13] For cooling; [14] For hot water; [15] For cooling; [16] Limited to ground heat source, etc.; [17] In high humidity region; [18] In arid region; [19] In high humidity region; [20] In arid region; [21] In high humidity region; [22] In arid region; [23] In high humidity region; [24] In arid region; [25] United States; [26] South European Union; [27] United States; [28] South European Union.

Evaluation ranks:

Visual representation	Stage of technology	Cost/Effectiveness	Appropriateness
•	Research phase (including laboratory and development) [R]	Expensive/Not effective [$$/-]	Not appropriate {-}
●	Demonstration phase [D]	Expensive/Effective [$$/+]	Appropriate {+}
⬤	Economically feasible under specific conditions [E]	Cheap/Effective [$/+]	Highly appropriate {++}
~	Mature Market (widespread commercially available without specific governmental support) {M]	'~' Not available	'~' Not available
µ	No Mature Market (not necessarily available/not necessarily mature market)		

6.5 Potential for and costs of greenhouse gas mitigation in buildings

The previous sections have demonstrated that there is already a plethora of technological, systemic and management options available in buildings to substantially reduce GHG emissions. This section aims at quantifying the reduction potential these options represent, as well as the costs associated with their implementation.

6.5.1 Recent advances in potential estimations from around the world

Chapter 3 of the TAR (IPCC, 2001) provided an overview of the global GHG emission reduction potential for the residential and commercial sectors, based on the work of IPCC (1996) and Brown *et al.* (1998). An update of this assessment has been conducted for this report, based on a review of 80 recent studies from 36 countries and 11 country groups, spanning all inhabited continents. While the current appraisal concentrates on new results since the TAR, a few older studies were also revisited if no recent study was located to represent a geopolitical region in order to provide more complete global coverage. Table 6.2 reviews the findings of a selection of major studies on CO_2 mitigation potential from various countries around the world that could be characterized in a common framework. Since the studies apply a variety of assumptions and analytical methods, these results should be compared with caution (see the notes for each row, for methodological aspects of such a comparison exercise).

According to Table 6.2, estimates of technical potential range from 18% of baseline CO_2 emissions in Pakistan (Asian Development Bank, 1998) where only a limited number of options were considered, to 54% in 2010[9] in a Greek study (Mirasgedis *et al.*, 2004) that covered a very comprehensive range of measures in the residential sector. The estimates of economic potential[10] vary from 12% in EU-15 in 2010[11] (Joosen and Blok, 2001) to 52% in Ecuador in 2030[12] (FEDEMA, 1999). Estimates of market potential[13] range from 14% in Croatia, focusing on four options only (UNFCCC NC1 of Croatia, 2001), to 37% in the USA, where a wide range of policies were appraised (Koomey *et al.*, 2001).

Our calculations based on the results of the reviewed studies (see Box 6.1) suggest that, globally, approximately 29% of the projected baseline emissions by 2020[14] can be avoided cost-effectively through mitigation measures in the residential and commercial sectors *(high agreement, much evidence*). Additionally at least 3% of baseline emissions can be avoided at costs up to 20 US$/t$CO_2$ and 4% more if costs up to 100 US$/t$CO_2$ are considered. Although due to the large opportunities at low-costs, the high-cost potential has been assessed to a limited extent and thus this figure is an underestimate *(high agreement, much evidence).* These estimates represent a reduction of approximately 3.2, 3.6 and 4.0 billion tonnes of CO_2-eq in 2020, at zero, 20 US$/t$CO_2$ and 100 US$/t$CO_2$, respectively. Due to the limited number of demand-side end-use efficiency options considered by the studies, the omission of non-technological options, the often significant co-benefits, as well as the exclusion of advanced integrated highly efficiency buildings, the real potential is likely to be higher (*high agreement, low evidence*). While occupant behaviour, culture and consumer choice as well as use of technologies are also major determinants of energy consumption in buildings and play a fundamental role in determining CO_2 emissions, the potential reduction through non-technological options is not assessed. These figures are very similar to those reported in the TAR for 2020, indicating the dynamics of GHG reduction opportunities. As previous estimates of additional energy efficiency and GHG reduction potential begin to be captured in a new baseline, they tend to be replaced by the identification of new energy-efficiency and GHG-mitigation options. For comparison with other sectors these potentials have been extrapolated to 2030. The robustness of these figures is significantly lower than those for 2020 due to the lack of research for this year. The extrapolation of the potentials to the year 2030 suggests that, globally, at least 31% of the projected baseline emissions can be mitigated cost-effectively by 2030 in the buildings sector. Additionally at least 4% of baseline emissions can be avoided at costs up to 20 US$/t$CO_2$ and 5% more at costs up to 100 US$/t$CO_2$ (*medium agreement, low evidence*)[15]. This mitigation potential would result in a reduction of approximately 4.5, 5.0 and 5.6 billion tonnes of CO_2-eq at zero, 20 US$/t$CO_2$ and 100 US$/t$CO_2$, respectively, in 2030. Both for 2020 and 2030, low-cost potentials are highest in the building sector from all sectors assessed in this report (see Table 11.3). The outlook to the long-term future assuming options in the building sector with a cost up to 25 US$/t$CO_2$ identifies the potential of approximately 7.7 billion tonnes of CO_2 in 2050 (IEA, 2006d).

The literature on future non-CO_2 emissions and potentials for their mitigation have been recently reviewed in the IPCC/TEAP report (2005). The report identifies that there are opportunities to reduce direct emissions significantly through the global application of best practices and recovery methods, with a reduction potential of about 665 million tonnes of CO_2-eq of

9 If the approx. formula of Potential $_{2020}$ = 1 - (1 - Potential $_{2010}$)$^{20/10}$ is used to extrapolate the potential as percentage of the baseline into the future (2000 is assumed as a start year), this corresponds to approx. 78% CO_2 savings in 2020.

10 In this chapter we refer to 'cost-effective' or 'economic' potential, to remain consistent with the energy-efficiency literature, considering a zero-carbon price.

11 Corresponds to an approx. 22% potential in 2020 if the extrapolation formula is used.

12 Corresponds to an approx. 38% potential in 2020 if the formula is applied to derive the intermediate potential.

13 For definitions of technical, economic, market and enhanced market potential, see Chapter 2 Section 2.4.3.1.

14 The baseline CO_2 emission projections were calculated on the basis of the reviewed studies, and are a composite of business-as-usual and frozen efficiency baseline.

15 These are the average figures of the low and high scenario of the potential developed for 2030.

Table 6.2: *Carbon dioxide emissions reduction potential for residential commercial sectors*

Country/ region	Reference	Type of potential	Description of mitigation scenarios	Potential: Million tCO_2	Potential: Baseline (%)	Measures with lowest costs	Measures with highest potential	Notes
Case studies providing information for demand-side measures								
EU-15	Joosen and Blok, 2001	Technical	25 options: retrofit (insulation); heating systems; new zero & low energy buildings, lights, office equipment & appliances; solar and geo-thermal heat production; BEMS for electricity, space heating and cooling.	310	21%	1. Efficient TV and peripheries; 2. Efficient refrigerators & freezers; 3. Lighting Best Practice.	1.Retrofit: insulated windows; 2.Retrofit: wall insulation; 3.BEMS for space heating and cooling.	[1].4%; [4].Fr-ef.; [5].TY 2010.
		Economic		175	12%			
Canada	Jaccard and Associates, 2002	Market	Mainly fuel switch in water and space heating, hot water efficiency and the multi-residential retrofit program in households; landfill gas, building shell efficiency actions and fuel switch in commerce.	22	24%	n.a. (not listed in the study)	1.Electricity demand reductions; 2.Commercial landfill gas; 3.Furnaces & shell improvements.	[1].10%; [5].TY 2010.
Greece	Mirasgedis et al., 2004	Technical	14 technological options: fuel switch, controls, insulation, lights, air conditioning and others.	13	54%	1. Replacement of central boilers; 2. Use of roof ventilators; 3. Replacement of AC.	1.Shell, esp. insulation; 2.Lighting & water heating; 3.Space heating systems.	[1].6%; [4].Fr-ef; [5]. TY 2010; [7]. R only.
		Economic		6	25%			
UK	DEFRA, 2006	Technical	41 options: insulation; low-e double glazing windows; various appliances; heating controls; better IT equipment, more efficient motors, shift to CFLs, BEMS, etc.	46	24% (res. only)	1. Efficient fridge/ freezers; 2. Efficient chest freezers; 3. Efficient dishwashers.	1.Efficient gas boilers; 2.Cavity insulation; 3.Loft insulation.	[1].7-5%: R/C; [4].BL: Johnston et al., 2005; [5].BY 2005.
Australia	Australian Greenhouse Office, 2005	Market	Fridges and other appliances, air conditioners, water heating, swimming pool equipment, chillers, ballasts, standards, greenlight Australia plan, refrigerated cabinets, water dispensers, standby.	18	15%	1.Standby programs; 2.MEPS for appliances 1999; 3.TVs on-mode.	1.Packaged air-conditioners; 2.Ballast program in 2003; 3.Fluorescent bulbs.	[1].5%; [4]. BL: scenario without measures; [5].BY 2005.
Estonia	Kallaste et al., 1999	Market	4 insulation measures: 3d window glass, new insulation into houses, renovation of roofs, additional attic insulation.	0.4	2.5% of nation. emis.	1. New insulation; 2. Attic insulation; 3. 3d window glass.	1.New insulation; 2.3d window glass; 3.Attic insulation.	[1].6%; [5]. BY 1995; TY 2025.
China	ERI, 2004	Enhanced market	Key policies: energy conservation standards, heat price reform, standards & labelling for appliances, energy efficiency projects, etc.	422	23%	n.a. (not listed in the study)	n.a. (not listed in the study)	[1].N.a.
New EU Member States[a)]	Petersdorff et al., 2005	Technical	Building envelope esp. insulation of walls, roofs, cellar/ground floor, windows with lower U-value; and renewal of energy supply.	62	-	1. Roof insulation; 2. Wall insulation; 3. Floor Insulation.	1. Window replacement; 2. Wall insulation; 3. Roof insulation.	[1] 6%; [4] Fr-ef; [5] BY 2006; TY 2015.
Hungary	Szlavik et al., 1999	Technical	25 technological options and measures: building envelope, space heating, hot water supply, ventilation, awareness, lighting, appliances.	22	45%	1. Individual metering of hot water; 2. Water flow controllers; 3. Retrofitted windows.	1. Post insulation; 2. Retrofit of windows; 3. Replacement of windows.	[1] 3%; [5] TY 2030.
		Economic		15	31%			
Myanmar	Asian Development Bank, 1998	Economic	5 options: shift to CFLs, switch to efficient biomass and LPG cooking stoves, improved kerosene lamps, efficient air conditioners.	3	N.a.	1. Biomass cooking stoves, 2. Kerosene lamps, 3. CFLs.	1. Biomass cooking stoves, 2. LPG cooking stoves, 3. CFLs.	[1] 10%.

Table 6.2. *Continued.*

Country/ region	Reference	Type of potential	Description of mitigation scenarios	Potential		Measures with lowest costs	Measures with highest potential	Notes
				Million tCO_2	Baseline (%)			
India	Reddy and Balachandra, 2006	Market	Lighting: mixture of incandescents, fluorescent tubes and CFLs, exchange of traditional kerosene and wood stoves and water heaters for efficient equipment.	17	33%	1. Efficient packages of lighting; 2. Kerosene stoves; 3. Wood stoves.	1. Wood stoves, 2. Efficient packages of lighting; 3. Kerosene stoves.	[1] n.a.; [5] TY 2010; [7] R only.
Republic of Korea	Asian Development Bank, 1998	Economic	7 options: heating - condensing gas boilers, solar hot water systems, insulation standards; cooling - air conditioners; improved lights - shift to fluorescents and CFLs; efficient motors and inverters.	20	17%	1. Heating: gas boilers, solar hot water, insulation standards; 2. Air conditioners; 3. Inverters & motors.	1. Improved lights; 2. Motors & inverters; 3. Gas boiler RES, solar hot water system, insulation standards.	[1] 8.5%; [5] BY1998.
Ecuador	FEDEMA, 1999	Economic	6 main options: improvements of appliances, lighting systems, electricity end-uses esp. in rural areas and in the services, solar water heating, public lighting.	7	52%	1. Lights; 2. Electric appliances (esp. rural areas); 3. Electricity end-use in services.	1. Improved electricity end-uses in rural areas; 2. Electric appliances (esp. in rural areas); 3. Light systems.	[1] 10%; [5] TY 2030.
Thailand	Asian Development Bank, 1998	Technical	3 technological programs: lighting (shift to fluorescents), refrigerator (insulation and compressors) and air-conditioning.	15	31%	1. Lighting, 2. Efficient refrigerators, 3. Air conditioning.	1. Efficient air-conditioning, 2. Efficient refrigerators, 3 Lighting.	[1] 10%; [5] BY 1997; [7] R only.
		Economic		6.1	13%			
Pakistan	Asian Development Bank, 1998	Technical	Energy efficiency improvements of electric appliances and other end-use devices such as lights, fans, refrigerators, water heaters and improvement of building design.	7	18%	1. Improved lights, 2. Efficient ceiling fans, 3. More efficient refrigerators.	1. Efficient ceiling fans, 2. Improved lights, 3. Improved building design.	[1] 8%; [5] BY 1998.
		Economic		6	16%			
Indonesia	AIM, 2004	Technical	9 Main technological options: energy efficient appliances such as refrigerator and air conditioners, lights (shift from incandescents to fluorescents), kerosene, electricity and gas water heater, kerosene and gas heater, wall and window insulation and others.	13.5	25%	Efficient refrigerator, electricity and gas water heater, kerosene and gas heater, lights, air-conditioners (not ranked).	1. Efficient refrigerators, 2. Fluorescent lamps, 3. Efficient electric water heater (ranking at negative marginal cost).	[1] 5%; [2] Integrated Assessment; [4] Fr-ef.; [7] R only.
		Economic		10.2	19%			
Argentina	AIM, 2004	Technical		3.8	22%			
		Economic		3.3	19%			
Brazil	AIM, 2004	Technical		5.4	41%			
		Economic		4.8	36%			
Poland	Gaj and Sadowski, 1997	Technical	13 options: lights in streets, commerce & households, gas boiler controls, appliances, heat meters, thermal insulation for walls and roofs, window tightening & replacement, fuel switch from coal to gas, solar or biomass, DH boilers.	43	26%	1. Efficient street lighting; 2. Improved controls of small gas boilers; 3. Efficient lighting in commerce.	1. Insulation of walls, 2. Improvement of home appliances, 3. Fuel switching from coal to gas, solar and biomass.	[1] n.a.; [4] BL: UNFCCC NC3 of Poland, 2001.
		Economic		30	18%			
Russia	Izrael et al., 1999	Technical	Downsized thermal generators (boilers and heaters), thermal insulation (improved panels, doors, balconies, windows), heat and hot water meters and controls, hot water distribution devices, electric appliances.	182	47%	n.a. (not listed in the study)	n.a. (not listed in the study)	[1] n.a.; [4] BL: UNFCCC NC3 of Russia, 2002; PNNL & CENEf, 2004; [5] TY 2010.
		Economic		52	13%			

Table 6.2. *Continued.*

Country/ region	Reference	Type of potential	Description of mitigation scenarios	Potential		Measures with lowest costs	Measures with highest potential	Notes
				Million tCO_2	Baseline (%)			
South Africa	De Villiers and Matibe, 2000	Technical	21 options: light practices; new & retrofits HVAC; stoves, thermal envelope; fuel switch in heaters; standards & labelling; for hot water: improved insulation, heat pumps, efficient use; solar heating.	41	23%	1. Energy star equipment; 2. Lighting retrofit; 3. New lighting systems.	1. Hybrid solar water heaters; 2. New building thermal design; 3. New HVAC systems.	[1] 6%; [4] Fr-ef.; [5] BY 2001; TY 2030.
	De Villiers, 2000	Economic		37	20%			
Croatia	UNFCCC NC1 of Croatia, 2001	Market	Electricity savings for not heating purposes (low energy bulbs, more efficient appliances, improved motors), solar energy use increase, thermal insulation improvement.	2	14%	1. Bulbs & appliances; 2. Solar energy use increase; 3. Insulation improvement	1. Insulation improvement; 2. Solar energy use increase; 3. Bulbs & appliances.	[1] n.a.
Studies providing information about both supply and demand-side options not separating them								
New EU Member States a)	Lechtenbohmer et al., 2005	Economic	Improvement in space and water heating, appliances and lighting, cooling/freezing, air-conditioning, cooking, motors, process heat, renewable energies, reduced emissions from electricity generation.	81	37%	n.a. (not listed in the study)	R: 1.Insulation; 2.Heating systems, fuel switch, DH&CHP; C: 1. Energy efficiency, 2. Renewables.	[1] 3-5%; [5] BY 2005; [7] C includes agriculture.
USA	Koomey et al., 2001	Market	Voluntary labelling, deployment programmes, building codes, new efficiency standards, government procurement, implementation of tax credits, expansion of cost-shared federal R&D expenditures.	898	37%	n.a. (The study did not examine a GHG potential supply cost curve).	1. Lighting; 2. Space cooling; 3.Space heating.	[1] 7%; [5] BY 1997.
Japan	Murakami et al., 2006	Technical	15 options: new and retrofit insulation, double glazing window, home appliances (water & space heating/cooling, lighting, cooking), PVs, solar heating, shift to energy efficient living style, low-carbon electricity generation.	46	28%	n.a. (not listed in the study)	1. Water heater; 2. Space heater; 3. Home appliances.	[1] n.a.; [7] R only.
Germany	Martinsen et al., 2002	Technical	Two options: fuel switch from coal and oil to natural gas and biomass and heat insulation.	31	26%	n.a. (not listed in the study)	1.Heat insulation; 2.Fuel switch from coal & oil to gas & biomass.	[1] n.a.; [5] BY 2002; [7] R only.

