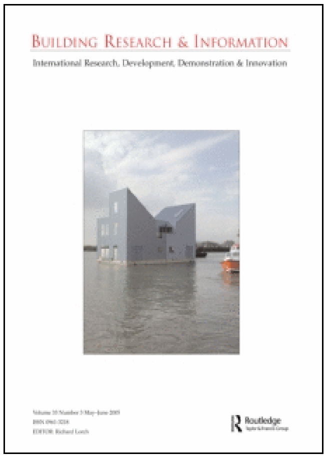

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Mitigating CO_2 emissions from energy use in the world's buildings

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An overview of climate change mitigation opportunities in the world's buildings is presented, based on the key building-specific findings of the Fourth Assessment Report from the Intergovernmental Panel of Climate Change. Buildings and the building stock can play a major role in mitigating climate change in the short- to medium-term, since substantial reductions in CO_2 emissions from their energy use can be achieved over the coming years. 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 negative cost. There are indications that the building stock has the highest share of negative- and low-cost greenhouse gas reduction potential among all sectors. Based on 80 collected national or regional studies estimating CO_2 mitigation potential in five continents, the global potential for CO_2 reductions through buildings is analysed and estimated. The co-benefits associated with the implementation of these measures are also substantial, helping policy-makers justify actions even in the absence of a strong climate commitment. Since the barriers to unlocking the high potentials in the residential and commercial sectors are especially strong, no single instrument can make a large impact. Instead, portfolios of targeted policies tailored to local conditions, combined with strong compliance and enforcement regimes, are needed.

Keywords: building stock, climate change, CO_2 reduction, design, energy efficiency, mitigation, policies

Cet article présente une vue générale des possibilités d'atténuation du changement climatique dans le monde en ce qui concerne le secteur du bâtiment; il repose sur les résultats propres à ce secteur et exposés dans le Quatrième rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC). Les bâtiments et les parcs de bâtiments peuvent jouer un rôle majeur dans l'atténuation du changement climatique à court et à moyen termes puisqu'au cours des années à venir on pourra réduire sensiblement les émissions de CO_2 issues de l'utilisation de l'énergie. Une partie non négligeable de ces économies peut être réalisée de façon à réduire les coûts des cycles de vie, ce qui permet d'obtenir des réductions des émissions de CO_2 ayant un coût négatif net. Certains signes indiquent que parmi tous les secteurs industriels, les parcs de bâtiments offrent la proportion la plus élevée de possibilités de réduction des gaz à effet de serre pour un coût négatif ou faible. S'appuyant sur 80 études nationales ou régionales consacrées à l'estimation des possibilités d'atténuation du CO_2 sur les cinq continents, cet article analyse et évalue les possibilités qu'offrent les bâtiments en matière de réduction des émissions de CO_2 dans le monde. Les avantages connexes associés à l'application de ces mesures sont également substantiels, ce qui aide les décideurs à justifier les mesures qu'ils prennent même lorsqu'ils ne font pas preuve d'un fort engagement envers les questions climatiques.

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Les obstacles au déblocage des possibilités de réduction de ces émissions dans les secteurs des immeubles d'habitation et des bâtiments commerciaux étant particulièrement robustes, aucune mesure prise isolément ne peut avoir un impact important. En revanche, il faut une panoplie de mesures ciblées, élaborées en fonction des conditions locales et associées à des règles fortes de conformité et d'application.

Mots-clés: parc de bâtiments, changement climatique, réduction du CO_2, conception, efficacité énergétique, atténuation, moyens

Introduction

The key findings of the work on mitigation of greenhouse gas (GHG) emissions from energy use in buildings conducted under the framework of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007) are presented here.[1] The aim of this paper is to review the relevance of climate change to professionals working in the construction industry and buildings research; identify the key options to reduce CO_2 emissions in buildings; assess the global potential CO_2 emission reductions buildings can contribute to solving the climate change challenge; identify the co-benefits associated with these mitigation measures as well as the barriers to unlocking the potentials; and, finally, to review the policy options to remove these barriers.

Why should building professionals and researchers be concerned?

Climate change is a matter of great concern to the building-design profession for two reasons. First, energy use in buildings is a significant source of greenhouse gas (GHG) emissions. Energy use in the buildings sector was responsible for 7.85 Gt carbon dioxide (CO_2) emissions in 2002, 33% of the global total of energy-related emissions. Buildings were also responsible for approximately 1.5 Gt CO_2 equivalent emissions from fluorinated gases. The commonly used IPCC Special Report on Emissions Scenarios (SRES) scenarios project growth of these emissions to 11 Gt (B2 scenario) and 15.6 Gt CO_2 (A1 scenario) by 2030 (Nakićenović *et al.*, 2000), with the share of the sector remaining at approximately 34% of the total. In Organization for Economic Co-operation and Development (OECD) countries as a whole, buildings account for about 35–40% of national CO_2 emissions from the use of fossil fuels. This includes direct on-site emissions from the use of natural gas and oil (primarily) for heating and cooling, as well as emissions from the generation of that portion of electricity used in buildings (buildings account for about 50% of total electricity consumption in OECD countries). In developing countries, coal and biomass are significant sources of energy for heating, invariably with significant adverse effects on the building occupants.

Second, global warming and associated changes in climate (such as possible increases in the intensity of tropical storms or in the intensity of heavy rainfall events) will directly impact buildings. Although heating energy use will decrease, the demand for cooling will increase. At the same time, many of the passive and low-energy techniques for cooling buildings that are needed to reduce the contribution of buildings to GHG emissions (such as evaporative cooling, or night ventilation) will become less effective as heat waves become more intense and longer-lasting.

A key parameter in assessing the severity of climatic change is *climate sensitivity* – commonly interpreted as the long-term, global average warming expected for a doubling of atmospheric CO_2 concentration (or for a combination of increases in CO_2 and other GHGs that trap the same amount of heat).[2] A very wide body of evidence indicates that the climate sensitivity is very likely to fall to between 1.5 and 4.5°C (for a compact summary, see Harvey, 2007).

Given that, under business-as-usual scenarios of increasing energy use and GHG emissions (Nakićenović *et al.*, 2000), the equivalent of twice the pre-industrial CO_2 concentration of 280 ppmv will be reached before mid-century, and the equivalent of three to four times pre-industrial CO_2 (if the heating effect of other GHGs is accounted for), it is clear that even a climate sensitivity of 2°C could lead to changes in global average climate of up to 4°C by the end of the century. A 4°C global mean warming is comparable with the difference between an ice age and interglacial climate (4–6°C), but the change would occur 100 times faster than the transition at the end of the last Ice Age. A larger climate sensitivity would produce a disproportionately larger temperature increase due to positive feedbacks between warming and the global carbon cycle (such that warming provokes additional, natural emissions of CO_2 from various hitherto stable carbon pools – another matter of grave concern). However, the IPCC AR4 WG2 assessment indicates that there is a continuum of increasingly severe and pervasive negative impacts beginning with as little as 0.6°C global mean warming, and indeed, we are already beginning to see a variety of negative ecological impacts.[3] At 1–2°C global mean warming most to all coral reefs will be severely degraded; while a warming of 2°C could commit one-sixth to one-third of animal species on land to extinction (Thomas *et al.*, 2004);

and a sustained 3–4°C warming is likely to provoke the complete melting of the Greenland Ice Cap and risks destabilizing the West Antarctic Ice Sheet, with an eventual sea level rise from the two of more than 10 m (Harvey, 2000). Severe water stress and crop failure would be common in many parts of the world not already subject to such hazards.