Notes specify those parameters which are different from those identified below (the number of a note is the number of the model parameter):
a) Hungary, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Poland and the Czech Republic
1. Discount Rate (DR) belongs to the interval [3%; 10%]. 2. Most models are Bottom-up (BU). 3. All models consider CO_2. If a study considered GHGs, CO_2 only was analysed, if the study assessed C, potential was converted into CO_2. 4. Baseline (BL) is Business-as-Usual Scenario (BAU) or similar (Frozen efficiency scenario is abbreviated as fr-ef). 5. Base year (BY) is 2000; Target year (TY) is 2020. 6. Costs covered: cost of incremental reduction, abatement costs, costs of avoided or saved or mitigated CO_2, marginal costs. 7. Estimations are made for Residential (R) and commercial (C) sectors in sum.

Box 6.1: Methodology for the global assessment of potentials and costs of CO_2 mitigation in buildings

This chapter evaluated the potential for GHG mitigation in buildings and associated costs based on the review of existing national and regional potential estimates. For this purpose, over 80 studies containing bottom-up mitigation potential estimates for buildings were identified from 36 countries and 11 country groups covering all inhabited continents. One study (AIM, 2004) covered the entire planet, but it was not suitable for the purposes of this report, as it assessed a very limited number of mitigation options.

To allow the comparison of studies in a common framework, their main results and related assumptions were processed and inserted into a database containing the key characteristics of the methods used and results. To eliminate the major effects of different methodological assumptions, only those studies were selected for further analysis whose assumptions fell into a range of common criteria. For instance, studies were only used for further assessment if their discount rates fell in the interval of 3–10%. For studies which did not report their baseline projections, these were taken from the latest available National Communications to the UNFCCC, or other recent related reports.

Table 6.2 presents the results of a selection of major mitigation studies meeting such criteria for different parts of the world. For definitions of various mitigation potentials see Chapter 2, Section 2.4.3.1.

The next step was to aggregate the results into global and regional potential estimates, as a function of CO_2 costs. Only three studies covered a 2030 target year and they were for countries with insignificant global emissions, thus this was only possible for 2020 in the first iteration. Since few studies reported potentials as a function of cost (typically only technical/economic or market potentials were reported), only 17 studies from the remaining subset meeting our other selection criteria could be used. IPCC SRES or WEO scenarios could not be used as a baseline because little information is available for these on the technology assumptions in buildings. In order to make sure the potentials are entirely consistent with the baseline, an average baseline was created from the studies used for the global potential estimates. For the global potential estimates and the baseline construction, the world was split into seven regions[16]. For each such region, two to four studies were located, thus dividing each region into two to four sub-regions represented by these marker countries in terms of emission growth rates and potential as a percentage of baseline. CO_2 baseline emissions in the seven regions were estimated starting with 2000 IPCC A1B and B2 (SRES) data and applying the CO_2 growth rates calculated for each region as the population weighted average CO_2 baseline growth rates of two to four sub-regions. The baseline projections were estimated for 2000–2020 based on mainly 2020 data from the studies; these trends were prolonged for the period 2020–2030. Since three of the seventeen studies used a frozen efficiency baseline, the baseline used in this chapter can be considered a business-as-usual one with some frozen efficiency elements. The resulting baseline is higher than the B2 (SRES) scenario but lower than A1B (SRES) and WEO scenarios.

Analogously, CO_2 potentials as a percentage of the baseline in cost categories (US\$/tCO_2: (<0); (0;20); (20;100)) were calculated based on population weighted average potentials in the sub-regions for each cost category .While the three studies using a frozen efficiency baseline result in a relatively higher potential than in studies using a BAU baseline, this does not compromise the validity of the global potential, since for the regions applying a frozen efficiency baseline, the latter baseline was used in calculating the global total. The results of these estimates are presented in Table 6.3.

As mentioned above, only three studies covered the baseline or mitigation potential for 2030. Therefore these figures were derived by extrapolating the 2020 figures to 2030. Since the simple exponential formula used for such extrapolations by other sectors was found to yield disputably high or low results in some cases, a modified exponential function was used which allows regulating the maximum potential considered theoretically achievable for different regions[17]. The results of the projections are presented in Table 6.4

16 OECD North America, OECD Pacific, Western Europe, Transition Economies, Latin America, Africa and Middle East, and Asia

17 $X(t) = X_{saturation} - C e^{-kt}$ (reached from the differential equation: $dx/dt = k (X_{saturation} - x)$), saturation illustrates that the closer potential is to this upper limit, the lower potential growth rate is experienced, and the potential does not exceed the maximum judged reasonable. C can be found from the starting conditions (in year 2000); thus if we know the potential in 2020, then:

$$X_{2030} = X_{saturation} \left(1 - EXP \frac{30}{20} LN \left(1 - \frac{X_{2020}}{X_{saturation}}\right)\right)$$

direct emissions in 2015, as compared to the BAU scenario. About 40% of this potential is attributed to HFC emission reduction covered by the Kyoto Protocol to the UNFCCC, while HCFCs and CFCs regulated by the Montreal Protocol contribute about 60% of the potential. A key factor determining whether this potential will be realized is the costs associated with the implementation of the measures to achieve the emission reduction. These vary considerably from a net benefit to 300 US$/t$CO_2$-eq. Refrigeration applications and stationary and mobile air conditioning contribute most to global direct GHG emissions. Action in these sub-sectors could therefore have a substantial influence on future emissions of HCFCs and HFCs. The available literature does not contain reliable estimates for non-CO_2 mitigation potentials in the long-term future, including the year 2030. Therefore, the 2015 figures can serve as low estimates of the potentials in 2030, taking into account that upcoming progressive policies in many countries have already led to new products with very low non-CO_2 emissions as compared to their previous analogues.

6.5.2 Recent advances in estimating the costs of GHG mitigation in buildings

Table 6.3 below and Table 6.4 provide information on the GHG abatement potentials in buildings as a function of costs and world regions for 2020 (Table 6.3) and for 2030 (Table 6.4). These demonstrate that the majority of measures for CO_2 abatement in buildings are cost-effective. The table also demonstrates that measures to save electricity in buildings typically offer larger and cheaper options to abate CO_2 emissions than measures related to fuel savings. This is especially true for developing countries located in warmer regions, which have less need for space and water heating.

6.5.3 Supply curves of conserved carbon dioxide

CO_2 conservation supply curves relate the quantity of CO_2 emissions that can be reduced by certain technological or other measures to the cost per unit CO_2 savings (Sathaye and Meyers,

Table 6.3: *CO_2 mitigation potential projections in 2020 as a function of CO_2 cost*

World regions	Baseline emissions in 2020 (GtCO_2-eq)	CO_2 mitigation potentials as share of the baseline CO_2 emission projections in cost categories in 2020 (costs in US$/t$CO_2$-eq)				CO_2 mitigation potentials in absolute values in cost categories in 2020, GtCO_2 (costs in US$/t$CO_2$-eq)			
		<0	0-20	20-100	<100	<0	0-20	20-100	<100
Globe	11.1	29%	3%	4%	36%	3.2	0.35	0.45	4.0
OECD (-EIT)	4.8	27%	3%	2%	32%	1.3	0.10	0.10	1.6
EIT	1.3	29%	12%	23%	64%	0.4	0.15	0.30	0.85
Non-OECD	5.0	30%	2%	1%	32%	1.5	0.10	0.05	1.6

Table 6.4: *Extrapolated CO_2 mitigation potential in 2030 as a function of CO_2 cost, GtCO_2*

Mitigation option	Region	Baseline projections in 2030	Potential at costs at below 100 US$/t$CO_2$-eq		Potential in different cost categories		
					<0 US$/t$CO_2$	0-20 US$/t$CO_2$	20-100 US$/t$CO_2$
			Low	High	<0 US$/tC	0-73 US$/tC	73-367 US$/tC
Electricity savings[a]	OECD	3.4	0.75	0.95	0.85	0.0	0.0
	EIT	0.4	0.15	0.20	0.20	0.0	0.0
	Non-OECD/ EIT	4.5	1.7	2.4	1.9	0.1	0.1
Fuel savings	OECD	2.0	1.0	1.2	0.85	0.2	0.1
	EIT	1.0	0.55	0.85	0.20	0.2	0.3
	Non-OECD/ EIT	3.0	0.70	0.80	0.65	0.1	0.0
Total	OECD	5.4	1.8	2.2	1.7	0.2	0.1
	EIT	1.4	0.70	1.1	0.40	0.2	0.3
	Non-OECD/ EIT	7.5	2.4	3.2	2.5	0.1	0.0
	Global	14.3	4.8	6.4	4.5	0.5	0.7

Note: a) The absolute values of the potentials resulting from electricity savings in Table 6.4 and Table 11.3 do not coincide due to application of different baselines. Table 6.4 uses the baseline constructed on the basis of the reviewed studies while Table 11.3 applies WEO 2004 baseline (IEA, 2004e) to calculate CO_2 emission reductions from electricity savings. The potential estimates as a percentage of the baseline are the same in both cases. Also Table 11.3 excludes the share of emission reductions which is already taken into account by the energy supply sector, while Table 6.4 does not separate this potential.

1995). The measures, or packages of measures, are considered in order of growing marginal CO_2 abatement cost, therefore forming a 'supply curve' for the commodity of CO_2 reduction.

Figure 6.4 depicts the potentials for CO_2 abatement as a function of costs for eight selected recent detailed studies from different world regions. The steepness of the curves, that is the rate at which the costs of the measures increase as more of the potential is captured, varies substantially by country and by study. While the shape of each supply curve is profoundly influenced by the underlying assumptions and methods used in the study, the figure attests that opportunities for cost-effective and low-cost CO_2 mitigation in buildings are abundant in each world region. All eight studies covered here identified measures at negative costs. The supply curves of developing countries and economies in transition are characterized by a flat slope and lie, in general, lower than the curves of developed countries. The flat slope justifies the general perception (for instance, which provided the main rationale for the Kyoto Flexibility Mechanisms) that there is a higher abundance of 'low-hanging fruit' in these countries. More concretely, the net costs of GHG mitigation in buildings in these countries do not grow rapidly even over 30–50% of emissions reductions. For developed countries, the baseline scenario assumes that many of the low-cost opportunities are already captured due to progressive policies in place or in the pipeline.

6.5.4 Most attractive measures in buildings

From a policy-design perspective, it is important to understand which technologies/end-uses entail the lowest unit abatement costs for society, as well as which ones offer the largest abatement potential. This section reviews the most attractive mitigation options in terms of overall potential. Both Table 6.4 and Table 11.3 in Chapter 11 demonstrate that CO_2-saving options are largest from fuel use in developed countries and countries in transition due to their more northern locations and, thus, larger potential for heat-saving measures. Conversely, electricity savings constitute the largest potential in developing countries located in the south, where the majority of emissions in the buildings sector are associated with appliances and cooling. This distribution of the potential also explains the difference in mitigation costs between developing and developed countries. The shift to more efficient appliances quickly pays back, while building shell retrofits and fuel switching, together providing approximately half of the potential in developed countries, are more expensive.

While it is impossible to draw universal conclusions regarding individual measures and end-uses, Table 6.2 attests that efficient lighting technologies are among the most promising measures in buildings, in terms of both cost-effectiveness and size of potential savings in almost all countries. The IEA

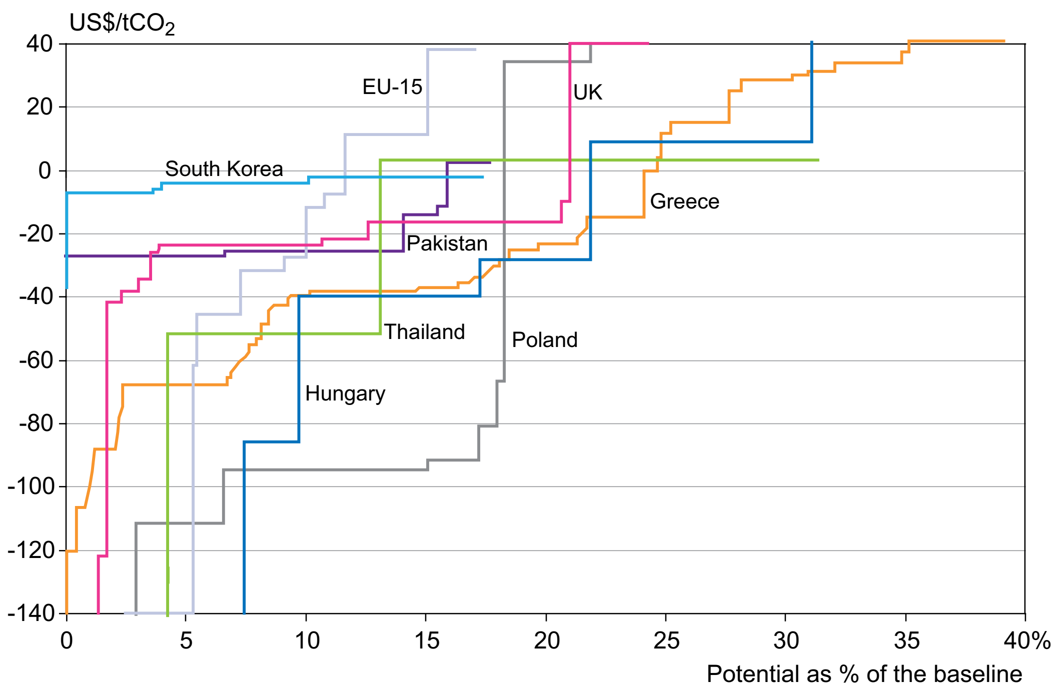

Figure 6.4: *Supply curves of conserved CO2 for commercial and residential sector[a] in 2020[b] for different world regions*

Notes:
a) Except for the UK, Thailand and Greece, for which the supply curves are for the residential sector only.
b) Except for EU-15 and Greece, for which the target year is 2010 and Hungary, for which the target year is 2030. Each step on the curve represents a type of measure, such as improved lighting or added insulation. The length of a step on the 'X' axis shows the abatement potential represented by the measure, while the cost of the measure is indicated by the value of the step on the 'Y' axis.

Sources for data: Joosen and Blok, 2001; Asian Development Bank, 1998; De Villiers and Matibe, 2000; De Villiers, 2000; Szlavik et al., 1999; DEFRA, 2006; Mirasgedis et al., 2004; Gaj and Sadowski, 1997.

(2006b) estimates that by 2020, approximately 760 Mt of CO_2 emissions can be abated by the adoption of least life-cycle cost lighting systems globally, at an average cost of US$–161/t$CO_2$. In developing countries, efficient cooking stoves rank second, while the second-place measures differ in the industrialized countries by climatic and geographic region. Almost all studies examining economies in transition (typically in cooler climates) have found heating-related measures to be most cost-effective, including insulation of walls, roofs, windows and floors, as well as improved heating controls for district heat. In developed countries, appliance-related measures are typically identified as the most cost-effective, with cooling-related equipment upgrades ranking high in the warmer climates.

In terms of the size of savings, improved insulation and district heating in the colder climates and efficiency measures related to space conditioning in the warmer climates come first in almost all studies,18 along with cooking stoves in developing countries. Other measures that rank high in terms of savings potential are solar water heating, efficient lighting and efficient appliances, as well as building energy management systems.

6.5.5 Energy and cost savings through use of the Integrated Design Process (IDP)

Despite the usefulness of supply curves for policy-making, the methods used to create them rarely consider buildings as integrated systems; instead, they focus on the energy savings potential of incremental improvements to individual energy-using devices. As demonstrated in the first part of this chapter, integrated building design not only can generate savings that are greater than achievable through individual measures, but can also improve cost-effectiveness. This suggests that studies relying solely on component estimates may underestimate the abatement potential or overestimate the costs, compared with a systems approach to building energy efficiency. Recent published analyses show that, with an integrated approach, (i) the cost of saving energy can go down as the amount of energy saved goes up, and (ii) highly energy-efficient buildings can cost less than buildings built according to standard practice (Harvey, 2006; Chapter 13).

6.6 Co-benefits of GHG mitigation in the residential and commercial sectors

Co-benefits of mitigation policies should be an important decision element for decision-makers in both the residential and commercial sectors. Although these co-benefits are often not quantified, monetized, or perhaps even identified by the decision-makers or economic modellers (Jochem and Madlener, 2003), they can still play a crucial role in making GHG emissions mitigation a higher priority. This is especially true in less economically advanced countries, where environmentalism – and climate change specifically – may not have a strong tradition or a priority role in either the policy agenda or the daily concerns of citizens. In these circumstances, every opportunity for policy integration can be of value in order to reach climate change mitigation goals.

6.6.1 Reduction in local/regional air pollution

Climate mitigation through energy efficiency in the residential and commercial sectors will improve local and regional air quality, particularly in large cities, contributing to improved public health (e.g., increased life expectancy, reduced emergency room visits, reduced asthma attacks, fewer lost working days) and avoidance of structural damage to buildings and public works. As an example in China, replacement of residential coal burning by large boiler houses providing district heating is among the abatement options providing the largest net benefit per tonne of CO_2 reduction, when the health benefits from improved ambient air conditions are accounted for (Mestl *et al.*, 2005). A study in Greece (Mirasgedis *et al.*, 2004) found that the economic GHG emissions abatement potential in the residential sector could be increased by almost 80% if the co-benefits from improved air quality are taken into account. Beyond the general synergies between improved air quality and climate change mitigation described in Chapter 11 (see Section 11.8.1), some of the most important co-benefits in the households of developing countries are due to reduced indoor air pollution through certain mitigation measures, discussed in sections 6.6.2 and 6.1.1.

6.6.2 Improved health, quality of life and comfort

In the least developed countries, one of the most important opportunities for achieving GHG mitigation as well as sustainable development in buildings is to focus on the health-related benefits of clean domestic energy services, including safe cooking. Indoor air pollution is a key environmental and public health peril for countless of the world's poorest, most vulnerable people. Approximately three billion people worldwide rely on biomass (wood, charcoal, crop residues and dung) and coal to meet their household cooking and heating energy needs (ITDG, 2002). Smoke from burning these fuels contributes to acute respiratory infections in young children and chronic obstructive pulmonary disease in adults. These health problems are responsible for nearly all of the 2.2 million deaths attributable to indoor air pollution each year, over 98% of which are in developing countries (Gopalan and Saksena, 1999; Smith *et al.*, 2004), (See Box 6.2). In addition, women and children also bear the brunt of the work of collecting biomass fuel. Clean-burning cooking stoves not only save substantial amounts of GHG emissions, but also prevent many of these

18 Note that several studies covered only electricity-related measures, and thus excluded some heating options.

Box 6.2: Traditional biomass-based cooking has severe health effects

In South Africa, children living in homes with wood stoves are almost five times more likely than others to develop respiratory infections severe enough to require hospitalization. In Tanzania, children younger than five years who die of acute respiratory infection are three times more likely than healthy children to have been sleeping in a room with an open cooking stove. In the Gambia, children carried on their mothers' backs as the mothers cook over smoky stoves contract pneumonia at a rate 2.5 times higher than unexposed children. In Colombia, women exposed to smoke during cooking are over three times more likely than others to suffer from chronic lung disease. In Mexico, urban women who use coal for cooking and heating over many years are subject to a risk of lung cancer two to six times higher than women who use gas. Rural coal smoke exposure can increase lung cancer risks by a factor of nine or more. In India, smoke exposure has been associated with a 50% increase in stillbirths.

Cleaner-burning improved cooking stoves (ICS), outlined in the previous sections of this chapter, help address many of the problems associated with traditional cooking methods. The benefits derived from ICS are: 1) reduced health risks for women and children due to improved indoor air quality; 2) reduced risks associated with fuel collection; 3) cost-effective and efficient energy use, which eases the pressure on the natural biomass resource; 4) a reduction in the amount of money spent on fuel in urban areas; and 5) a reduction in fuel collection and cooking time, which translates into an increase in time available for other economic and developmental activities.

Source: UN, 2002

health problems and provide many other benefits identified in Box 6.2.

In developed countries, the diffusion of new technologies for energy use and/or savings in residential and commercial buildings contributes to an improved quality of life and increases the value of buildings. Jakob (2006) lists examples of this type of co-benefit, such as improved thermal comfort (fewer cold surfaces such as windows) and the substantially reduced level of outdoor noise infiltration in residential or commercial buildings due to triple-glazed windows or high-performance wall and roof insulation. At noisy locations, an improvement of 10–15 dB could result in gross economic benefits up to the amount of 3–7% of the rental income from a building (Jakob, 2006). Lastly, better-insulated buildings eliminate moisture problems associated with, for example, thermal bridges and damp basements and thus reduce the risk of mould build-up and associated health risks.

6.6.3 Improved productivity

There is increasing evidence that well-designed, energy efficient buildings often have the co-benefits of improving occupant productivity and health (Leaman and Bordass, 1999; Fisk, 2000; Fisk, 2002). Assessing these productivity gains is difficult (CIBSE (The Chartered Institution of Building Services Engineers), 1999) but in a study of 16 buildings in the UK, occupants estimated that their productivity was influenced by the environment by between –10% and +11% (Leaman and Bordass, 1999).

The implementation of new technologies for GHG emissions mitigation achieves substantial learning and economies of scale, resulting in cost reductions. Jacob and Madlener (2004) analyzed the technological progress and marginal cost developments for energy efficiency measures related to the building envelope using data for the time period 1975 to 2001 in Switzerland. The analysis yields technical progress factors of around 3% per annum for wall insulation and 3.3% per annum for double glazing windows, while real prices decreases of 0.6% since 1985 for facades and 25% over the last 30 years for double glazing windows (Jacob and Madlener, 2004).

6.6.4 Employment creation and new business opportunities

Most studies agree that energy-efficiency investments will have positive effects on employment, directly by creating new business opportunities and indirectly through the economic multiplier effects of spending the money saved on energy costs in other ways (Laitner et al., 1998; Jochem and Madlener, 2003). Providing energy-efficiency services has proven to be a lucrative business opportunity. Experts estimate a market opportunity of € 5–10 billion in energy service markets in Europe (Butson, 1998). The data on energy service company (ESCO) industry revenues in Section 6.8.3.5 demonstrates that the energy services business appears to be both a very promising and a quickly growing business sector worldwide. The European Commission (2005) estimates that a 20% reduction in EU energy consumption by 2020 can potentially create (directly or indirectly) as many as one million new jobs in Europe, especially in the area of semi-skilled labour in the buildings trades (Jeeninga et al., 1999; European Commission, 2003).

6.6.5 Improved social welfare and poverty alleviation

Improving residential energy efficiency helps households cope with the burden of paying utility bills and helps them afford adequate energy services. One study estimated that an average EU household could save € 200–1000 (US$ 248–1240) in utility costs through cost-effective improvements in energy efficiency (European Commission, 2005). Reducing the economic burden of utility bills is an important co-benefit of energy efficiency for less affluent households. This is especially true in former communist countries and others (e.g., in Asia and Latin America) where energy subsidies have been removed and energy expenditures are a major burden for much of the population (Ürge-Vorsatz *et al*., 2006). In economies in transition, this situation provides an opportunity to redirect those social programmes aimed at compensating for increasing energy costs towards energy-efficiency efforts. In this way resources can be invested in long-term bill reduction through energy efficiency instead of one-time subsidies to help pay current utility bills (Ürge-Vorsatz and Miladinova, 2005).

Fuel poverty, or the inability to afford basic energy services to meet minimal needs or comfort standards, is also found in even the wealthiest countries. In the UK in 1996, about 20% of all households were estimated to live in fuel poverty. The number of annual excess winter deaths, estimated by the UK Department of Health at around 30 thousand annually between 1997 and 2005, can largely be attributed to inadequate heating (Boardman, 1991; DoH (UK Department of Health), 2000). Improving energy efficiency in these homes is a major component of strategies to eradicate fuel poverty.

In developing countries, energy-efficient household equipment and low-energy building design can contribute to poverty alleviation through minimizing energy expenditures, therefore making more energy services affordable for low-income households (Goldemberg, 2000). Clean and efficient utilization of locally available renewable energy sources reduces or replaces the need for energy and fuel purchases, increasing the access to energy services. Therefore, sustainable development strategies aimed at improving social welfare go hand-in-hand with energy efficiency and renewable energy development.

6.6.6 Energy security

Additional co-benefits of building-level GHG mitigation include improved energy security and system reliability (IEA, 2004f), discussed in more detail in Chapter 4. Improving end-use energy efficiency is among the top priorities on the European Commission's agenda to increase energy security, with the recognition that energy efficiency is likely to generate additional macro-economic benefits because reduced energy imports will improve the trade balances of importing countries (European Commission, 2003).

6.6.7 Summary of co-benefits

In summary, investments in residential and commercial building energy efficiency and renewable energy technologies can yield a wide spectrum of benefits well beyond the value of saved energy and reduced GHG emissions. Several climate mitigation studies focusing on the buildings sector maintain that, if co-benefits of the various mitigation options are included in the economic analysis, their economic attractiveness may increase considerably – along with their priority levels in the view of decision-makers (Jakob *et al.*, 2002; Mirasgedis *et al.*, 2004; Banfi *et al.*, 2006). Strategic alliances with other policy fields, such as employment, competitiveness, health, environment, social welfare, poverty alleviation and energy security, can provide broader societal support for climate change mitigation goals and may improve the economics of climate mitigation efforts substantially through sharing the costs or enhancing the dividends (European Commission, 2005). In developing countries, residential and commercial-sector energy efficiency and modern technologies to utilize locally available renewable energy forms, can form essential components of sustainable development strategies.

6.7 Barriers to adopting building technologies and practices that reduce GHG emissions

The previous sections have shown the significant cost-effective potential for CO_2 mitigation through energy efficiency in buildings. The question often arises: If these represent profitable investment opportunities, or energy cost savings foregone by households and businesses, why are these opportunities not pursued? If there are profits to be made, why do markets not capture these potentials?

Certain characteristics of markets, technologies and end-users can inhibit rational, energy-saving choices in building design, construction and operation, as well as in the purchase and use of appliances. The Carbon Trust (2005) suggests a classification of these barriers into four main categories: financial costs/benefits; hidden costs/benefits; real market failures; and behavioural/organizational non-optimalities. Table 6.5 gives characteristic examples of barriers that fall into these four main categories. The most important among them that pertain to buildings are discussed below in further detail.

6.7.1 Limitations of the traditional building design process and fragmented market structure

One of the most significant barriers to energy-efficient building design is that buildings are complex systems. While the typical design process is linear and sequential, minimizing energy use requires optimizing the system as a whole by systematically addressing building form, orientation, envelope,

Table 6.5: *Taxonomy of barriers that hinder the penetration of energy efficient technologies/practices in the buildings sector*

Barrier categories	Definition	Examples
Financial costs/ benefits	Ratio of investment cost to value of energy savings	Higher up-front costs for more efficient equipment Lack of access to financing Energy subsidies Lack of internalization of environmental, health and other external costs
Hidden costs/benefits	Cost or risks (real or perceived) that are not captured directly in financial flows	Costs and risks due to potential incompatibilities, performance risks, transaction costs etc. Poor power quality, particularly in some developing countries
Market failures	Market structures and constraints that prevent the consistent trade-off between specific energy-efficient investment and the energy saving benefits	Limitations of the typical building design process Fragmented market structure Landlord/tenant split and misplaced incentives Administrative and regulatory barriers (e.g., in the incorporation of distributed generation technologies) Imperfect information
Behavioural and organizational non-optimalities	Behavioural characteristics of individuals and organizational characteristics of companies that hinder energy efficiency technologies and practices	Tendency to ignore small opportunities for energy conservation Organizational failures (e.g., internal split incentives) Non-payment and electricity theft Tradition, behaviour, lack of awareness and lifestyle Corruption

Source: Carbon Trust, 2005.

glazing area and a host of interaction and control issues involving the building's mechanical and electrical systems.

Compounding the flaws in the typical design process is fragmentation in the building industry as a whole. Assuring the long-term energy performance and sustainability of buildings is all the more difficult when decisions at each stage of design, construction and operation involve multiple stakeholders. This division of responsibilities often contributes to suboptimal results (e.g., under-investment in energy-efficient approaches to envelope design because of a failure to capitalize on opportunities to down-size HVAC equipment). In Switzerland, this barrier is being addressed by the integration of architects into the selection and installation of energy-using devices in buildings (Jefferson, 2000); while the European Directive on the Energy Performance of Buildings in the EU (see Box 6.3) aims to bring engineers in at early stages of the design process through its whole-building, performance-based approach.

6.7.2 Misplaced incentives

Misplaced incentives, or the agent-principal barrier takes place when intermediaries are involved in decisions to purchase energy-saving technologies, or agents responsible for investment decisions are different from those benefiting from the energy savings, for instance due to fragmented institutional organizational structures. This limits the consumer's role and often leads to an under-emphasis on investments in energy efficiency. For example, in residential buildings, landlords often provide the AC equipment and major appliances and decide on building renovation, while the tenant pays the energy bill. As a result, the landlord is not likely to invest in energy efficiency, since he or she is not the one rewarded for the investment (Scott, 1997; Schleich and Gruber, 2007). Decisions about the energy features of a building (e.g., whether to install high-efficiency windows or lighting) are often made by agents not responsible for the energy bills or not using the equipment, divorcing the interests of the builder/investor and the occupant. For example, in many countries the energy bills of hospitals are paid from central public funds while investment expenditures must come either from the institution itself or from the local government (Rezessy *et al.*, 2006). Finally, the prevailing selection criteria and fee structures for building designers may emphasize initial costs over life-cycle costs, hindering energy-efficiency considerations (Lovins, 1992; Jones *et al.*, 2002).