It is therefore of the utmost urgency to reduce global GHG emissions as rapidly as possible. Because of the significant contribution of buildings to GHG emissions, building engineers and architects need to become deeply involved in the drive to reduce energy use in buildings – both in the design of new buildings and through the refurbishment of existing buildings. A difficult but still feasible goal would be for atmospheric CO_2 concentration to peak at 450 ppmv (compared with 380 ppmv at present and a pre-industrial concentration of 280 ppmv). With the heating effect from other GHGs, this is the equivalent of a CO_2 doubling, and so already runs a substantial risk of severe negative impacts (given a climate sensitivity of 2–5°C). For CO_2 to peak at 450 ppmv, fossil fuel emissions will have to be eliminated by the end of this century (Harvey, 2004). That in turn requires a massive increase in the supply of carbon-neutral energy sources combined with dramatic improvements in the efficiency with which energy is used in all sectors. In particular, reductions in the building energy intensity (on-site energy use per year per unit of floor area) by a factor of 2–3 by 2050 will likely be necessary (as discussed by Harvey, 2006, ch. 1). Depending on the rate of renovation or replacement of existing buildings, this requires reductions in the energy intensity of new buildings by a factor of 3–4 compared with recent practice, and reductions by at least a factor of 2 during renovations. This is an awesome challenge.

However, the present paper demonstrates that there is a plethora of opportunities in buildings to achieve these goals in the vast majority of climatic regions, at little or moderate extra cost. In fact, the IPCC Fourth Assessment Report concludes (2007, ch. 11) that among all sectors, buildings[4] house by far the largest portion of negative- and low-cost mitigation opportunities. Therefore, being one of the largest GHG emitters as well as offering many of the lowest-cost reduction measures, the buildings sector is fundamentally important for any climate change mitigation effort.

CO_2 mitigation options in buildings and equipment

Overview of energy use in buildings

In order to assess the potential to reduce energy use in buildings at a global scale, it is important to know the relative importance of different uses of energy in different kinds of buildings in different climates, the relative shares of different kinds of buildings to total building energy use, and how these might change over time.

Figures 1 and 2 show the breakdown of energy use in residential and commercial buildings in the US, Canada and European Union (EU). The single largest use of energy in residential buildings in these regions is for space heating, followed by water heating. Space heating is also the single largest use of energy in commercial buildings in Canada and the EU, accounting for up to two-thirds of total energy use. 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.

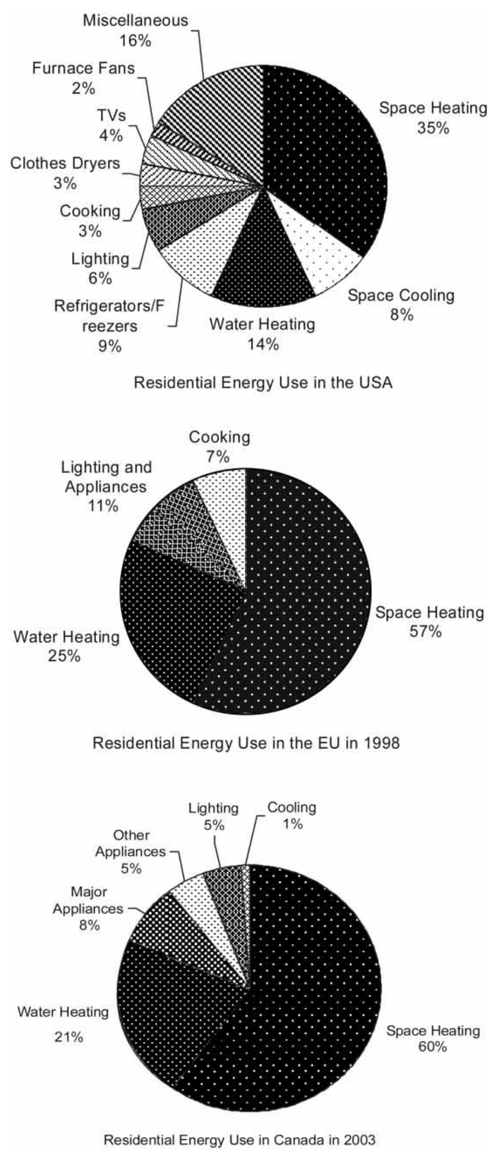

Figure 1 Breakdown of residential energy use in (a) the US, (b) the European Union and (c) Canada. Sources: (a) Koomey *et al.* (2000), (b) European Commission (2001) and (c) NRCan (2005)

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.

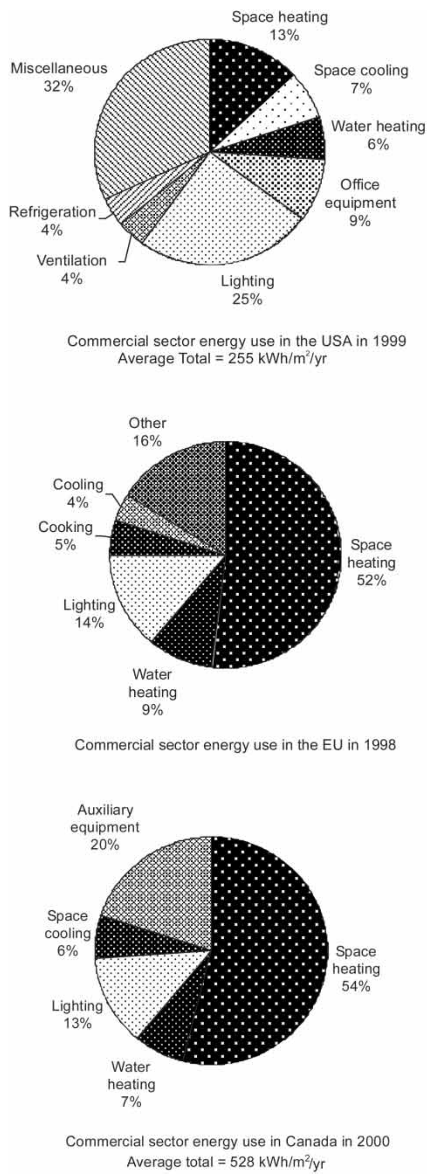

Figure 2 Breakdown of commercial sector energy use in (a) the US in 1999, (b) the European Union in 1998 and (c) Canada in 2000. Sources: (a) Energy Information Administration (http://www.eia.doe.gov), (b) European Commission (2001) and (c) Anne Auger, Natural Resources Canada, personal communication, 2005

Reduce heating and cooling loads

Heating loads can be reduced through the use of a high-performance envelope (insulation, windows, air tightness) combined with heat-recovery ventilation. Optimized building form and orientation can also make a significant contribution, as can extensive equatorward-facing windows combined with internal thermal mass to avoid daytime overheating and to release stored heat at night. The European Passive House Standard and advanced houses in Canada and the US achieved reductions in heating energy use by 75–90% in this way compared with recent conventional practice (Harvey, 2006, ch. 13, sect. 13.2). A number of commercial buildings have achieved 50–80% reductions in heating energy use in cold climates compared with recent conventional practice (Harvey, 2006, ch. 13, sect. 13.3). Vacuum insulation, although presently expensive, can be very effective in upgrading insulation levels in existing buildings, as the allowable thickness of the insulation is a constraint, but vacuum insulation panels are about ten times thinner than regular insulation for the same thermal resistance.