6.7.3 Energy subsidies, non-payment and theft

In many countries, electricity historically has been subsidized to residential customers (and sometimes to commercial or government customers as well), creating a disincentive for energy efficiency. This is particularly the case in many developing countries and historically in Eastern Europe and the former Soviet Union – for example widespread fuel poverty in Russia has driven the government to subsidize energy costs (Gritsevich, 2000). Energy pricing that does not reflect the long-term marginal costs of energy, including direct subsidies to some customers, hinders the penetration of efficient technologies (Alam *et al.*, 1998).

However, the abrupt lifting of historically prevailing subsidies may also have adverse effects. After major tariff increases, non-payment has been reported to be a serious issue in some countries. In the late 1990s, energy bill collection rates in Albania, Armenia and Georgia were around 60% of billings. Besides non-payment, electricity theft has been occurring on a large scale in many countries – estimates show that distribution losses due to theft are as high as 50% in some states in India (New Delhi, Orissa and Jammu-Kashmir) (EIA (Energy Information Administration), 2004). Even in the United States, it has been estimated to cost utilities billions of dollars each year (Suriyamongkol, 2002). The failure of recipients to pay in full for energy services tends to induce waste and discourage energy efficiency.

6.7.4 Regulatory barriers

A range of regulatory barriers has been shown to stand in the way of building-level distributed generation technologies such as PV, reciprocating engines, gas turbines and fuel cells (Alderfer *et al.*, 2000). In many countries, these barriers include variations in environmental permitting requirements, which impose significant burdens on project developers. Similar variations in metering policies cause confusion in the marketplace and represent barriers to distributed generation. Public procurement regulations often inhibit the involvement of ESCOs or the implementation of energy performance contracts. Finally, in some countries the rental market is regulated in a way that discourages investments in general and energy-efficient investments in particular.

6.7.5 Small project size, transaction costs and perceived risk

Many energy-efficiency projects and ventures in buildings are too small to attract the attention of investors and financial institutions. Small project size, coupled with disproportionately high transaction costs – these are costs related to verifying technical information, preparing viable projects and negotiating and executing contracts – prevent some energy-efficiency investments. Furthermore, the small share of energy expenditures in the disposable incomes of affluent population groups, and the opportunity costs involved with spending the often limited free time of these groups on finding and implementing the efficient solutions, severely limits the incentives for improved efficiency in the residential sector. Similarly, small enterprises often receive higher returns on their investments into marketing or other business-related activities than investing their resources, including human resources, into energy-related activities. Conservative, asset-based lending practices of financial institutions, a limited understanding of energy-efficiency technologies on the part of both lenders and their consumers, lack of traditions in energy performance contracting, volatile prices for fuel (and in some markets, electricity), and small, non-diversified portfolios of energy projects all increase the perception of market and technology risk (Ostertag, 2003; Westling, 2003; Vine, 2005). As discussed in Section 6.8 below, policies can be adopted that can help reduce these transaction costs, thus improving the economics and financing options for energy-efficiency investments.

6.7.6 Imperfect information

Information about energy-efficiency options is often incomplete, unavailable, expensive and difficult to obtain or trust. In addition, few small enterprises in the building industry have access to sufficient training in new technologies, new standards, new regulations and best practices. This insufficient knowledge is compounded by uncertainties associated with energy price fluctuations (Hassett and Metcalf, 1993). It is particularly difficult to learn about the performance and costs of energy-efficient technologies and practices, because their benefits are often not directly observable. For example, households typically receive an energy bill that provides no breakdown of individual end-uses and no information on GHG emissions, while infrequent meter readings (e.g., once a year, as is typical in many EU countries) provide insufficient feedback to consumers on their energy use and on the potential impact of their efficiency investments. Trading off energy savings against higher purchase prices for many energy-efficient products involves comparing the time-discounted value of the energy savings with the present cost of the equipment – a calculation that can be difficult for purchasers to understand and compute.

6.7.7 Culture, behaviour, lifestyle and the rebound effect

Another broad category of barriers stems from the cultural and behavioural characteristics of individuals. The potential impact of lifestyle and tradition on energy use is most easily seen by cross-country comparisons. For example, dishwasher usage was 21% of residential energy use in UK residences in 1998 but 51% in Sweden (European Commission, 2001). Cold water is traditionally used for clothes washing in China (Biermayer and Lin, 2004) whereas hot water washing is common in Europe. Similarly, there are substantial differences among countries in how lighting is used at night, room temperatures considered comfortable, preferred temperatures of food or drink, the operating hours of commercial buildings, the size and composition of households, etc. (IEA, 1997; Chappells and Shove, 2004). Variation across countries in quantity of energy used per capita, which is large both at economy and household levels (IEA, 1997), can be explained only partly by weather and wealth; this is also appropriately attributed to different lifestyles. Even in identical houses with the same number of residents, energy consumption has been shown to differ by a factor of two or more (Socolow, 1978). Studies aimed at understanding these issues suggest that while lifestyle, traditions and culture can act as barriers, retaining and supporting lower-consuming lifestyles may also be effective in constraining GHG emissions (e.g., EEA, 2001).

The ‘rebound effect’ has often been cited as a barrier to the implementation of energy-efficiency policies. This takes place when increased energy efficiency is accompanied by increased demand for energy services (Moezzi and Diamond, 2005). The literature is divided about the magnitude of this effect (Herring, 2006).

6.7.8 Other barriers

Due to space limitations, not all barriers to energy efficiency identified in Table 6.5 can be detailed here. Other important barriers in the buildings sector include the limited availability of capital and limited access to capital markets of low-income households and small businesses, especially in developing countries (Reddy, 1991); limited availability of energy-efficient equipment along the retail chain (Brown *et al.*, 1991); the case of poor power quality in some developing countries interfering with the operation of the electronics needed for energy efficient end-use devices (EAP UNDP, 2000); and the inadequate levels of energy services (e.g., insufficient illumination levels in schools, or unsafe wiring) in many public buildings in developing countries and economies in transition. This latter problem can severely limit the cost-effectiveness of efficiency investments, since a proposed efficiency upgrade must also address these issues, offsetting most or all of the energy and cost savings associated with improved efficiency and in turn make it difficult to secure financing or pay back a loan from energy cost savings.

6.8 Policies to promote GHG mitigation in buildings

Preceding sections have demonstrated the high potential for reducing GHG emissions in buildings through cost-effective energy-efficiency measures and distributed (renewable) energy generation technologies. The previous section has demonstrated that even the cost-effective part of the potential is unlikely to be captured by markets alone, due to the high number of barriers. Although there is no quantitative or qualitative evidence in the literature, it is possible that barriers to the implementation of economically attractive GHG reduction measures are the most numerous and strongest in the building sector, especially in households. Since policies can reduce or eliminate barriers and associated transaction costs (Brown, 2001), special efforts targeted at removing the barriers in the buildings sector may be especially warranted for GHG mitigation efforts.

Sections 6.8.1–6.8.5 describe a selection of the major instruments summarized in Table 6.6 that complement the more general discussion of Chapter 13, with a focus on policy tools specific to or specially applied to buildings. The rest of Table 6.6 is discussed in Section 6.8.5.

6.8.1 Policies and programmes aimed at building construction, retrofits, and installed equipment and systems

6.8.1.1 Building codes

Building regulations originally addressed questions related to safety and the protection of occupants. Oil price shocks in the 1970s led most OECD countries to extend their regulations to include energy efficiency. Nineteen out of twenty OECD countries surveyed have such energy standards and regulations, although coverage varies among countries (OECD, 2003).

Building energy codes may be classified as follows: 1) Overall performance-based codes that require compliance with an annual energy consumption level or energy cost budget, calculated using a standard method. This type of code provides flexibility but requires well-trained professionals for implementation; 2) Prescriptive codes that set separate performance levels for major envelope and equipment components, such as minimum thermal resistance of walls, maximum window heat loss/gain and minimum boiler efficiency. There are also examples of codes addressing electricity demand. Several cantons in Switzerland specify maximum installed electric loads for lighting ventilation and cooling in new commercial buildings (SIA, 2006); and 3) A combination of an overall performance requirement plus some component performance requirements, such as wall insulation and maximum window area.

Energy codes are often considered to be an important driver for improved energy efficiency in new buildings. However, the implementation of these codes in practice needs to be well prepared and to be monitored and verified. Compliance can be difficult to enforce and varies among countries and localities (XENERGY, 2001; City of Fort Collins, 2002; OECD, 2003; Ürge-Vorsatz *et al.*, 2003).

Prescriptive codes are often easier to enforce than performance-based codes (Australian Greenhouse Office, 2000; City of Fort Collins, 2002; Smith and McCullough, 2001). However, there is a clear trend in many countries towards performance-based codes that address the overall energy consumption of the buildings. This trend reflects the fact that performance-based policies allow optimization of integrated design and leave room for the creativity of designers and innovative technologies. However, successful implementation of performance-based codes requires education and training – of both building officials and inspectors – and demonstration projects showing that the building code can be achieved without much additional cost and without technical problems (Joosen, 2006). New software-based design and education tools, including continuous e-learning tools, are examples of tools that can provide good design techniques, continuous learning by professionals, easier inspection methods and virtual testing of new technologies for construction and building systems.

Public policies in many countries are also increasingly addressing energy efficiency in existing buildings. For instance, the EU Commission introduced the Directive on the Energy Performance of Buildings in 2003 (see Box 6.3), which standardized and strengthened building energy-efficiency requirements for all EU Member States. To date, most codes for existing buildings include requirements for minimum levels of performance of the components used to retrofit building elements or installations. In some countries, the codes may even prohibit the use of certain technologies – for example Sweden's prohibition of direct electric resistance heating systems, which has led to the rapid introduction of heat pumps in the last five years. Finally, the EU Directive also mandated regular inspection and maintenance of boilers and space conditioning installations in existing buildings (see Box 6.3).

According to the OECD (2003), there is still much room for further upgrading building energy-efficiency codes throughout the OECD member countries. To remain effective, these codes have to be regularly upgraded as technologies improve and costs of energy-efficient features and equipment decline. Setting flexible (e.g., performance-based) codes can help keep compliance costs low and may provide more incentives for innovation.

6.8.1.2 Building certification and labelling systems

The purpose of building labelling and certification is to overcome barriers relating to the lack of information, the high transaction costs, the long lifetime of buildings and the problem of displaced incentives between the builder and buyer, or between the owner and tenant. Certification and labelling schemes can be either mandatory or voluntary.

With the introduction of the EU Directive on the Energy Performance of Buildings (see Box 6.3), building certification is to be instituted throughout Europe. Voluntary certification and/or labelling systems have also been developed for building products such as windows, insulation materials and HVAC components in North America, the EU and a few other countries (McMahon and Wiel, 2001; Menanteau, 2001). The voluntary Energy Star Buildings rating and Energy Star Homes label in the USA and the NF-MI voluntary certificate for houses in France have proven to be effective in ensuring compliance with energy code requirements and sometimes in achieving higher performance levels (Hicks and Von Neida, 1999). Switzerland has developed the 'Minergie' label for new buildings that have a 50% lower energy demand than buildings fulfilling the mandatory requirements; such buildings typically require roughly 6% additional investment costs (OPET Network, 2004). Several local governments in Japan apply the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) (IBEC, 2006). The Australian city of Canberra (ACT) has a requirement for all houses to be energy-efficiency rated on sale. The impact on the market has been to place a financial value on energy efficiency through a well-informed marketplace (ACT, 2006).

6.8.1.3 Education, training and energy audit programmes

Lack of awareness of energy-savings opportunities among practicing architects, engineers, interior designers and

Box 6.3: The European Directive on the Energy Performance of Buildings

One of the most advanced and comprehensive pieces of regulation targeted at the improvement of energy efficiency in buildings is the new European Union Directive on the Energy Performance of Buildings (European Commission, 2002). The Directive introduces four major actions. The *first action* is the establishment of 'common methodology for calculating the integrated energy performance of buildings', which may be differentiated at the regional level. The *second action* is to require member states to 'apply the new methods to minimum energy performance standards' for new buildings. The Directive also requires that a non-residential building, when it is renovated, be brought to the level of efficiency of new buildings. This latter requirement is a very important action due to the slow turnover and renovation cycle of buildings, and considering that major renovations to inefficient older buildings may occur several times before they are finally removed from the stock. This represents a pioneer effort in energy-efficiency policy; it is one of the few policies worldwide to target existing buildings. The *third action* is to set up 'certification schemes for new and existing buildings' (both residential and non-residential), and in the case of public buildings to require the public display of energy performance certificates. These certificates are intended to address the landlord/tenant barrier, by facilitating the transfer of information on the relative energy performance of buildings and apartments. Information from the certification process must be made available for new and existing commercial buildings and for dwellings when they are constructed, sold, or rented. *The last action* mandates Member States to establish 'regular inspection and assessment of boilers and heating/cooling installations'.

The European Climate Change Programme (ECCP, 2001) estimated that CO_2 emissions to be tapped by implementation of this directive by 2010 are 35–45 million tCO_2-eq at costs below 20 EUR/tCO_2-eq, which is 16–20% of the total cost-effective potential associated with buildings at these costs in 2010.

professionals in the building industry, including plumbers and electricians, is a major impediment to the construction of low-energy buildings. In part, this reflects inadequate training at universities and technical schools, where the curricula often mirror the fragmentation seen in the building design profession. There is a significant need in most countries to create comprehensive, integrated programmes at universities and other educational establishments to train the future building professional in the design and construction of low-energy buildings. The value of such programmes is significantly enhanced if they have an outreach component to upgrade the skills and knowledge of practicing professionals – for example, by assisting in the use of computer simulation tools as part of the integrated design process.

The education of end-users and raising their awareness about energy-efficiency opportunities is also important. Good explanation (e.g., user-friendly manuals) is often a condition for proper installation and functioning of energy-efficient buildings and components. Since optimal operation and regular maintenance are often as important as the technological efficiency in determining overall energy consumption of equipment, accessible information and awareness raising about these issues during and after purchase are necessary. This need for widespread education is beginning to be reflected in the curricula of some countries: Japan's and Germany's schools increasingly teach the importance of energy savings (ECCJ, 2006; Hamburger-bildungsserver, 2006). Better education is also relevant for professionals such as plumbers and electricians. Incentives for consumers are generally needed along with the information programs to have significant effect (Shipworth, 2000).

Energy audit programmes assist consumers in identifying opportunities for upgrading the energy efficiency of buildings. Occasionally with financial support from government or utility companies, these programmes may provide trained energy auditors to conduct on-site inspections of buildings, perform most of the calculations for the building owner and offer recommendations for energy-efficiency investments or operational measures, as well as other cost-saving actions (e.g., reducing peak electrical demand, fuel-switching). The implementation of the audit recommendations can be voluntary for the owner, or mandated-such as in the Czech Republic and Bulgaria, which require that installations with energy consumption above a certain limit conduct an energy-efficiency audit and implement the low-cost measures (Ürge-Vorsatz *et al.*, 2003). In India, all large commercial buildings have to conduct an energy audit at specified intervals of time (The Energy Conservation Act, 2001). The EU EPB Directive mandates audits and the display of the resulting certificate in an increasing number of situations (see Box 6.3).

6.8.2 Policies and programmes aimed at appliances, lighting and office/consumer plug loads

Appliances, equipment (including information and communication technology) and lighting systems in buildings typically have very different characteristics from those of the building shell and installed equipment, including lower investment costs, shorter lifetimes, different ownership characteristics and simpler installation and maintenance. Thus, the barriers to energy-efficient alternatives are also different to some extent, warranting a different policy approach. This section provides an overview of policies specific to appliances, lighting and plug-in equipment.

Box 6.4: Global efforts to combat unneeded standby and low-power mode consumption in appliances

Standby and low-power-mode (LoPoMo) electricity consumption of appliances is growing dramatically worldwide, while technologies exist that can eliminate or reduce a significant share of related emissions. The IEA (2001) estimated that standby power and LoPoMo waste may account for as much as 1% of global CO_2 emissions and 2.2% of OECD electricity consumption. Lebot *et al.* (2000) estimated that the total standby power consumption in an average household could be reduced by 72%, which would result in emission reductions of 49 million tCO_2 in the OECD. Various instruments – including minimum energy efficiency performance standards (MEPS), labelling, voluntary agreements, quality marks, incentives, tax rebates and energy-efficient procurement policies – are applied globally to reduce the standby consumption in buildings (Commission of the European Communities, 1999), but most of them capture only a small share of this potential. The international expert community has been urging a 1-Watt target (IEA, 2001). In 2002, the Australian government introduced a 'one-watt' plan aimed at reducing the standby power consumption of individual products to less than one watt. To reach this, the National Appliance and Equipment Energy Efficiency Committee has introduced a range of voluntary and mandatory measures to reduce standby – including voluntary labelling, product surveys, MEPS, industry agreements and mandatory labelling (Commonwealth of Australia, 2002). As of mid-2006, the only mandatory standard regarding standby losses in the world has been introduced in California (California Energy Commission, 2006), although in the USA the Energy Policy Act of 2005 directed the USDOE to evaluate and adopt low standby power standards for battery chargers.

6.8.2.1 *Standards and labelling*

Energy-efficiency performance standards and labels (S&L) for appliances and lighting are increasingly proving to be effective vehicles for transforming markets and stimulating adoption of new, more efficient technologies and products. Since the 1990s, 57 countries have legislated efficiency standards and/or labels, applied to a total of 46 products as of 2004 (Wiel and McMahon, 2005). Today, S&L programmes are among the most cost-effective instruments across the economy to reduce GHG emissions, with typically large negative costs (see Table 6.6). Products subject to standards or labels cover all end-uses and fuel types, with a focus on appliances, information and communications devices, lighting, heating and cooling equipment and other energy-consuming products.

Endorsement and comparison labels[19] induce manufacturers to improve energy efficiency and provide the means to inform consumers of the product's relative or absolute performance and (sometimes) energy operating costs. According to studies evaluating the effectiveness of labels (Thorne and Egan, 2002), those that show the annual energy cost savings appear to be more effective than labels that present life-cycle cost savings. An advantage of a 'categorical' labelling scheme, showing a number of stars or an A-B-C rating, is that it is often easiest for consumers to understand and to transfer their understanding of the categories from one product purchase to others. The categories also provide a useful framework for implementing rebates, tax incentives, or preferential public procurement programmes, while categorical labels on HVAC and other installed equipment make it easy for the building inspector to check for code compliance. A downside of a categorical labelling system can be that if standards are not revised from time to time, there is no stimulus to the manufacturers to develop more efficient appliances and the whole market will be able to deliver appliances fitting the highest efficiency class.

Despite widely divergent approaches, national S&L programmes have resulted in significant cost-effective GHG savings. The US programme of national, mandatory energy-efficiency standards began in 1978. By 2004, the programme had developed (and, in 17 cases, updated) standards for 39 residential and commercial products. The total federal expenditure for implementing the US appliance standards adopted so far (US$ 2 per household) is estimated to have induced US$ 1270 per household of net-present-value savings during the lifetimes of the products affected. Projected annual residential carbon reductions in 2020 due to these appliance standards amount roughly to 9% of projected US residential carbon emissions in the 2020 (base case) (Meyers *et al.*, 2002). In addition, the US Energy Star endorsement label programme estimates savings of 13.2 million tCO_2-eq and US$ 4.2 billion in 2004 (US EPA, 2005), and projects that the programme will save 0.7 billion tonnes of CO_2 over the period 2003 to 2010, growing to 1.8 billion tonnes of CO_2 over the period 2003 to 2020, if the market target penetration is reached (Webber *et al.*, 2003). According to the IEA (2003a), GHG abatement through appliance standards and labelling in Europe by 2020 will be achieved at a cost of –65 US$/$tCO_2$ in North America and –169 €/tCO_2 (–191 US$/$tCO_2$) (i.e., both at substantial 'net benefit'). An evaluation of the impact of the EU appliance-labelling scheme showed a dramatic shift in the efficiency of refrigerators sold in the EU in the first decade of its S&L programme, as displayed in Figure 6.5 (Bertoldi, 2000). Japan imposes stringent energy efficiency standards on equipment through its 'Top Runner Programme' by distinctly setting the target values based on the most energy-efficient model on the market at the time of the value-setting process. Energy-efficiency values and a rating mark are voluntarily displayed in promotional materials so that consumers can consider energy-efficiency when purchasing (Murakoshi and Nakagami, 2005).

A recent IEA report (2003a) concludes that, without existing policy measures such as energy labelling, voluntary agreements, and MEPS, electricity consumption in OECD countries in 2020 would be about 12% (393 TWh) higher than is now predicted. The report further concludes that the current policies are on course to produce cumulative *net* cost savings of € 137 billion (US$ 155 billion) in OECD-Europe from 1990 to 2020. As large as these benefits are, the report found that much greater benefits could be attained if existing policies were strengthened.

A study of China's energy-efficiency standards (Fridley and Lin, 2004) estimated savings from eight new MEPS and nine energy-efficiency endorsement labels. The study concluded that, during the first 10 years of implementation, these measures will save 200 TWh (equivalent to all of China's residential electricity consumption in 2002) and 250 $MtCO_2$. Among other countries, Korea shows similar evidence of the impact of labelling, as does the EU (CLASP, 2006). Recently, Australia transformed its S&L programme in order to aggressively improve energy efficiency (NAEEEC, 2006).

In the past few years, strong regional and global S&L efforts have also emerged, offering a more coordinated pathway to promote S&L and improve the cost-effectiveness and market impact of the programmes. One of these pathways is regional harmonization. The IEA (2003b) identifies several forms of multilateral cooperation, including: 'collaboration' in the design of tests, labels and standards; 'harmonization' of the test procedures and the energy-efficiency thresholds used in labels and standards; and 'coordination' of programme implementation and monitoring efforts. However, while easing certain trade restrictions, harmonization of standards and testing methods

19 Endorsement labels (or "quality marks") define a group of products as "efficient" when they meet pre-specified criteria, while comparison labels allow buyers to compare the efficiency of products based on factual information about their absolute or relative performance.

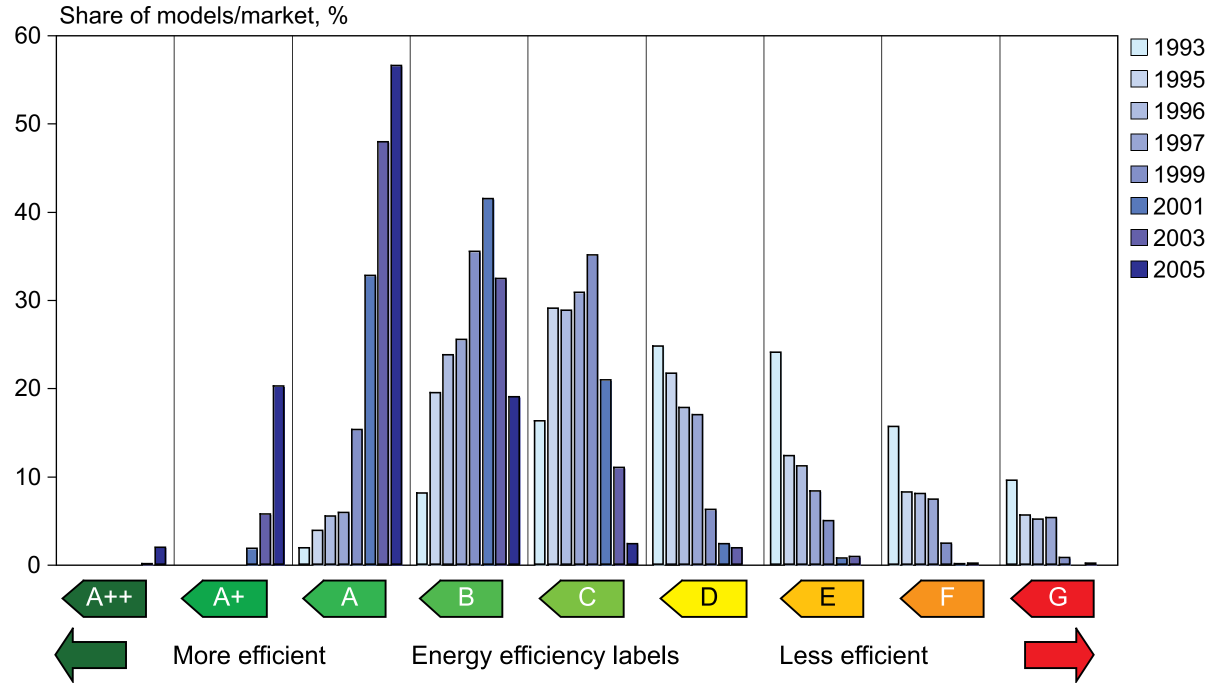

Figure 6.5: *The Impact of the EU Appliance Label (A++ to G, with G being the least efficient) on the Market of Cold Appliances in EU-25.*
Source: CECED, 2005.

can have the unintended consequence of overcoming cultural and other differences that affect consumer preferences, possibly leading to increased levels of energy consumption (Moezzi and Maithili, 2002; Biermayer and Lin, 2004).

6.8.2.2 Voluntary agreements

Voluntary agreements, in which the government and manufacturers agree to a mutually acceptable level of energy use per product, are being used in place of, or in conjunction with, mandatory MEPS to improve the energy efficiency of appliances and equipment. In the European context, this includes a wide range of industry actions such as industry covenants, negotiated agreements, long-term agreements, self-regulation, codes of conduct, benchmarking and monitoring schemes (Rezessy and Bertoldi, 2005). Voluntary measures can cover equipment, building design and operation and public, and private sector energy management policies and practices. Examples include Green Lights in the EU and the Energy Star programmes in the USA, as well as successful EU actions for the reduction of standby losses and efficiency improvement of washing machines and cold appliances. Industry often favours voluntary agreements to avoid the introduction of mandatory standards (Bertoldi, 1999). For the public authorities, voluntary agreements offer a faster approach than mandatory regulation and are often acceptable if they include the following three elements: (i) commitments by those manufacturers accounting for most of the equipment sold, (ii) quantified commitments to significant improvements in the energy efficiencies of the equipment over a reasonable time scale, and (iii) an effective monitoring scheme (Commission of the European Communities, 1999). Voluntary agreements are considered especially useful in conjunction with other instruments and if mandatory measures are available as a backup or to encourage industry to deliver the targeted savings, such as for the case of cold appliances in the EU (Commission of the European Communities, 1999; Jäger-Waldau, 2004).

6.8.3 Cross-cutting policies and programmes that support energy efficiency and/or CO_2 mitigation in buildings

This section reviews a range of policies and programmes that do not focus specifically on either buildings and installed equipment, or on appliances and smaller plug-in devices in buildings, but may support energy efficiency and emissions reductions – including effects across other end-use sectors.

6.8.3.1 Utility demand-side management programmes

One of the most successful approaches to achieving energy efficiency in buildings in the USA has been utility-run demand-side management (DSM) programmes. However, there are important disincentives that need to be removed or lowered for utilities to be motivated in pursuing DSM programmes. The most important of these difficulties, (i.e., that utilities make profits from selling electricity, not from reducing sales) can be overcome by regulatory changes in which the utility will avoid revenue losses from reduced sales, and in some cases also receive profits from successful execution of DSM programmes.

The major large-scale experience with utility DSM has been in the United States primarily in the west coast and New England, but now spreading to other parts of the country. Spending on DSM was US$ 1.35 billion in 2003 (York and Kushler, 2005), and since California is more than doubling its expenditure to US$ 700 million/yr for the next three years, DSM spending in the United States will increase substantially.

These programmes have had a major impact. For the United States as a whole, where DSM investments have been 0.5% of revenues, savings are estimated to be 1.9% of revenues. For California, cumulative annual savings are estimated to be 7.5% of sales, while DSM investment has been less than 2% (1.2% in 2003). Overall, for each of the years 1996 through 2003, DSM has produced average annual savings of about 33.5 $MtCO_2$-eq annually for the USA, an annual net savings of more than US$ 3.7 billion (York and Kushler, 2005).

There are numerous opportunities to expand utility DSM programmes: in the United States, by having other states catch up with the leaders (especially California at present), much more so in Europe and other OECD countries, which have little experience with such programmes offered by utilities, and over time in developing countries, as well.

6.8.3.2 *Energy prices, pricing schemes, energy price subsidies and taxes*

Market-based energy pricing and energy taxes represent a broad measure for saving energy in buildings. The effect of energy taxes depends on energy price elasticity, that is the percent change in energy demand associated with each 1% change in price. In general, residential energy price elasticities are low in the richest countries. In the UK, long-run price elasticity for the household sector is only –0.19 (Eyre, 1998), in the Netherlands –0.25 (Jeeninga and Boots, 2001) and in Texas only –0.08 (Bernstein and Griffin, 2005). However, if energy expenditures reach a significant proportion of disposable incomes, as in many developing countries and economies in transition, elasticities – and therefore the expected impact of taxes and subsidy removal – may be higher, although literature is sparse on the subject. In Indonesia, price elasticity was –0.57 in the period from 1973 to 1990 and in Pakistan –0.33 (De Vita *et al.*, 2006). Low elasticity means that taxes on their own have little impact; it is behavioural and structural barriers that need to be addressed (Carbon Trust, 2005). To have a significant impact on CO_2 emission reduction, excise taxes have to be substantial. This is only the case in a few countries (Figure 6.6): the share of excise tax compared to total fuel price differs considerably by country.

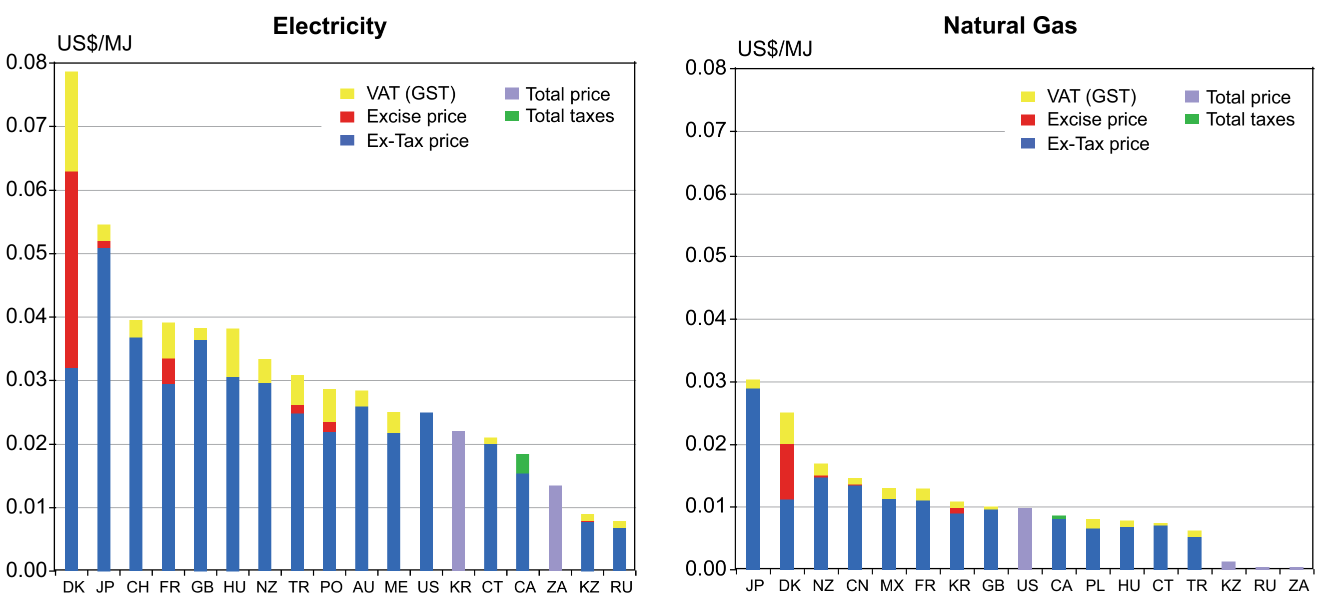

Figure 6.6: *Electricity and gas prices and taxes for households in 2004*

Notes: Total price is listed when no breakdown available to show taxes; total taxes are provided when no breakdown on excise and VAT (GST). Country name abbreviations (according to the ISO codes except Chinese Taipei): DK – Denmark, JP – Japan, CH – Switzerland, FR – France, GB – United Kingdom, HU – Hungary, TR – Turkey, PO – Poland, NZ – New Zealand, AU - Australia, MX – Mexico, US – United States of America, KR – South Korea, CT – Chinese Taipei, CA – Canada, ZA – South Africa*, KZ – Kazakhstan, RU – Russia. * South Africa data is for 2003.