External cooling loads can be reduced through the use of high-reflectivity building surfaces, external shading devices aided by optimal building form and orientation, glazing with low solar-heat gain, and a combination of night-time ventilation, internal thermal mass, and external insulation. High-efficiency lighting systems and efficient equipment (which produce less waste heat) can significantly reduce internal heat gains. Overall load reductions by a factor of 2 are possible in many climates.

As noted above, thermal mass in combination with other design features can be used to reduce both heating and cooling loads. Increased thermal mass implies an increase in the amount of energy embodied in the materials that go into the building. However, the building operating energy is usually equal to only a few years' operating energy, so an increase in the embodied energy – if optimized to reduce operating energy – can result in a substantial decrease in life cycle energy use, as discussed by Harvey (2006, ch. 14). Increased thermal mass can also provide increased resistance to storms.

Utilize passive solar energy for heating and ventilation and passive heat sinks for cooling

Solar energy can be utilized passively for heating through the use of high-performance windows (whole-window *U*-value <1 W/m^2/K) facing south. Such windows are a net source of heat over the course of the heating season in moderately cold climates such as Central Europe or Southern Canada. Solar energy can also be used passively for ventilation. Natural ventilation can be driven by pressure differences between different parts of the building, which in turn are due to temperature differences between the inside and outside that in turn depend on differential solar heating, and will be strongest during the winter. Systems such as transpired solar collectors and air-flow windows can be used to at least partially preheat cold outside air as it is drawn inside. Solar chimneys and design features such as atria and interior courtyards with cross-flow pathways can be particularly effective in inducing natural ventilation during the summer. Natural ventilation can also be induced through wind towers and wind cowls designed to enhance natural driving forces from winds. Cooling towers – in which a fine mist is used to cool air evaporatively to create a cool downdraft – are another option that has been used successively in India and in the Southwest US.

In temperate climates there will be many weeks when natural ventilation with ambient air will provide adequate cooling, whereas mechanical cooling would be required in the absence of outdoor ventilation because building temperatures tend to rise several degrees above ambient temperatures in the absence of ventilation. The potential saving in energy use is amplified by the fact that building occupants have been found to tolerate warmer temperatures better if a building is naturally rather than mechanically ventilated (de Dear and Brager, 2002). Double-skin facades serve as an architecturally interesting option for facilitating natural ventilation along with external adjustable shading devices. Some passively driven systems draw outside air through an underground earth-pipe, preheating the air in the winter but cooling it during the summer, thereby extending the time during which mechanical cooling can be avoided. In many climates, night-time ventilation combined with internal thermal mass (which absorbs heat during the day and releases it to cool night air) and external insulation (so that the thermal mass interacts largely with interior air) is an effective, low-energy method to reduce cooling energy requirements (Springer *et al.*, 2000; da Graça *et al.*, 2002).

Evaporation of liquid water cools the remaining liquid water, which in turn will draw sensible heat from the surrounding air. The temperature that can be achieved in this way is referred to as the wetbulb temperature, and in most parts of the world the wetbulb temperature is cool enough to provide adequate cooling most of the time (see the summary tables in Harvey, 2006, ch. 6). 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.

A group in California has developed an indirect-direct evaporative cooling system with a coefficient of performance (COP, or cooling power divided by fan power, a direct measure of efficiency) ranging from about 12 when the fan is operating at high speed to about 40 at low speed (Davis Energy Group (DEG), 2004). Simulations for a house in a variety of California climate zones indicate savings in annual cooling energy use of 92–95%; estimated cooling energy savings for a modular school classroom are 89–91% (DEG, 2004).

Desiccants can be used to extend the range of evaporative cooling fully into hot–humid climates while making use of solar energy. Desiccant dehumidification and cooling involves using a material (desiccant) that removes moisture from the air and which is regenerated using heat. Solid desiccants are a commercially available technology. The energy used for dehumidification can be reduced by 30–50% compared to a conventional system, and by 50–75% if solar energy is used to regenerate the desiccant (Fischer *et al.*, 2002; Niu *et al.*, 2002).

Utilize active solar energy

Building-integrated photovoltaic panels (BiPV) can be used to generate electricity on-site, and can also serve other functions – such as external shading or being an architectural design element in their own right. Flat-plate solar thermal collectors can also be integrated into the building envelope and used to provide a portion of hot water requirements year round, space heating requirements in winter, and to regenerate desiccants in summer when humidification and cooling are required. BiPV systems are expensive at present, as modules are currently around US\$3–4/W_p, but they can be expected to reach US\$1/W_p within a decade or so (Hegedus, 2006; Swanson, 2006), which would make BiPV competitive for peak power in many jurisdictions. Solar thermal energy is competitive and used widely for water heating in many jurisdictions at present, including Israel, Greece and Malta.

Utilize efficient HVAC systems

The energy used by HVAC systems depends as much if not more on the way in which the system components are configured, as it does on the efficiency of the individual components. Five important principles in minimizing HVAC energy use are as follows:

- to separate heating/cooling and ventilation functions
- to separate cooling and dehumidification functions
- to distribute heat at the lowest possible temperature and coldness at the warmest possible temperature

- to use displacement ventilation rather than turbulent ventilation
- to account for psychological adaptation to changing outdoor temperatures

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. Water is 25–100 times more effective than air as a heat transfer fluid. Thus, energy can be saved by using chilled or hot water for temperature control, and circulating only the volume of air needed for ventilation. This allows use of 100% outside air (at much lower volumes) rather than recirculating a portion of the indoor air, thereby providing health benefits and providing further energy savings due to the fact that internal heat gains are directly vented to the outside rather than partly recirculated, as in conventional systems. Savings with fixed ventilation rates but decoupled from cooling of 20–30% are reasonable. However, the required ventilation airflow – now decoupled from heating or cooling functions – can be made to vary with changing building occupancy. A demand-controlled ventilation (DCV) system uses CO_2 and/or other sensors to adjust the ventilation rate, with 20–30% savings in total HVAC energy use compared with ventilation at a fixed rate based on maximum occupancy (Brandemuehl and Braun, 1999).

In most commercial buildings with air-conditioning, dehumidification is accomplished by overcooling the air so as to condense sufficient water vapour, then reheating the air so that it can be supplied at a comfortable temperature. As previously noted, dehumidification can be decoupled from cooling through a variety of desiccant-based techniques, with energy use savings of 25–30%, or by up to 50% if solar heat is used to regenerate the desiccant (Harvey, 2006, ch. 7).

A room may be cooled by chilling a large fraction of the ceiling by circulating water through pipes or lightweight panels. This is referred to as *chilled ceiling* cooling. Significant energy savings arise because of the aforementioned greater effectiveness of water than air in transporting heat, and because the chilled water is supplied at 16–20°C rather than at 5–7°C, as in conventional hydronic cooling systems. 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).

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. This is more effective at removing contaminants than conventional turbulent mixing ventilation, permitting a factor of 2 smaller airflow rate. Also, the supply air temperature is significantly higher for the same comfort conditions (about 18°C versus about 13°C in a conventional mixing ventilation system), resulting in more efficient chiller operation. DV can reduce energy use for cooling and ventilation by 30–60% depending on the climate (Bourassa *et al.*, 2002; Howe *et al.*, 2003).