Sources: IEA, 2006a; RAO, 2006.

In stark contrast to imposing energy taxes, energy prices are *subsidized* in many countries. This results in under-pricing of energy, which reduces the incentive to use it more efficiently. Energy subsidies are also typically much larger, per GJ, in developing and transition countries than in most industrial economies (Markandya, 2000). The total value of energy subsidies of eight of the largest non-OECD countries (China, Russia, India, Indonesia, Iran, South Africa, Venezuela and Kazakhstan), covering almost 60% of total non-OECD energy demand, was around US$ 95 billion in 1998 (UNEP OECD/IEA, 2002). In 1999, the IEA estimated that removing the energy subsidies in those eight countries would reduce primary energy use by 13%, lower CO_2 emissions by 16% and raise GDP by almost 1%.

While it may be economically and environmentally desirable, it is a socially sensitive task to remove end-user subsidies, especially in the residential sector. Since the bulk of these subsidies are found in countries with low incomes and high fuel-poverty rates, their removal can cause a substantial financial burden for families and even institutions. This, in turn, can lead to bankruptcy, increased payment arrears, energy theft and generally increased social tensions (ERRA/LGI, 2002; Ürge-Vorsatz *et al.*, 2003), ultimately leading to disincentives to improve efficiency. Therefore, a drastic subsidy removal is often accompanied by social compensation programmes. One potentially important form of alternative compensation – although not frequently used to date – is assistance to low-income households to invest in energy-saving measures that reduce fuel costs and GHG emissions in the long term as opposed to direct cash assistance providing short-term relief (ERRA/LGI, 2002). For a number of years, the US government has provided 1.5–2.0 billion US$/yr to help low-income households pay their energy bills (LIHEAP, 2005), and smaller amounts budgeted for grants to 'weatherize' many of these same households with efficiency measures that help to permanently reduce monthly fuel and electricity bills (Schweitzer and Berry, 1999).

Some forms of energy subsidies can have positive energy and environmental effects. For example, subsidies on oil products and electricity in developing countries reduce deforestation and also reduce indoor pollution as poor, rural households switch away from traditional energy sources, such as wood, straw, crop residues and dung. These positive effects, however, can be better achieved through other means – e.g., the introduction of safe and efficient cookers and heaters utilizing these renewable sources. The challenge is to design and reform energy subsidies so they favour the efficient and environmentally sound use of energy systems (UNEP OECD/IEA, 2002)

6.8.3.3 *Investment subsidies, financial incentives and other fiscal measures*

As noted in Section 6.5.5, applying an integrated design process (IDP) can result in buildings that use 35–70% less energy than conventional designs, at little or no additional capital cost, but with a potential increase in the design cost. Providing financial incentives for the design process rather than financial incentives for the capital cost of the building is an approach used in several regions, such as by Canada in its Commercial Building Incentive Program (Larsson, 2001), by California in its Savings By Design programme and in Germany under the *SolarBau* programme (Reinhart *et al.*, 2000).

Going beyond IDP, other measures – particularly those that include renewable energy options – entail significant added capital costs. Many developed countries offer incentives for such measures (IEA, 2004f). Types of financial support include subsidies, tax reduction (or tax credit) schemes and preferential loans or funds, with investment subsidies being the most frequently used (IEA, 2004f). Capital subsidy programmes and tax exemption schemes for both new construction and existing buildings have been introduced in nine OECD countries out of 20 surveyed (OECD, 2003). Several countries (USA, France, Belgium, UK and the Netherlands) combine their financial incentive policy for the existing building stock with social policy to assist low-income households (IEA, 2004a; VROM, 2006; USDOE, 2006). Increasingly, eligibility requirements for financial support are tied to CO_2 emission reduction (IEA, 2004a; KfW Group, 2006). Within the Energy Star Homes programme in the USA, houses that meet the energy-efficiency standard are eligible for a special mortgage (Nevin and Watson, 1998; Energystar, 2006). Financial incentives for the purchase of energy-efficient appliances are in place in some countries, including Mexico, the USA, Belgium, Japan and Greece (Boardman, 2004; IEA, 2004f). Incentives also encourage connection to district heating in Austria, Denmark and Italy.

There has been limited assessment of the efficiency of these schemes. The cost-effectiveness of subsidy-type schemes can vary widely, depending on programme design. Joosen *et al.* (2004) have estimated that subsidy programmes for residential buildings cost Dutch society 32–105 US$/t$CO_2$, whereas this range for the commercial sector was between 64 and 123 US$/t$CO_2$. A variety of financial incentives available simultaneously may make the decision process difficult; simplicity of the schemes might be an asset (Barnerjee and Solomon, 2003). A combination of government financial incentives and private bank loans may be more effective than a government-subsidized loan, as may combining building rating or labelling with a loan-especially when the labelling scheme has public approval.

6.8.3.4 *Public sector leadership programmes and public procurement policies*

Government agencies, and ultimately taxpayers, are responsible for a wide range of energy-consuming facilities and services such as government office buildings, schools and health care facilities. The government itself is often a country's largest consumer of energy and largest buyer of energy-using equipment. The US federal government spends over US$ 10 billion/yr for energy-using equipment (Harris and Johnson, 2000). Government policies and actions can thus contribute, both directly and indirectly, to energy savings and associated GHG reductions (Van Wie McGrory *et al.*, 2002). A recent study for several EU countries (Borg *et al.*, 2003) found a potential for direct energy savings of 20% or more in EU government facilities and operations. According to the USDOE's Federal Energy Management Program (FEMP), average energy intensity (site energy per square meter) in federal buildings has been reduced by about 25% since 1985, while average energy intensity in US commercial buildings has stayed roughly constant (USDOE/EERE, 2005; USDOE/FEMP, 2005).

Indirect beneficial impacts occur when Governments act effectively as market leaders. First, government buying power can create or expand demand for energy-efficient products and services. Second, visible government energy-saving actions can serve as an example for others. Public sector energy efficiency programmes fall into five categories (Harris *et al*., 2005): (i) Policies and targets (energy/cost savings; CO_2 reductions); (ii) Public buildings (energy-saving retrofit and operation of existing facilities, as well as sustainability in new construction), (iii) Energy-efficient government procurement; (iv) Efficiency and renewable energy use in public infrastructure (transit, roads, water and other public services); and (v) Information, training, incentives and recognition of leadership by agencies and individuals. The following paragraphs provide selected examples.

The EU Directive on Energy Performance of Buildings discussed above and in Box 6.3, includes special requirements for public building certification. UK policy requires all new and refurbished government buildings to be rated under the British Research Establishment Environmental Assessment Method (BREEAM), which includes credits for energy efficiency and reduced CO_2 emissions. New government buildings must achieve a BREEAM rating of 'Excellent,' while major refurbishments require a 'Good' rating (UK/DEFRA, 2004). In the USA, a recent law requires new federal buildings to be designed 30% better for energy performance than that required by current commercial and residential building codes (U.S. Congress, 2005).

Energy-efficient government purchasing and public procurement can be powerful market tools. (Borg *et al.*, 2003; Harris *et al*., 2004). Energy-efficient government procurement policies are in place in several EU countries, as well as in Japan, Korea, Mexico, China and the USA (Harris *et al*., 2005). In the USA, in 2005, Congress passed a law mandating that all federal agencies specify and buy efficient products that qualify for the Energy Star label, or (in cases where that label does not apply) products designated by USDOE/FEMP as being among the top 25th percentile of efficient products (US Congress, 2005). Federal purchasing policies are expected to save 1.1 million tonnes CO_2-eq and US$ 224 million/yr in 2010 (Harris and Johnson, 2000).

Public procurement policies can have their greatest impact on the market when they are based on widely harmonized energy-efficiency specifications that can send a strong market signal to manufacturers and suppliers (Borg *et al.*, 2003). If US agencies at all levels of government adopt the federal efficiency criteria for their own purchases, estimated annual electricity savings in the USA would be 10.8 million tonnes CO_2-eq, allowing for at least one billion US$/yr savings on public energy bills (Harris and Johnson, 2000).

6.8.3.5 Promotion of energy service companies (ESCOs) and energy performance contracting (EPC)

While not a 'policy instrument', ESCOs have become favoured vehicles to deliver energy-efficiency improvements and are promoted by a number of policies. An ESCO is a company that offers energy services, such as energy analysis and audits, energy management, project design and implementation, maintenance and operation, monitoring and evaluation of savings, property/facility management, energy and/or equipment supply and provision of energy services (e.g., space heating, lighting). ESCOs guarantee the energy savings and/or the provision of a specified level of energy service at lower cost by taking responsibility for energy-efficiency investments or/ and improved maintenance and operation of the facility. This is typically executed legally through an arrangement called 'energy performance contracting' (EPC). In many cases, the ESCO's compensation is directly tied to the energy savings achieved. ESCOs can also directly provide or arrange for project financing, or assist with financing by providing an energy (cost) savings guarantee for their projects. Finally, ESCOs often retain an ongoing operational role, provide training to on-site personnel, and take responsibility for measuring and verifying the savings over the term of the project loan.

In 2006, the US ESCO market is considered the most advanced in the world (Goldman *et al*., 2005), with revenues reaching about US$ 2 billion in 2002 (Lin and Deng, 2004). Most US ESCO activity (approximately 75%) is in the public sector. The market for energy-efficiency services in Western Europe was estimated to be € 150 million/yr in 2000, while the market potential was estimated at € 5–10 billion/yr (Butson, 1998; Bertoldi and Starter, 2003). Germany and Austria are the ESCO leaders in Europe, with street-lighting projects among the most common demand-side EPC projects, and public buildings the most targeted sector (Bertoldi *et al*., 2005; Rezessy *et al.*, 2005). Between 1998 and 2003, 600–700 public buildings were renovated in Austria using energy performance contracting by ESCOs. Austria is now using EPCs to renovate 50% of the total floor area of federal buildings (Leutgöb, 2003). In Germany, more than 200 EPCs have been signed since the mid-1990s, primarily for public buildings (Seefeldt, 2003). In Japan, the ESCO market is growing quickly, with a focus on the commercial and public sectors (office buildings and hospitals) (Murakoshi and Nakagami, 2003). In India and Mexico, ESCOs also have targeted at least 50% of their activity in the public and commercial sectors (Vine, 2005). Most ESCOs do not target the residential sector, although exceptions exist (e.g., in Nepal and South Africa).

ESCOs greatly facilitate the access of building owners and operators to technical expertise and innovative project financing. They can play a central role in improving energy efficiency without burdening public budgets and regulatory intervention to markets. However, the ESCO industry does not always develop on its own and policies and initiatives may be necessary to kick-start the market. The commitment of federal and municipal authorities to use ESCOs for their energy-efficiency projects, along with supportive policies and public-private partnerships has been crucial in countries such as Germany and Austria (Brand and Geissler, 2003). In some cases, obligations imposed on electricity companies have fostered the development of ESCO activities, as in the case of Brazil, where power utilities are required to invest 1% of their net operating revenues in energy efficiency.

6.8.3.6 Energy-efficiency obligations and tradable energy-efficiency certificates

Recognising that traditional energy policy tools have not achieved the magnitude of carbon savings needed to meet climate stabilization targets, a few new innovative instruments are being introduced or planned in a number of countries. Among them are the so-called ‘white certificates’, a cap-and-trade scheme (or, in some cases, an obligation without the trading element) applied to achieve energy efficiency improvements. The basic principle is an obligation for some category of economic actors (e.g., utility companies, product manufacturers or distributors and large consumers) to meet specified energy savings or programme-delivery goals, potentially coupled with a trading system based on verified and certified savings achieved (or expected) for energy-efficiency measures (the ‘white’ certificate) (ECEEE, 2004; Oikonomou *et al.*, 2004). Energy efficiency obligation programmes without certificate trading have been operating in the UK since 1994 and in Flanders (Belgium) since 2003; white certificate schemes with a trading element were in place in 2006 in Italy, France and New South Wales. Other European countries have announced their intention to introduce similar schemes.

Capturing the desired benefit of certificate trading schemes – that is minimising the costs of meeting energy savings goals – depends on the liquidity of the market. There is a trade-off between liquidity, crucial to minimizing the costs, and manageability and transaction costs. Where transaction costs turn out to be very high, a simple energy savings obligation for electricity and gas distributors, without the complication of trading, may be a better way to deliver the desired outcome (Bertoldi and Rezessy, 2006). Since the first white certificate schemes are just starting, it remains to be seen whether this policy instrument will deliver the expected level of savings and at what cost.

In the UK, the Energy Efficiency Commitment (EEC) requires that all large gas and electricity suppliers deliver a certain quantity of energy savings by assisting customers to take energy-efficiency actions in their homes. The delivered overall savings of the first phase, 87 TWh, largely exceeded the target of 65 TWh and the target has since been increased to 130.2 TWh (Lees, 2006).

6.8.3.7 The Kyoto Protocol’s Flexibility Mechanisms

The flexibility mechanisms of the Kyoto Protocol (KP), especially the clean development mechanism (CDM) and joint implementation (JI), could offer major benefits for buildings in developing countries and economies in transition, in terms of financing, transfer of advanced technologies and know-how, building of local capacity and demonstration effects (Woerdman, 2000; Grubb *et al.*, 2002). Buildings should be prime targets for project-based mechanisms due to the variety and magnitude of cost-effective potentials (see section 6.5). For instance, Trexler and Associates (Margaree Consultants, 2003) estimated that building and appliance efficiency accounts for 32% of total potential in CDM in 2010 under 0 US\$/tCO_2 and 20% under 20 US\$/tCO_2. However, evidence until 2006 shows that little of this potential is expected to be unlocked during the first commitment period (Novikova *et al.*, 2006). After initial enthusiasm in the activities implemented jointly (AIJ) phase, where 18 out of 156 registered projects were targeted to buildings, JI and CDM experience to date suggests that this pilot phase brought disappointment in building-related projects. As of February 2006, only four CDM projects out of 149 projects registered or seeking validation were for buildings, and none of the 152 approved and submitted JI projects was due to invest in buildings (Novikova *et al.*, 2006).

While it is too early to conclude that the Kyoto Protocols’s project-based mechanisms do not work well for buildings, there are no indications that this trend will reverse. A number of barriers prevent these mechanisms from fully mobilizing their benefits for buildings (Tangen and Heggelund, 2003; ECON Analysis, 2005). Chief among these is the proportionately high transaction costs due to the relatively small size of building-related projects: although these costs are around 100 €/tCO_2 (124 US\$/tCO_2) for building-related projects, they amount only to 0.1 €/tCO_2 (0.12 US\$/tCO_2) for very large-scale projects (Michaelowa and Jotzo, 2005). While a few hypothetical solutions have been suggested to overcome the barriers (Novikova *et al.*, 2006), their implementation is uncertain. Another major chance opens for buildings in former communist countries with large emission surpluses through Green Investment Schemes, or the ‘greening’ of these surplus emission units, if they are constructed to accommodate small-scale energy-efficiency investments better than CDM or JI, potentially delivering over a billion tonnes of real CO_2 reductions.