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). In particular, temperatures up to 28°C are acceptable on hot days, particularly if individually controlled fans are available to create air speeds of about 0.5 m/s and if natural ventilation through operable windows is allowed. Computer simulations indicate that increasing the thermostat from 24 to 28°C will reduce annual cooling energy use by more than a factor of 3 for a typical office building in Zurich, Switzerland, and by more than a factor of 2 in Rome, Italy (Jaboyedoff *et al.*, 2004). Simulations by Lin and Deng (2004) point to a factor of 2–3 reduction if the thermostat setting is increased from 23 to 27°C for night-time air-conditioning of bedrooms in apartments in Hong Kong.

Utilize efficient equipment, properly sized, and fully commissioned

The efficiency of equipment in buildings continues to increase in most industrialized and in many developing countries, as it has over the past quarter century. Choosing the most efficient equipment (boilers, motors, fans, chillers, air-conditioners, appliances, and office equipment) reduces energy consumption directly and also reduces cooling loads. However, most heating and cooling equipment is grossly oversized, leading to less efficient part-load operation. For example, based on a detailed analysis of six buildings in Hong Kong, Lee *et al.* (2001) found that more realistic sizing of the cooling equipment alone would have reduced annual cooling energy use by 6–22% and reduced the size of the chilling equipment by 32–46% (thus significantly reducing the capital cost).

Building energy management systems (BEMSs) involve computer and distributed, microprocessor-based systems for monitoring, data storage, communication, and control (Levermore, 2000). Estimates of energy savings using BEMSs range from 5 to 40% (Hyvarinen, 1992; Brandemuehl and Braun 1999; Levermore, 2000); up to 20% in space heating energy consumption and 10% for lighting and ventilation; and 5–20% overall (Roth *et al.*, 2005).

Proper commissioning of the energy systems in a commercial building is a key to its efficient operation. Building commissioning is a quality control process that begins with the early stages of design. Recent results of building commissioning in the US show energy savings of up to 38% in cooling and/or 62% in heating, and an average higher than 30% (Claridge *et al.*, 2003).

Utilize efficient lighting systems complemented with daylighting

Continuous improvements in the efficacy[5] of electric lighting devices have occurred during the past five to ten years, and can be expected to continue. Advances have also occurred in occupancy-sensor technology (Garg and Bansal, 2000). Compact fluorescent lamps (CFLs) provide four to five times the lumens per watt of incandescent lamps, and can be purchased for as low as US$2 in many countries – a significant drop during the last few years. Altogether, a reduction in residential lighting energy use of a factor of 4–5 can be achieved compared with incandescent/halogen lighting.

For lighting systems providing uniform lighting in commercial buildings, the energy required can be reduced by 50% or more compared with old T12 systems through use of efficient lamps (T5 or recent T8), ballasts, and reflectors, occupancy sensors, and lighter colour finishes and furnishings. A further 40–80% of the remaining energy use can be saved in perimeter zones through daylighting (e.g. Rubinstein and Johnson, 1998; Bodart and Herde, 2002). A simple strategy to reduce energy use further 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 also it provides a greater degree of individual control over personal lighting levels.

System approaches to energy efficiency and the critical role of the design process

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 are no more expensive than conventional buildings, but with much increased energy efficiency (for examples, see Harvey, 2006, chs 4 and 13).

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: (1) selecting a high-performance envelope and highly efficient equipment, properly sized; (2) incorporating a building energy-management system that optimizes the equipment operation and human behaviour; and (3) fully commissioning and maintaining the equipment (Todesco, 2004). These steps alone can usually achieve energy savings on the order of 35–50% for a new commercial building compared with standard practice, while utilization of more advanced or less conventional approaches has often achieved savings on the order of 50–80% (Harvey, 2006, ch. 13).

Energy savings through retrofits of existing buildings

There is a large stock of existing, inefficient buildings, most of which will still be here in 2025 and even 2050. The 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.

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 and window joists; weather stripping of windows and doors; and adding insulation in attics 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 door wood frames, sealing of suspended timber ground floors, and repair of defects 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 believe that a reduction of 50% could be achieved at modest cost using well-proven (early 1980s) technologies, and a further 30–40% reduction through additional measures.

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 8 measured reduction in the heating energy use (http://www.3lh.de). An envelope upgrade of an apartment block in Switzerland after retrofitting reduced the heating requirement by a factor of 2, 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 75% (Humm, 2000).

There are numerous published studies, summarized by Harvey (2006, ch. 14), showing that energy savings of 50–75% can be achieved in commercial buildings through aggressive implementation of integrated sets of retrofit 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 US$10 million 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.

Standard retrofit measures such as thermal envelope upgrades can be combined with more radical measures that 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 facade-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 facade over the original facade. Energy savings of 40–70% have been achieved in this way, as documented by Boonstra and Thijssen (1997), Haller *et al.* (1997), and Voss (2000a, b).

Costs and potentials

Analysis of CO_2 reduction potential in buildings worldwide

There is a general lack of literature that quantifies the global potential for GHG mitigation or energy-efficiency improvements in the world's buildings. To fill this gap an analysis was conducted in the context of this study based on national and regional studies, which are more abundant. The present findings are based on 80 collected national or regional studies estimating CO_2 mitigation potential in five continents. While there were methodological challenges associated with aggregating the figures to a global level and in comparing results from analyses resting on different assumptions, a rigorous methodology was applied to minimize the impacts of these variances. It is beyond the scope of this paper to describe these methods, but they are described in more detail in other publications (Ürge-Vorsatz and Novikova, 2006). In summary, mainly bottom-up studies estimating CO_2 savings from the demand-side in 2020 using either the business-as-usual scenario or frozen efficiency baseline and discount rate in the interval of [3%; 10%] were selected and analysed. Since most studies reviewed covered a limited number of measures or options, the estimates are low estimates of the real mitigation potential.

Table 1 provides a summary for the estimates of different types of CO_2 mitigation potential in different world regions and countries and it ranks the most promising options in terms of the size of potential and its mitigation cost. According to Table 1, estimates of technical potential range from 18% of CO_2 emissions in Pakistan in 2020, where only a limited number of options was considered, to 54% in 2010[6] in a Greek study that covered a very comprehensive range of measures in the residential sector. The estimates of economic potential vary from 12% in the EU-15 in 2010[7] to 52% in Ecuador in 2030.[8] Estimates of market potential in developed countries range from 14% in Croatia focusing on four options only to 37% in the US, where a wide range of policies were appraised.

Table 1 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. 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 (EiT, which have typically cooler climates) have found heating-related measures to be most cost-effective, including insulation

Table 1 Greenhouse gas emissions reduction potential for the buildings stock in 2020

Economic region	Countries/country groups reviewed for region	Potential as a percentage of the national baseline for buildings	Measures covering the largest potential	Measures providing the cheapest mitigation options
Developed countries	US, EU-15, Canada, Greece, New Zealand, Australia, Republic of Korea, UK, Japan, Germany	Technical: 21–54%[a] Economic: 12–25%[b] Market: 15–37%	1. Shell retrofit, including insulation, especially windows and walls 2. Space heating systems and standards for them 3. Efficient lights, especially shift to CFLs and efficient ballasts	1. Appliances such as efficient televisions and peripheries (both on-mode and standby), refrigerators and freezers, followed by ventilators and air-conditioners 2. Water heating equipment 3. Lighting best practices
Economies in transition	Hungary, Russia, Poland, As a group: Latvia–Lithuania–Estonia, Slovakia, Slovenia, Hungary, Malta, Cyprus, Poland, Czech Republic	Technical: 26–47%[c] Economic: 13–37%[d] Market: 14%	1. Pre- and post-insulation and replacement of building components, especially windows 2. Efficient lighting, especially shift to CFLs 3. Efficient appliances such as refrigerators and water heaters	1. Efficient lighting and its controls 2. Water and space heating control systems 3. Retrofit and replacement of building components, especially windows
Developing countries	India, Indonesia, Argentina, Brazil, China, Ecuador, Thailand, Pakistan, Middle East as a group	Technical: 18–41%[e] Economic: 13–52%[f] Market: 23%	1. Efficient lights, especially shift to CFLs, light retrofit, and kerosene lamps 2. Various types of improved cook stoves, especially biomass stoves, followed by LPG and kerosene stoves 3. Efficient appliances such as air-conditioners and refrigerators	1. Improved lights, especially shift to CFLs light retrofit, and efficient kerosene lamps 2. Various types of improved cook stoves, especially biomass based, followed by kerosene stoves 3. Efficient electric appliances such as refrigerators and air-conditioners

Notes: [a]Both numbers are for 2010. If the approximate formula of [$\text{Potential}_{2020} = (1 - (1 - \text{Potential}_{2010})^{20/10}$] is used to extrapolate the potential to 2020 as a percentage of the baseline into the future (2000 is assumed as a start year), this interval would be 38–79%.

[b]Both for 2010; if the suggested extrapolation formula is used, this interval would be 22–44%.

[c]Last figure is for 2010; it corresponds to an approximately 72% potential in 2020 if the suggested extrapolation formula is used.

[d]First figure is for 2010; it corresponds to 24% in 2020 if the extrapolation formula is used.

[e]Studies that investigated and identified very high economic potential in developing countries did not focus on the details of the technical potential. This is why the highest threshold of the technical potential is lower than that of the economic potential for this group of countries.

[f]Last figure is for 2030; it corresponds to 38% in 2020 if the suggested extrapolation formula is applied to derive the intermediate potential.

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. Air-conditioning savings can be more expensive than other efficiency measures but can still be cost-effective because they tend to displace more expensive peak power. 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, 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.

Global CO_2 mitigation potential as a function of cost

While there are methodological challenges in aggregating figures of the discussed studies having differing assumptions, the authors have made a best estimate for the regional and global potentials in the buildings sector. The calculations suggest that by 2020, globally, approximately 29% of the sectoral baseline emissions in 2020 can be avoided through mitigation measures in the buildings sector cost-effectively; additionally at least 7% of baseline emissions can be mitigated if costs up to US$100/t CO_2 will be considered, although this figure probably does not represent the real potential in this category but rather the fact that few studies assessed potentials in these high cost categories when significant low-cost potentials exist. Using the baseline CO_2 emission projections calculated on the basis of reviewed studies, this estimate of the global economic potential represents a reduction of approximately 3.2 billion tons of CO_2 equivalent in 2020. Due to the limited number of demand-side end-use efficiency options considered by studies, the actual economic potential is likely to be higher.

Table 2 provides more detailed information on the CO_2 mitigation potential in buildings split into different country groups. It demonstrates that transition economies promise the largest technical and economic potentials. This phenomenon is explained by the large stock of old appliances and by use of traditional lights, whose turnover would quickly pay itself back through electricity savings. Additionally, generous and cheap energy savings and CO_2 emission reductions are related to the installation of heat, water heat, and light controls in the buildings of this region. Developing countries enjoy the largest share of cheap potential in the total amount due to abundant opportunities to save electricity in buildings, typically from lights and appliances.

Summary: potentials and costs of CO_2 mitigation in the world's buildings

This section shows that substantial cost-effective reduction in CO_2 emissions from energy end-use in the buildings sector can be achieved over the coming years. For the countries reviewed, these estimates were in the range 12–52% of their business-as-usual scenarios in 2020. The conclusion is that in 2020 the low global estimate of economic mitigation potential is 29% of the business-as-usual CO_2 emission projections. Using the baseline CO_2 emission projections calculated on the basis of reviewed studies, this estimate represents a reduction of approximately 3.2 billion

Table 2 Potential for CO_2 emission reduction in buildings in 2020

Regions	Baseline projections in 2020	CO_2 mitigation potential in 2020 (at cost up to 100 US$2000/tonnes CO_2)	CO_2 mitigation potential as a share (%) of the baseline in cost categories in 2020 (costs are in US$2000/tonne CO_2)			
	billion tonnes CO_2	total, billion tonnes CO_2	<0	0–20	20–100	Total
Global total	**11.1**	**4.0**	**29**	**3**	**4**	**36**
Developed countries	4.8	1.6	27	3	2	32
Pacific OECD	0.65	1.0	33	2	1	36
North America OECD	2.7	0.10	18	0	1	19
Western Europe	1.4	0.45	21	4	6	31
Transition economies: CEE and FSU	1.3	0.85	29	12	23	64
Developing countries	5.0	1.6	30	2	1	32
Latin America	0.45	0.30	27	0	0	27
Africa/Middle East	1.3	0.10	18	3	4	25
Asia	3.3	1.2	35	1	0	36

Note: CEE, Central European Economies; FSU, Former Soviet Union.

tons of CO_2 equivalent in 2020. The analysis shows that transition economies as well as developing countries still have a higher abundance of 'low-hanging fruit'. This high potential in transition economies is associated with cheap electricity savings from the exchange of old appliances and lights; at the same time these countries accumulated a large potential associated with more efficient but expensive shell retrofit and fuel-switching options. In addition, developing countries possess the largest share of cheap potential in the total amount as compared with other regions due to prevailing electricity-saving options.

Additional promises: co-benefits associated with measures to reduce CO_2 emissions in buildings

The paper so far has identified the large number of opportunities in buildings that can cut CO_2 emissions, as well as operational costs, to a significant extent. Many of them are associated with little to no extra life-cycle expenditures. A global analysis has attested that buildings are among the ideal targets of GHG mitigation strategies: they house a significant amount of low-cost reduction potential, larger than in any other sector. In addition to these benefits already highlighted, this section will identify a range of other benefits associated with the implementation of the aforementioned CO_2 saving measures. Identifying the co-benefits is important for a policy-making perspective: while a single goal, such as GHG emission reduction or costs savings for consumers, alone might not appear to be sufficient for political attention or to justify government action, a combination of these benefits might. At the same time, accounting for these co-benefits, the specific costs of such policies or measures can be significantly reduced. Thus, a proper assessment of co-benefits provides major opportunities for policy integration.

Improved social welfare and poverty alleviation

Improving residential energy efficiency and local energy generation 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 per year 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 countries where energy subsidies have been removed. This process is often combined with social subsidies to ease the burden of growing utility bills. In economies in transition this situation provides an opportunity to redirect social programmes aimed at compensating for increasing fuel tariffs 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 Novikova, 2006).

In developing countries, energy-efficient household equipment and low-energy building design can contribute to poverty alleviation by minimizing energy expenditures, therefore making more energy services affordable for constrained incomes (Goldemberg, 2000). The 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.

Reduction in local/regional air pollution

Climate change mitigation through energy efficiency in the residential and commercial sectors will improve local and regional air quality, particularly in large cities where huge amounts of primary energy sources are consumed for space heating and other energy uses, contributing to improved public health (e.g. increased life expectancy, reduced emergency room visits, reduced asthma attacks, fewer lost work days) and avoidance of structural damage to buildings and public works. As an example in China, the replacement of residential coal burning by large boiler houses providing district heating is shown to be among the abatement options providing the largest net benefit per ton of CO_2 reduction, when the health benefits from improved ambient air conditions are accounted for (Mestl *et al.*, 2005). Furthermore, 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 in the economic analysis.