In summary, if the KP is here to stay, the architecture of the flexible mechanisms could be revisited to address these shortcomings, so that the major opportunities from buildings in developing countries and EITs do not stay unutilised. A potential criterion for appraising climate regimes – in terms of their success in leveraging lowest costs mitigation options, as well as in meeting sustainable development goals – could be their success in promoting buildings-level investments in developing countries and economies in transition, reflecting their recognized importance in minimized-cost global emission mitigation efforts.

6.8.3.8 Technology research, development, demonstration and deployment (RD&D)

Section 6.4 attested that there is already a broad array of accessible and cost-effective technologies and know-how that can abate GHG emissions in existing and new buildings to a significant extent that have not been widely adopted yet. At the same time, several recently developed technologies, including high performance windows, active glazing, vacuum insulated panels, phase change materials to increase building thermal mass, high performance reversible heat pumps and many other technologies may be combined with integrated passive solar design and result in up to 80% reduction of building energy consumption and GHG emissions. Large-scale GHG reduction in buildings requires fast and large-scale dissemination and transfer in many countries, including efficient and continuous training of professionals in the integrated approach to design and optimized use of combinations of technologies. Integrated intelligent building control systems, building- or community-level renewable energy generation, heat and coldness networks, coupled to building renewable energy capture components and intelligent management of the local energy market need more research, development and demonstration, and could develop significantly in the next two decades.

Between 1996 and 2003 the annual worldwide RD&D budget for energy efficiency in buildings has been approximately US$ 225–280 million/yr (IEA, 2004d). The USA has been the leading country in energy research and development for buildings for over a decade. Despite the decline in US funds by 2/3rd between 1993 and 2003, down from a peak of US$ 180 million, the USA is still responsible for half of the total global expenditures (IEA, 2004d). Substantial buildings-related energy-efficiency RD&D is also sponsored in Japan (15% of global expenditure).

The overall share of energy-efficiency in total energy RD&D expenditure is low, especially compared to its envisioned role in global GHG mitigation needs. In the period from 2001 to 2005 on average only 14% of all energy RD&D expenditure in IEA countries has been designated for energy-efficiency improvement (IEA, 2006c), whereas its contribution to CO_2 emission reduction needs by 2050 is 45% according to the most commonly used 'Map' scenario of the IEA (2006d). The share dedicated to energy efficiency improvements in buildings was only 3%, in stark contrast with their 18% projected role in the envisioned necessary 32 Gt global CO_2 reduction by 2050 (IEA, 2006d).

6.8.4 Policies affecting non-CO_2 gases

In the buildings sector, non-CO_2 greenhouse gases (halocarbons) are used as the working fluid in most vapour-compression cooling equipment, and as a blowing agent in some insulation foams including polyurethane spray foam. Background in this report is in Section 6.4.15, which is in turn a brief summary of IPCC/TEAP (2005).

6.8.4.1 Stationary refrigeration, air conditioning and heat pump applications

A number of countries have established legislative and voluntary regimes to control emissions and use of fluorinated gases. In Europe, a number of countries have existing policies that aim at reducing leakage or discouraging the use of refrigerants containing fluorine. Regulations in the Netherlands minimize leakage rates through improved maintenance and regular inspection. Substantial taxes for refrigerants containing fluorine are levied in Scandinavian countries, and legislation in Luxembourg requires all new large cooling systems to use natural refrigerants (Harmelink *et al.*, 2005). Some countries such as Denmark and Austria have banned the use of HFCs in selected air conditioning and refrigeration applications. In 2006 the EU Regulation 842/2006 entered into force, which requires that all medium and large stationary air conditioning applications in the EU will use certified and trained service personnel, and assures recovery of refrigerants at the end-of-life (Harmelink *et al.*, 2005).

In the USA, it has been illegal under the Clean Air Act since 1995, to vent substitutes for CFC and HCFC refrigerants during maintenance, repair and disposal of air conditioning and refrigeration equipment (US EPA, 2006). Japan, has established a target to limit HFC, PFC and SF6 emissions. Measures to meet this target include voluntary action plans by industries, mandatory recovery systems for HFCs used as refrigerants (since April 2002) and the research and development of alternatives (UNFCCC, 2006). Australia has developed an Ozone Protection and Synthetic Greenhouse Gas Management Act. Measures include supply controls though the licensing of importers, exporters and manufacturers of fluorinated gases and pre-charged refrigeration and air conditioning equipment; end-use regulations on handling, use, recovery, sale and reporting are in place (Australian Government, 2006). Canada has established a National Action Plan for the Environmental Control of ODS and their Halocarbon Alternatives (NAP). This ensures that HFCs are only used in applications where they replace ODS and requires recovery, recycling and reclamation for CFCs, HCFCs and HFCs (Canadian Council of Ministers of the Environment, 2001).

6.8.4.2 *Insulating foams and SF_6 in sound-insulating glazing*

Within the European Union, Denmark and Austria have introduced legislation to ban the use of HFC for the production of several foam types (Cheminfo, 2004). Since 2006 the EU Regulation 842/2006 on certain Fluorinated Gases limits emissions and certain uses of fluorinated gases (European Commission, 2006), banning the use of HFCs in One-Component Foam from 2008, except where required to meet national safety standards. Japan has established a target to limit HFC, PFC and SF6 emissions. Measures to meet this target include voluntary action plans by industries, improved containment during the production process, less blowing agent per product, improved productivity per product and the use of non-fluorocarbon low GWP alternatives. Australia has developed an act for industries covered by the Montreal Protocol and extended voluntary arrangements for non-Montreal Protocol industries. Measures include supply controls though the licensing of importers, exporters and manufacturers of HFCs.

Although there are no international proposals to phase out the use of HFCs in foams, the high costs of HFCs have naturally contributed to the minimization of their use in formulations (often by use with co-blowing agents) and by early replacement by alternative technologies based primarily on CO_2, water or hydrocarbons (e.g. pentane). There is more regulatory uncertainty at regional level and in Japan some pressure exists to stop HFC-use in the foam sector. In Europe, the recently published F-Gas regulation (European Commission, 2006) only impacts the use of HFCs in one component foam (OCF) which is used primarily for gap filling in the construction sector. However, there is a requirement to put in place provisions for recovery of blowing agent at end-of-life where such provisions are technically feasible and do not entail disproportionate cost.

6.8.5 Policy options for GHG abatement in buildings: summary and conclusion

Section 6.8 demonstrates that there is a variety of government policies, programmes, and market mechanisms in many countries for successfully reducing energy-related CO_2 emissions in buildings (*high agreement, medium evidence*). Table 6.6 (below) reviews 20 of the most important policy tools used in buildings according to two criteria from the list of criteria suggested in Chapter 13 (of the ones for which literature was available in policy evaluations): emission reduction effectiveness and cost-effectiveness. Sixty-six ex post (with a few exceptions) policy evaluation studies were identified from over 30 countries and country groups that served as a basis for the assessment.

The first column in Table 6.6 identifies the key policy instruments grouped by four major categories using a typology synthesized from several sources including Grubb (1991); Crossley *et al.* (2000) and Verbruggen and Bongaerts (2003): (i) control and regulatory mechanisms, (ii) economic and market-based instruments, (iii) financial instruments and incentives, and (iv) support and information programmes and voluntary action. The second column identifies a selection of countries where the policy instrument is applied[20]. Then, the effectiveness in achieving CO_2 reduction and cost-effectiveness were rated qualitatively based on available literature as well as quantitatively based on one or more selected case studies. Since any instrument can perform poorly if not designed carefully, or if its implementation and enforcement are compromised, the qualitative and quantitative comparisons are based on identified best practices, in order to demonstrate what impact an instrument can achieve if applied well. Finally, the table lists special conditions for success, major strengths and limitations, and co-benefits.

While the 66 studies represent the majority of such evaluations available in the public domain in 2006, this sample still leaves few studies in certain categories. Therefore, the comparative findings of this assessment should be viewed as indicative rather than conclusive. Although a general caveat of comparative policy assessments is that policies act as parts of portfolios and therefore the impact of an individual instrument is difficult to delineate from those of other tools, this concern affects the assessment to a limited extent since the literature used already completed this disaggregation before evaluating individual instruments.

All the instruments reviewed can achieve significant energy and CO_2 savings; however the costs per tonne of CO_2 saved diverge greatly. In our sample, appliance standard, building code, labelling and tax exemption policies achieved the highest CO_2 emission reductions. Appliance standards, energy efficiency obligations, demand-side management programmes, public benefit charges and mandatory labelling were among the most cost-effective policy tools in the sample, all achieving significant energy savings at negative costs. Investment subsidies (as opposed to rebates for purchases of energy efficient appliances) were revealed as the least cost-effective instrument. Tax reductions for investments in energy efficiency appeared more effective than taxation. Labelling and voluntary programmes can lead to large savings at low-costs if they are combined with other policy instruments. Finally, information programmes can also achieve significant savings and effectively accompany most other policy measures.

20 Since we made a strong effort to highlight best practices from developing countries where possible, major front-running developed countries where the instrument is applied may not be listed in each applicable row of the table.

Table 6.6: *The impact and effectiveness of various policy instruments aimed to mitigate GHG emission in the buildings sector*

Policy instrument[a]	Examples of countries	Effectiveness[b]	Energy or emission reductions for selected best practices	Cost-effectiveness	Cost of GHG emission reduction for selected best practices[c]	Special conditions for success, major strengths and limitations, co-benefits	References
Control and regulatory mechanisms							
Appliance standards	EU, US, JP, AU, BR, CN	High	JP: 31 M tCO_2 in 2010; CN: 240 $MtCO_2$ in 10 yrs; US: 2.5% of electricity use in 2000 = 65 $MtCO_2$, 6.5% = 223.87 $MtCO_2$ in 2010.	High	AU: –15 $/tCO_2$ in 2012; US: –65 $/tCO_2$ in 2020; EU: –194 $/tCO_2$ in 2020.	Factors for success: periodical update of standards, independent control, information, communication and education.	IEA, 2005; Schlomann *et al*. 2001; Gillingham *et al.*, 2004; ECS, 2002; World Energy Council, 2004; Australian Greenhouse Office, 2005; IEA 2003a; Fridley and Lin, 2004.
Building codes	SG, PH, DZ, EG, US, GB, CN, EU	High	HK: 1% of total electricity saved; US: 79.6 $MtCO_2$ in 2000; EU: 35–45 $MtCO_2$, max 60% energy savings in new buildings.	Medium	NL: from –189 $/tCO_2$ to –5 $/tCO_2$ for end-users, 46–109 $/tCO_2$ for society.	No incentive to improve beyond target. Only effective if enforced.	World Energy Council, 2001; Lee & Yik, 2004; Schaefer *et al*., 2000; Joosen *et al*., 2004; Geller *et al*., 2006; ECCP, 2001.
Procurement regulations	US, EU, CN, MX, KR, JP	High	MX: 4 cities saved 3.3 $ktCO_2$-eq in one year; CN: 3.6 $MtCO_2$ expected; EU: 20–44 $MtCO_2$ potential.	Medium	MX: $1Million in purchases saves $726,000/yr; EU: <21 $/tCO_2$.	Success factors: enabling legislation, energy efficiency labelling & testing, ambitious energy efficiency specifications.	Borg *et al*., 2003; Harris *et al*., 2005; Van Wie McGrory *et al*., 2006.
Mandatory labelling and certification programmes	US, CA, AU, JP, MX, CN, CR, EU	High	AU: 5 M tCO_2 savings 1992–2000; DK: 3.568 $MtCO_2$.	High	AU: –30 $/tCO_2$ abated.	Effectiveness can be boosted by combination with other instrument and regular updates.	World Energy Council, 2001; OPET network, 2004; Holt & Harrington, 2003.
Energy efficiency obligations and quotas	GB, BE, FR, IT, DK, IE	High	GB: 1.4 $MtCO_2$/yr.	High	Flanders: –216 $/tCO_2$ for households, –60 $/tCO2 for other sector in 2003; GB: –139 $/tCO_2$.	Continuous improvements necessary: new energy efficiency measures, short-term incentives to transform markets etc.	UK government, 2006; Sorell, 2003; Lees, 2006; Collys, 2005; Bertoldi & Rezessy, 2006; Defra, 2006.
Utility demand-side management programmes	US, CH, DK, NL, DE, AT	High	US: 36.7 $MtCO_2$ in 2000.	High	US: Average costs approx. –35 $/tCO_2$.	DSM programmes for commercial sector tend to be more cost-effective than those for residences.	IEA, 2005; Kushler *et al*., 2004.
Economic and market-based instruments							
Energy performance contracting	DE, AT, FR, SE, FI, US, JP, HU	High	FR, SE, US, FI: 20–40% of buildings energy saved; EU:40–55$MtCO_2$ by 2010; US: 3.2 $MtCO_2$/yr.	Medium	EU: mostly at no cost, rest at <22 $/tCO2; US: Public sector: B/C ratio 1.6, Priv. sector: 2.1	Strength: no need for public spending or market intervention, co-benefit of improved competitiveness.	ECCP, 2003; OPET network, 2004; Singer, 2002; IEA, 2003a; World Energy Council, 2004; Goldman *et al*., 2005.

Table 6.6. Continued.

Policy instrument[a]	Examples of countries	Effectiveness[b]	Energy or emission reductions for selected best practices	Cost-effectiveness	Cost of GHG emission reduction for selected best practices[c]	Special conditions for success, major strengths and limitations, co-benefits	References
Co-operative procurement	DE, IT, GB, SE, AT, IE, JP, PO, SK, CH	High	Varies, German telecom company: up to 60% energy savings for specific units.	High	0: Energy-efficient purchasing relies on funds that would have been spent anyway.	Success condition: energy efficiency needs to be prioritized in purchasing decisions.	Oak Ridge National Laboratory, 2001; Le Fur 2002; Borg *et al*., 2003.
Energy efficiency certificate schemes	IT, FR	Medium	IT: 3.64 Mt CO_2 eq by 2009 expected.	Medium	n.a.	No long-term experience yet. Transaction costs can be high. Monitoring and verification crucial. Benefits for employment.	OPET network, 2004; Bertoldi & Rezessy, 2006; Lees, 2006; Defra, 2006.
Kyoto Protocol flexible mechanisms[d]	CN, TH, CEE (JI & AIJ)	Low	CEE: 220 K tCO_2 in 2000.	Low	63 $/$tCO_2$.	So far limited number of CDM & JI projects in buildings.	ECS, 2005; Novikova. *et al*., 2006.
Financial instruments and incentives							
Taxation (on CO_2 or household fuels)	NO, DE, GB, NL, DK, CH	Low	DE: household consumption reduced by 0.9%.	Low		Effect depends on price elasticity. Revenues can be earmarked for further efficiency. More effective when combined with other tools.	World Energy Council, 2001; Kohlhaas, 2005.
Tax exemptions / reductions	US, FR, NL, KO	High	US: 88 $MtCO_2$ in 2006.	High	Overall B/C ratio – Commercial buildings: 5.4 – New homes: 1.6.	If properly structured, stimulate introduction of highly efficient equipment and new buildings.	Quinlan *et al*., 2001; Geller & Attali, 2005.
Public benefit charges	BE, DK, FR, NL, US states	Medium/ low	US: 0.1–0.8% of total electricity sales saved /yr, average of 0.4%.	high in reported cases	From –53 US$/ tCO_2 to –17 $/$tCO_2$.		Western Regional Air Partnership, 2000; Kushler *et al*., 2004.
Capital subsidies, grants, subsidized loans	JP, SI, NL, DE, CH, US, HK, GB	High	SI: up to 24% energy savings for buildings, GB: 3.3 $MtCO_2$; US:29.1 Mio BTU/yr gas savings.	Low	NL: 41–105 US$/ tCO_2 for soc; GB:29 US$/$tCO_2$ for soc, –66 $/$tCO_2$ for end-user.	Positive for low-income households, risk of free-riders, may induce pioneering investments.	ECS, 2001; Martin *et al*., 1998; Schaefer *et al*., 2000; Geller *et al*., 2006; Berry & Schweitzer, 2003; Joosen *et al*., 2004; Shorrock, 2001.
Support, information and voluntary action							
Voluntary certification and labelling	DE, CH, US, TH, BR, FR	Medium/ high	BR: 169.6 $ktCO_2$ in 1998, US: 13.2 $MtCO_2$ in 2004, 2.1 bio tCO_2-eq in total by 2010; TH: 192 tCO_2.	High	BR: US$ 20 million saved.	Effective with financial incentives, voluntary agreements and regulations.	OPET network, 2004; Word Energy Council, 2001; Geller *et al*., 2006; Egan *et al*., 2000; Webber *et al*., 2003.