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 3 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 to chronic obstructive pulmonary disease in adults that 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; UN, 2002; Smith *et al.*, 2004).

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. The value of these co-benefits may amount to the same order of magnitude as the economic value of the energy saved or more (Jochem and Madlener, 2003). In addition, better insulated buildings eliminate moisture problems associated with, for example, thermal bridges (i.e. heat losses through the structural components of a building) and damp basements, and thus reduce the risk of mould build-up and associated health risks.

Improved productivity and economic competitiveness

There is increasing evidence that well-designed, energy-efficient buildings often have better productivity and occupant health (Leaman and Bordass, 1999; Fisk, 2000, 2002). As an example, it has been shown that high-quality energy-efficient space conditioning and lighting enhance employee productivity and reduce absenteeism in offices, factories, and schools, and can increase sales in retail environments. Assessing these productivity gains is difficult (CIBSE, 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, 2001).

Employment creation and new business opportunities

Most studies agree that energy-efficiency investments will have positive effects on employment by creating new business opportunities and thus jobs via domestically produced energy-efficient technologies and services, and through the economic multiplier effects of spending in other ways the money saved on energy costs (Jochem and Madlener, 2003). Further, a national policy that promotes both the production and use of energy-efficient technologies helps all sectors of the country to compete internationally, thus contributing to economic development and job creation.

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). Data on energy service company (ESCO) industry revenues demonstrate that the energy services business appears to be both a very promising and a quickly growing trade worldwide. In the US, for example, the ESCO industry's revenues have grown from US$450 million per year in 1995 to approximately US$2 billion in 2000 with a yearly growth rate of almost 24%.

The European Commission (2005) estimates that a 20% reduction in EU energy consumption by 2020 can potentially create (directly or indirectly) as many as 1 million new jobs in Europe. The strongest effects are expected in the area of semi-skilled labour in the buildings trade, which also affords the strongest regional policy effects (Jeeninga *et al.*, 1999; European Commission, 2003). The German Council for Sustainable Development (2003, cited in European Commission, 2005) estimates that more than 2000 full-time jobs could be created for each 1 million tons of oil equivalent that will be saved as a result of measures and/or investments specifically taken to improve energy efficiency, as compared with equivalent investments in energy production. Energy efficiency can also contribute to regional and rural development benefits and to social cohesion because of the decentralized nature of energy-efficiency actions.

Energy security

Additional co-benefits of improved energy efficiency and building-integrated distributed generation include improved energy security and system reliability (International Energy Agency (IEA), 2004), as energy conservation measures and enhanced exploitation of renewables lead to less dependence on (often imported) expensive fuels, lower energy costs to the economy, and slower resource depletion. 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 macroeconomic benefits because reduced energy imports will improve the trade balances of importing countries (European Commission, 2003).

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. 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). 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.

Barriers

The previous sections have shown the significant cost-effective potential for CO_2 mitigation through energy efficiency in buildings. There are, however, substantial barriers that need to be overcome to achieve these reductions in GHG emissions. 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. These barriers could be classified into four main categories: real market failures; financial costs/benefits; behavioural/organizational non-optimalities; and hidden costs/benefits (Carbon Trust, 2005). The most important among them that pertain to buildings are discussed below in further detail.

The first category is based on *market failures* that prevent the benefits of energy-efficiency investments. For example, a fragmented market structure and the linear and sequential process that is followed in the typical design process prevent energy-efficient building design. Minimizing energy use requires optimizing the system as a whole by systematically addressing building form, orientation, envelope, glazing area, and a host of interaction and control issues involving the building's mechanical and electrical systems. This is more evident in larger, commercial buildings, but is present to some degree even in smaller residential and non-residential buildings. However, the division of responsibilities in the typical design process often contributes to suboptimal results.

Furthermore, the end-users of the buildings have been separated from the process that creates the building in which they live or work. The primary focus of the developer is minimizing cost and this often leads to poor levels of energy-efficiency investment (Jones *et al.*, 2002). More generally when intermediaries are involved in decisions to purchase energy-using or energy-saving technologies, the consumer's role is limited and often leads to lower investments in energy efficiency. For example, in residential buildings, landlords often provide the air-conditioning equipment and major appliances, while the tenant pays the electricity bill. As a result, the landlord is not likely to invest in energy efficiency, since he is not rewarded for the investment. These and similarly misplaced incentives have been referred to in the literature as the principal–agent barrier.

There are also several regulatory barriers that hinder the penetration of energy-efficient technologies and particularly building-level-distributed generation technologies such as photovoltaic panels, reciprocating engines, gas turbines, and fuel cells (Alderfer *et al.*, 2000). In many countries these barriers include variances in environmental-permitting requirements that impose significant burdens on project developers.

Lastly, information about energy-efficiency options is often incomplete, unavailable, expensive and difficult to obtain or trust (Lützkendorf and Lorenz, 2005; Lützkendorf and Speer, 2005). In addition, only a few small enterprises in the building industry have access to sufficient training in new technologies, new standards, new regulations and best practices. A similar situation exists for building officers in local authorities. This insufficient knowledge is compounded by uncertainties associated with energy price fluctuations, which lead to high hurdle rates (i.e. the expected rate of return on a potential investment required by the investor) and a slow pace of technology diffusion (Hassett and Metcalf, 1993).

A second category of barriers concerns the *economics of the various energy-efficiency opportunities*. The vast majority of energy-efficient technologies and interventions are characterized by generally higher up-front cost but lower operating cost compared with a baseline or business as usual situation. However, the limited availability of capital as well as limited access of low-income households and small businesses to capital markets hinders the penetration of these technologies in the buildings sector in many countries and particularly in developing countries (Reddy, 1991).

Furthermore, in many countries several fuels, including electricity, natural gas and district heat for residential customers, and sometimes for commercial or governmental customers as well, historically has been subsidised, 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 (Gritsevich, 2000). Energy pricing that does not reflect the long-term marginal costs of energy, or that includes 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.

In addition, in almost all countries energy and electricity prices do not fully reflect the environmental damage and the other externalities associated with energy production and consumption. Several climate mitigation studies focusing on the buildings sector maintain that if these externalities associated with the implementation of 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).

Finally, one should take into account the fact that 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 (i.e. costs related to verifying technical information, preparing viable projects, and negotiating and executing contracts), prevent energy-efficiency investments. For households in more affluent social groups, energy expenditures also often represent a very small share of disposable income, with high-income consumers often lacking free time to undertake energy-efficiency-related investments. In summary, while reduced energy costs could make a difference for low-income households and businesses, they often lack the finances or access to finances, whereas those with higher incomes and access to capital lack the motivation to invest in energy efficiency.

The third 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 occurred in 21% in UK residences in 1998 but in 51% in Sweden (European Commission, 2001). Cold water is traditionally used for washing clothes in China (Biermayer and Lin, 2004), whereas hot water washing is common in Europe. Similarly, there are substantial differences among countries in how lighting should be used at night, the room temperatures considered comfortable,[9] the preferred temperatures for food or drink, the operating hours of commercial buildings, in the size and composition of households (IEA, 1997; Chappells and Shove, 2005). 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 should be also attributed to the different lifestyles and culture. Even in identical houses in the same location with the same number of residents, energy consumption has been shown to differ by a factor of two or more (Socolow 1978).

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. Depending on the definitions and methods used, estimates of the magnitude of the rebound effect range from tiny – for the direct rebound effect for some residential technologies in the US – to huge (Herring, 2004).

Furthermore, non-payment and electricity theft has been occurring at a large scale in many countries. Estimates show that distribution losses due to theft are as high as 50% in some states in India, while in the late 1990s, collection rates in Albania, Armenia and Georgia were around 60% of billings. Electricity theft does not appear to be a problem limited to developing countries or economies in transition. In the US, it has been estimated to cost utilities billions of dollars each year (Suriyamongkol, 2002). The failure of recipients to pay in full for energy tends to induce waste and discourage energy efficiency.

Finally, a last category of barriers concerns a number of *costs or risks (real or perceived) that are not captured directly in financial flows*. For example, if more efficient equipment is more advanced but less reliable, or is harder to get serviced, this results in a real cost to the user (Carbon Trust, 2005). Also potential incompatibilities (e.g. if new lightbulbs do not fit in the old sockets) increase the real cost of energy-efficient technologies. The poor power quality, particularly in some developing countries, may results in a sub-par operation or even damage of some energy-efficient end-use devices (Energy and Atmosphere Programme of United Nations Development Programme (EAP UNDP), 2000).

Policies to promote CO_2 emission reductions

A wide range of policies has been demonstrated in several countries to be successful in overcoming the numerous, diverse, and strong barriers that hinder the implementation of energy-efficiency investments and in cutting CO_2 emissions related to buildings.

Table 3 reviews 20 of the most important policy tools used in buildings according to two criteria: emission reduction effectiveness, and cost-effectiveness. Using these criteria, 66 *ex-post* (with a few exceptions) policy evaluation studies were identified from over 30 countries and country groups that served as a basis for this assessment. The first column identifies the policy instruments grouped in four major categories using a typology synthesized from several sources (including Grubb, 1991; IEA, 1997; Crossley *et al.*, 2000; Verbruggen and Bongaerts, 2003; and Vine *et al.*, 2003), namely: (1) control and regulatory mechanisms, (2) economic and market-based instruments, (3) financial instruments and incentives, and (4) support and information programmes and voluntary action. In the other two columns the policy instruments

Table 3 Impact and effectiveness of various policy instruments aimed to mitigate CO_2 emissions in the buildings sector

Policy instrument	Overall effectiveness[a]	Cost-effectiveness
Control and regulatory mechanisms		
Appliance standards	High	High
Building codes	High	Medium/high
Procurement regulations	High	Medium
Energy-efficiency obligations and quotas	High	High
Demand-side management programmes	High	High
Economic and market-based instruments		
Energy performance contracting/ESCO support	High	Medium
Cooperative procurement	High	High
Energy-efficiency certificate schemes	High	High
Kyoto Protocol flexible mechanisms	Medium	Medium
Fiscal instruments and incentives		
Taxation (on CO_2 or fuels)	Generally low	Medium
Tax exemptions/reductions	High	High
Public benefit charges	Medium/high	High
Capital subsidies, grants	Medium/high	High/Medium
Support and information programmes and voluntary action		
Mandatory labelling and certification	High	High
Voluntary labelling and certification	Medium/high	Medium
Voluntary and negotiated agreements	Medium	Medium
Public leadership programmes	High	High
Education and information programmes	Medium/high	High
Mandatory audit and energy management	High, but variable	Medium
Detailed billing and disclosure programmes	Medium	Medium

Note: [a]Includes ease of implementation; feasibility and simplicity of enforcement; applicability in many locations; and other factors contributing to the overall magnitude of realized savings.

evaluated on the basis of two generalized criteria, namely effectiveness and cost effectiveness, are shown. The effectiveness in GHG emissions reduction and cost was rated qualitatively based on the available literature and quantitative estimations of 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 comparisons are based on identified best practices in order to demonstrate what impact an instrument can achieve if applied well.

All of the instruments reviewed can achieve significant energy and CO_2 emissions savings; however, the costs per ton of CO_2 eq. saved diverge greatly. Control and regulatory mechanisms are generally effective but their cost-effectiveness is sometimes limited because of, for example, high enforcement costs. Specifically, building codes and appliance standards were found to achieve the highest CO_2 emission reductions in the sample, while appliance standards and energy-efficiency obligations and quotas were found to be among the most cost-effective policy tools, achieving significant reductions in CO_2 emissions at negative net costs. Economic and market-based mechanisms are relatively new in the buildings sector. Energy performance contracting, cooperative procurement and energy-efficiency certificate schemes all seem to be effective tools in cutting CO_2 emissions from buildings at generally low cost. On the other hand, energy efficiency investments in buildings have not benefited to date from the project-based mechanisms of the Kyoto Protocol mainly due to the high transaction costs and relatively small project size. Regarding fiscal instruments, tax exemption policies if properly structured are generally considered as one of the most effective policies in the building sector and could play a valuable role in stimulating the introduction of important energy efficiency technologies and initialization of sales of very efficient new homes and commercial buildings. On the other hand, taxes on CO_2 or household fuel are generally not effective. With the exemption of public benefit charges (invested in carbon abatement mechanisms such as demand-side management) fiscal instruments were found to be less cost-effective compared with other instruments. Finally, labelling and voluntary programmes can lead to large savings at low costs in buildings, while information programmes can also achieve significant savings and effectively accompany most other policy measures. For a more detailed assessment of different policy instruments for mitigation in buildings providing some best-practice examples of successful policy implementation to policy-makers, see Ürge-Vorsatz *et al.* (2007).

These policies, while applied in many industrialized countries with favourable results, have rarely been pursued aggressively. As a result, in most developed countries the energy consumption in buildings is still increasing. 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: (1) slow implementation processes (e.g. as of 2006, not all European countries are on time with the implementation of the EU Buildings Directive); (2) the lack of regular updating of building codes (requirements of many policies are often close to common practices, despite the fact that low-energy design without major financial sacrifices is already possible) and appliance standards and labelling; and (3) insufficient enforcement.

There is no single policy instrument that can capture the entire potential for GHG mitigation. Due to the especially diverse and strong barriers in this sector, buildings require a diverse portfolio of policy instruments for effective and far-reaching GHG abatement and for taking advantage of synergistic effects. An overview of which policies could be used to overcome certain categories of barriers is presented in Figure 3. While the implementation of a portfolio of different types of policy instruments could overcome market failures, economic barriers and hidden costs and risks, support and information programmes are crucial to changing the cultural and behavioural characteristics that influence energy consumption by the final consumers. More generally, 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.