Table 6.6. Continued.

Policy instrument[a]			Energy or emission reductions for selected best practices	Cost-effectiveness	Cost of GHG emission reduction for selected best practices[c]	Special conditions for success, major strengths and limitations, co-benefits	References
Voluntary and negotiated agreements	Mainly Western Europe, JP, US	Medium/ High	US: 88 $MtCO_2$-eq/yr UK: 15.8 $MtCO_2$	Medium	GB: 54.5–104 US$/$tCO_2$ (Climate Change Agreements).	Can be effective when regulations are difficult to enforce. Effective if combined with financial incentives and threat of regulation.	Geller *et al*., 2006; Cottrell, 2004.
Public leadership programmes	NZ, MX, PH, AR, BR, EC	High	De: 25% public sector CO_2 reduction over 15 years.	High	US DOE/FEMP estimates 4 US$ savings for every 1 US$ of public funds invested.	Can be used to demonstrate new technologies and practices. Mandatory programmes have higher potential than voluntary ones.	Borg *et al*., 2003; Harris *et al*., 2005; Van Wie McGrory *et al*., 2006; OPET, 2004.
Awareness raising, education / information campaigns	DK, US, GB, CA, BR, JP	Low/ Medium	GB: Energy Efficiency Advice Centres: 10.4 K tCO_2 annually.	High	BR: –66 US$/ tCO_2; GB: 8 US$/ tCO_2 (for all programmes of Energy Trust).	More applicable in residential sector than commercial.	Bender *et al*., 2004; Dias *et al*., 2004; Darby, 2006; IEA, 2005; Lutzenhiser, 1993; Ueno et al. 2006; Energy Saving Trust, 2005.
Mandatory audit & energy management requirement	US, FR, NZ, EG, AU, CZ	High, but variable	US: Weatherization Program: 22% saved in weatherized households.	Medium	US Weatherization Program: BC-ratio: 2.4.	Most effective if combined with other measures such as financial incentives	World Energy Council, 2001
Detailed billing and disclosure programmes	ON, IT, SE, FI, JP, NO, CL	Medium	Up to 20% energy savings.	Medium	n.a.	Success conditions: combination with other measures and periodic evaluation. Comparability with other households is positive.	Crossley *et al.,* 2000; Darby 2000; Roberts & Baker, 2003; Energywatch, 2005.

Notes:

Country name abbreviations (according to the ISO codes except California, Ontario, Central and Eastern Europe and European Union): DZ – Algeria, AR – Argentina, AU – Australia, AT – Austria, BE – Belgium, BR – Brazil, CL – California, CA – Canada, CEE – Central and Eastern Europe, CN – China, CR – Costa Rica, CZ – Czech Republic, DE – Germany, Denmark – DK, EC – Ecuador, EG – Egypt, EU – European Union, FI – Finland, FR – France, GB – United Kingdom, HK – Hong Kong, HU – Hungary, IN – India, IE – Ireland, IT – Italy, JP – Japan, KR – Korea (South), MX – Mexico, NL – Netherlands, NO – Norway, ON – Ontario, NZ – New Zealand, NG – Nigeria, PH – Philippines, PO – Poland, SG – Singapore, SK – Slovakia, SI – Slovenia, CH – Switzerland, SE – Sweden, TH – Thailand, US – United States.

a) For definitions of the instruments see: Crossley et al. (1999), Crossley et al. (2000), EFA (2002), Vine et al. (2003) and Wuppertal Institute (2002).

b) Effectiveness of CO2 emission reduction: includes ease of implementation; feasibility and simplicity of enforcement; applicability in many locations; and other factors contributing to overall magnitude of realized savings.

c) Cost-effectiveness is related to specific societal cost per unit of carbon emissions avoided. Energy savings were recalculated into emission savings using the following references for the emission factors: Davis (2003), UNEP (2000), Center for Clean Air Policy (2001). The country-specific energy price was subtracted from the cost of saved energy in order to account for the financial benefits of energy savings (Koomey and Krause, 1989), if they were not considered originally.

d) Kyoto flexible mechanisms: Joint Implementation (JI), Clean Development Mechanism (CDM), International Emissions Trading (includes the Green Investment Schemes).

The effectiveness of economic instruments, information programmes and regulation can be substantially enhanced if these are appropriately combined into policy packages that take advantage of synergistic effects (Ott *et al.*, 2005). A typical example is the co-ordination of energy audit programmes with economic instruments, such as energy taxes and capital subsidy schemes. In addition, ESCOs can flourish when public procurement legislation accommodates EPCs and includes ambitious energy-efficiency or renewable energy provisions, or in the presence of an energy-saving obligation.

Section 6.8 demonstrates that, during the last decades, many new policies have been initiated. However, so far only incremental progress has been achieved by these policies. In most developed countries, the energy consumption in buildings is still increasing (IEA, 2004f). Although some of this growth is offset by increased efficiency of major energy-consuming appliances, overall consumption continues to increase due to the growing demand for amenities, such as new electric appliances and increased comfort. The limited overall impact of policies so far is due to several factors: (i) slow implementation processes (e.g., as of 2006, not all European countries are on time with the implementation of the EU Buildings Directive); (ii) the lack of regular updating of building codes (requirements of many policies are often close to common practices, despite the fact that CO_2-neutral construction without major financial sacrifices is already possible) and appliance standards and labelling; and (iii) insufficient enforcement. In addition, Section 6.7 demonstrated that barriers in the building sector are numerous; diverse by region, sector and end-user group, and are especially strong.

There is no single policy instrument that can capture the entire potential for GHG mitigation. Due to the especially strong and diverse barriers in the residential and commercial sectors, overcoming these is only possible through a diverse portfolio of policy instruments for effective and far-reaching GHG abatement and for taking advantage of synergistic effects. Since climate change literacy, awareness of technological, cultural and behavioural choices and their impacts on emissions are important preconditions to fully operating policies, these policy approaches need to go hand in hand with programmes that increase consumer access to information, awareness and knowledge *(high agreement, medium evidence)*.

In summary, significant CO_2 and other GHG savings can be achieved in buildings, often at net benefit to society (in addition to avoided climate change) and also meeting many other sustainable development and economic objectives, but this requires a stronger political commitment and more ambitious policy-making than today, including careful design of policies as well as enforcement and regular monitoring.

6.9 Interactions of mitigation options with vulnerability, adaptation and sustainable development

6.9.1 Interactions of mitigation options with vulnerability and adaptation

In formulating climate change strategies, mitigation efforts need to be balanced with those aimed at adaptation. There are interactions between vulnerability, adaptation and mitigation in buildings through climatic conditions and energy systems. As a result of a warming climate, heating energy consumption will decline, but energy demand for cooling will increase while at the same time passive cooling techniques will become less effective. The net impact of these changes on GHG emissions is related to the available choice of primary energy used and the efficiency of technologies that are used for heating and cooling needs. Mansur *et al.* (2005) find that the combination of climate warming and fuel switching in US buildings from fuels to electricity results in increases in the overall energy demand, especially electricity. Other studies indicate that in European countries with moderate climate the increase in electricity for additional cooling is higher than the decrease for heating demand in winter (Levermore *et al.*, 2004; Aebischer *et al.*, 2006; Mirasgedis *et al.*, 2006). Aebischer *et al.* (2006) finds that in Europe there is likely to be a net increase in power demand in all but the most northerly countries, and in the south a significant increase in summer peak demand is expected. Depending on the generation mix in particular countries, the net effect on carbon dioxide emissions may be an increase even where overall demand for final energy declines. Since in many countries electricity generation is largely based on fossil fuels, the resulting net difference between heating reduction and cooling increases may significantly increase the total amount of GHG emissions. This causes a positive feedback loop: more mechanical cooling emits more GHGs, thereby exacerbating warming, although the effect maybe moderate.

Vulnerability of energy demand to climate is country- and region-specific. For instance, a temperature increase of 2°C is associated with an 11.6% increase in residential per capita electricity use in Florida, but with a 7.2% decrease in Washington DC (Sailor, 2001). Increased net energy demand translates into increased welfare losses. Mansur *et al.* (2005) found that, for a 5°C increase in temperature by 2100, the annual welfare loss in increased energy expenditures is predicted to reach US$ 40 billion for US households.

Fortunately, there are many potential synergies where investments in the buildings sector may reduce the overall cost of climate change-in terms of both mitigation and adaptation. For instance, if new buildings are constructed, the design can address both mitigation and adaptation aspects. Among the most important of these are reduced cooling loads. For instance, using advanced insulation techniques and passive solar design to reduce the expected increase in air conditioning load. In addition, if high-efficiency electric appliances are used, the savings are increased due to reduced electricity demand for air conditioning, especially in commercial buildings. Roof retrofits can incorporate increased insulation and storm security in one investment. In addition, the integrated design of well-insulated, air-tight buildings, with efficient air management and energy systems, leads not only to lower GHG emissions, but also to reduced thermal stress to occupants, reducing extreme weather-related mortality and other health effects. Furthermore, adaptive comfort, where occupants accept higher indoor (comfort) temperatures when the outside temperature is high, is now incorporated in design considerations, especially for predominantly naturally ventilated buildings (see Box 6.5).

Policies that actively promote integrated building solutions for both mitigating and adapting to climate change are especially important for the buildings sector. It has been observed that building users responding to a warmer climate generally choose options that increase cooling energy consumption rather than other means, such as insulation, shading, or ventilation, which consume less energy. A prime example of this is the tendency of occupants of existing, poorly performing buildings (mainly in developing countries) to buy portable air conditioning units. These trends – which clearly will accelerate in warmer summers to come – may result in a significant increase of GHG emissions from the sector, enhancing the positive feedback process. However, well-designed policies supporting less energy-intensive cooling alternatives can help combat these trends (see Box 6.5 and Section 6.4.4.1). Good urban planning, including increasing green areas as well as cool roofs in cities, has proven to be an efficient way to limit the heat island effect, which also aggravates the increased cooling needs (Sailor, 2002).

6.9.2 Synergies with sustainability in developing countries

The failure of numerous development strategies in the least developed countries, most of them in Africa, to yield the expected results has been attributed to the fact that the strategies failed to address the core needs of such countries – these are economic growth, poverty alleviation and employment creation (OECD, 2001). Often a tension exists between the main agenda of most of these countries (poverty alleviation through increased access to energy) and climate change concerns. Increased access to modern energy for the mostly rural population has been a priority in recent years. Most countries, therefore, place more policy emphasis on increasing the supply of petroleum and electricity than on renewables or energy efficiency (Karakezi and Ranja, 2002). The success of climate change mitigation policies depends largely on the positive management of these tensions. GHG reduction strategies in developing countries have a higher chance of success if they are 'embedded' in poverty eradication efforts, rather than executed independently.

Fortunately, buildings offer perhaps the largest portfolio of options where such synergies can be identified. Matrices in Chapter 12 demonstrate that the impact of mitigation options in the building sector on sustainable development, for both industrialized countries and developing countries, is reported to be positive for all of the criteria used. Both Sections 6.6 above and Box 6.1 discuss many of the opportunities for positive synergies in detail; the next paragraph revisits a few of them.

The dual challenges of climate change and sustainable development were strongly emphasised in the 2002 Millennium Development Goals (MDGs). GHG mitigation strategies are more realizable if they work mutually with MDGs towards the realization of these set objectives. For example, MDG goal seven is to ensure sustainable development, in part by reducing the proportion of people using solid fuels which will lead to the reduction of indoor air pollution (see sections 6.6.1). GHG mitigation and public health are co-benefactors in the achievement of this goal. Similarly, increased energy efficiency in buildings, or considering energy efficiency as the guiding principle during the construction of new homes, will result in both reduced energy bills – enhancing the affordability of increased energy services – and GHG abatement. If technologies that utilise locally available renewable resources in an efficient and clean way are used broadly, this provides access to 'free'

Box 6.5: Mitigation and adaptation case study: Japanese dress codes

In 2005, the Ministry of the Environment (MOE) in Japan widely encouraged businesses and the public to set air conditioning thermostats in offices to around 28˚C during summer. As a part of the campaign, MOE has been promoting summer business styles ('Cool Biz') to encourage business people to wear cool and comfortable clothes, allowing them to work efficiently in these warmer offices.

In 2005, a survey of 562 respondents by the MOE (Murakami *et al.*, 2006) showed that 96% of the respondents were aware of 'Cool Biz' and 33% answered that their offices set the thermostat higher than in previous years. Based on this result, CO_2 emissions were reduced by approximately 460,000 tonnes in 2005, which is equivalent to the amount of CO_2 emitted from about one million Japanese households for one month. MOE will continue to encourage offices to set air conditioning in offices at 28˚C and will continue to promote 'Cool Biz.'

energy to impoverished communities for many years and contributes to meeting other MDGs.

However, for the poorest people in both developing countries and industrialised countries, the main barrier to energy-efficiency and renewable energy investments is the availability of financing for the investments. Devoting international aid or other public and private funds aimed at sustainable development to energy efficiency and renewable energy initiatives in buildings can achieve a multitude of development objectives and result in a long-lasting impact. These investments need not necessarily be executed through public subsidies, but may increasingly be achieved through innovative financing schemes, such as ESCOs or public-private partnerships. These schemes offer win-win opportunities, and leverage and strengthen markets (Blair *et al.*, 2005).

With a few exceptions, energy policies and practices in residential and commercial buildings in sub-Saharan Africa (SSA) do not take efficiency into consideration. However, energy efficiency in buildings has recently been recognised as one of the ways of increasing energy security and benefiting the environment, through energy savings (Winkler *et al.,* 2002). South Africa, for example, has drafted an energy-efficiency strategy to promote efficiency in buildings (DME, 2004). Such policies can be promoted in other SSA countries by linking energy efficiency in buildings directly to the countries' development agendas, by demonstrating how energy efficiency practises contribute to energy security. The positive impacts of these practices, including GHG mitigation, could then be considered as co-benefits.

6.10 Critical gaps in knowledge

During the review of the global literature, a few important areas have been identified which are not adequately researched or documented. First, there is a critical lack of literature and data about GHG emissions and mitigation options in developing countries. Whereas the situation is somewhat better in developed regions, in the vast majority of countries detailed end-use data is poorly collected or reported publicly, making analyses and policy recommendations insufficiently robust. Furthermore, there is a severe lack of robust, comprehensive, detailed and up-to-date bottom-up assessments of GHG reduction opportunities and associated costs in buildings worldwide, preferably using a harmonized methodology for analysis. In existing assessments of mitigation options, co-benefits are typically not included, and in general, there is an important need to quantify and monetize these so that they can be integrated into policy decision frameworks. Moreover, there is a critical lack of understanding, characterisation and taxonomization of non-technological options to reduce GHG emissions. These are rarely included in global GHG mitigation assessment models, potentially largely underestimating overall potentials. However, our policy leverage to realise these options is also poorly understood. Finally, literature on energy price elasticities in the residential and commercial sectors in the different regions is very limited, while essential for the design of any policies influencing energy tariffs, including GHG taxes and subsidy removal.

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