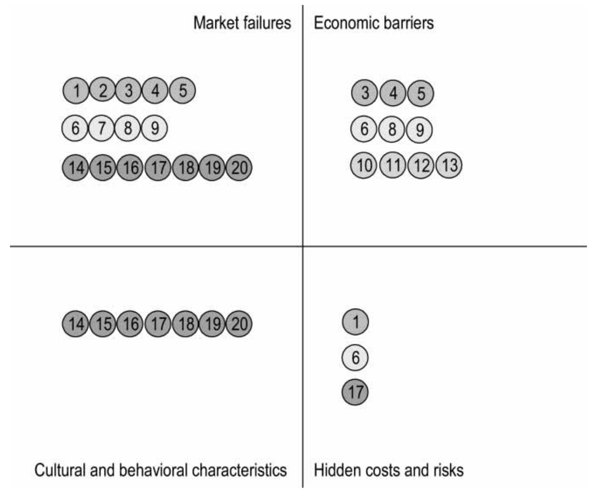

Figure 3 Relevance of policy instruments per barrier category affecting the implementation of energy efficiency interventions in buildings. The policy instruments examined are as follows: 1, Appliance standards; 2, building codes; 3, procurement regulations; 4, energy-efficiency obligations and quotas; 5, demand-side management programmes; 6, energy performance contracting/ESCO support; 7, cooperative procurement; 8, energy-efficiency certificate schemes; 9, Kyoto Protocol flexible mechanisms; 10, taxation (on CO_2 or fuels); 11, tax exemptions/reductions; 12, public benefit charges; 13, capital subsidies; grants; 14, mandatory labelling and certification; 15, voluntary labelling and certification; 16, voluntary and negotiated agreements; 17, public leadership programmes; 18, education and information programmes; 19, mandatory audit and energy management; and 20, detailed billing and disclosure programmes. Policies 1–5 refer to control and regulatory mechanisms; policies 6–9 refer to economic and market-based instruments; policies 10–13 refer to fiscal instruments and incentives; and policies 14–20 refer to support and information programmes and voluntary action

Conclusions

Energy use in the buildings sector is a key contributor to anthropogenic climate change: it was responsible for 7.85 Gt CO_2 emissions in 2002, 33% of the global total, as well as approximately 1.5 Gt CO_2 equivalent emissions from halocarbons. The SRES scenarios project growth of these emissions to 11 Gt/year (B2 scenario) to 15.6 Gt/year (A1 scenario) by 2030, with the share of the sector remaining at approximately 34% of total.

GHG emissions from buildings can be cut in three major ways: by reducing energy consumption in buildings, by switching to low-carbon fuels including a higher share of renewable energy, and by controlling the emissions of non-CO_2 GHG gases. This paper devoted 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 paper is that substantial reductions in CO_2 emissions from energy use in buildings can be achieved over the coming years. 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 negative cost.

There is 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 have not as yet been widely adopted. Nevertheless, there are many areas where further research, practical experience and cost reduction are crucial in achieving the deep reductions in energy use needed to reduce the risk of significant harm due to climate change. Among these are: (1) vacuum insulation panels, (2) liquid desiccant dehumidification and cooling systems, (3) daylighting systems and controls (which are still difficult and costly to implement), and

(4) cost reductions in PV and solar thermal systems. In addition, non-technological opportunities for cutting GHG emissions need to be better understood. Whereas technologies have been greatly advanced during the past few decades, our understanding of the influence of culture, values, behaviour or just energy use patterns is still very limited, and no quantification of the potentials and associated costs with the reduction opportunities in these areas have been conducted. Furthermore, there is a significant need to raise the overall level of building design through use of the integrated design process and, where appropriate, through use of computer simulation tools as an integral part of the design process (rather than merely for equipment sizing or for post-design confirmation of compliance with building regulations). An increased commitment to excellence must somehow permeate all the players involved in the design process.

While there are methodological challenges in aggregating potential GHG reductions to a global level due to limited research and differing assumptions used in the existing studies, the authors have made a best estimate for the global economic potential. The calculations suggest that, globally, by 2020, approximately 29% of the business-as-usual CO_2 equivalent emissions or about 3.2 billion tons of CO_2 equivalent can be avoided annually in a cost-effective way through mitigation measures in the residential and commercial sectors. Due to the limited number of demand-side end-use efficiency options considered by the reviewed studies and the exclusion of the positive integration effects, the real potential is likely to be higher.

Implementing carbon mitigation options in buildings is associated with a wide range of ancillary benefits. These include the creation of jobs and business opportunities, increased economic competitiveness and energy security, social welfare benefits for low-income households, increased access to energy services, improved indoor and outdoor air quality, as well as increased comfort, health and quality of life. According to some studies, the aggregate value of co-benefits associated with many GHG reduction measures in buildings exceeds the direct benefits through energy savings.

Despite the significant potentials at negative costs and the substantial co-benefits identified in this paper, these potentials are difficult to unlock. This is due to the especially diverse and especially strong barriers that prevail in the residential and commercial sectors and that hamper energy-efficiency and distributed energy generation investments.

A variety of policies have been demonstrated in many countries to be successful in removing or lowering these barriers and thus cutting CO_2 emissions in buildings. Among these are appliance standards, building energy codes, appliance and building labelling, pricing measures and financial incentives, utility demand-side management programmes, and public sector energy leadership programmes including procurement policies. The greatest challenge is the development of effective strategies for retrofitting existing buildings. These and other actions, including continuously tightening building and appliance standards, providing assistance to the building design process, and promoting energy service companies, will all be needed because of the large number of barriers to energy efficiency and distributed low-carbon energy generation in buildings. Because culture and occupant behaviour are major determinants of energy use in buildings, these policy approaches need to go hand in hand with programmes that increase consumer access to information, awareness and knowledge.

In sum, buildings can contribute to addressing the climate change challenge in a significant and low-cost way. However, while there are many practical and cost-effective technologies and practices available today – and new options likely to emerge from ongoing research, development and demonstration – achieving a lower carbon future will require very significant efforts to enhance programmes and policies for energy efficiency in buildings and low-carbon electricity sources, well beyond what is happening today.

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Endnotes

[1]The IPCC was established by the United Nations in 1988, in affiliation with the United Nations Environment Program and the World Meteorological Organization, to provide periodic comprehensive scientific reviews of the state of knowledge concerning the science of human-induced climatic change (commonly referred to as global warming), concerning potential impacts and the response options from technical, economic and policy points of view. The first three assessments were published in 1990, 1995 and 2001. AR4 is due to be released in autumn 2007, in time to serve as input to the negotiations concerning future steps in emission reduction. Like previous assessments, AR4 consists of three working group reports, divided this time as follows: WG1 on the background science, WG2 on impacts, vulnerability and adaptation, and WG3 on mitigation options. The material summarized in this paper is taken largely from the buildings chapter of the WG3 report.

[2]Readers interested in recent advances in the background science are urged to consult the IPCC Working Group 1 (WG1) AR4 report when it is released (particularly Chapter 3 on recent trends in temperature, Chapter 6 on past climates, and Chapter 9 on the attribution of observed changes).

[3]Particularly pertinent are WG2 Chapter 4 (Ecosystems, their Properties, Goods, and Services), especially Table 4.2, WG2 Chapter 5 (Food, Fibre, and Forest Products), and Chapter 19 (Key Vulnerabilities).

[4]In this paper the residential, commercial and service sectors (or tertiary, as they are classified to in some countries) are referred to in short as the 'buildings' sector.

[5]Ratio of light output (lumens) to input power (watts).

[6]To extrapolate the potential as a percentage of the baseline into the future (i.e. to estimate the potential for 2020 from a given value for 2010 assuming 2000 as the starting year), the following formula was used: [$\text{Potential}_{2020} = 1 - (1 - \text{Potential}_{2010})^{(20/10)}$]. The implementation of this formula results to approximately 78% CO_2 savings in 2020.

[7]This corresponds to an approximate 22% potential in 2020 if the suggested extrapolation formula is used.

[8]This corresponds to an approximate 38% in 2020 if the suggested extrapolation formula is applied to derive the intermediate potential.

[9]Conversely, many residents find higher indoor temperatures acceptable in winter than in summer.