10

Energy End-Use: Buildings

Convening Lead Author (CLA)
Diana Ürge-Vorsatz (Central European University, Hungary)

Lead Authors (LA)
Nick Eyre (Oxford University, UK)
Peter Graham (University of New South Wales, Australia)
Danny Harvey (University of Toronto, Canada)
Edgar Hertwich (Norwegian University of Science and Technology)
Yi Jiang (Tsinghua University, China)
Christian Kornevall (World Business Council for Sustainable Development, Switzerland)
Mili Majumdar (The Energy and Resources Institute, India)
James E. McMahon (Lawrence Berkeley National Laboratory, USA)
Sevastianos Mirasgedis (National Observatory of Athens, Greece)
Shuzo Murakami (Keio University, Japan)
Aleksandra Novikova (Climate Policy Initiative and German Institute for Economic Research, Germany)

Contributing Authors (CA)
Kathryn Janda (Environmental Change Institute, Oxford University, UK)
Omar Masera (National Autonomous University of Mexico)
Michael McNeil (Lawrence Berkeley National Laboratory, USA)
Ksenia Petrichenko (Central European University, Hungary)
Sergio Tirado Herrero (Central European University, Hungary)

Review Editor
Eberhard Jochem (Fraunhofer Institute for Systems and Innovation Research, Germany)

Contents

Executive Summary

Buildings are key to a sustainable future because their design, construction, operation, and the activities in buildings are significant contributors to energy-related sustainability challenges – reducing energy demand in buildings can play one of the most important roles in solving these challenges. More specifically:

- The buildings sector[1] and people's activities in buildings are responsible for approximately 31% of global final energy demand, approximately one-third of energy-related CO_2 emissions, approximately two-thirds of halocarbon, and approximately 25–33% of black carbon emissions.

- Several energy-related problems affecting human health and productivity take place in buildings, including mortality and morbidity due to poor indoor air quality or inadequate indoor temperatures. Therefore, improving buildings and their equipment offers one of the entry points to addressing these challenges.

- More efficient energy and material use, as well as sustainable energy supply in buildings, are critical to tackling the sustainability-related challenges outlined in the GEA. Recent major advances in building design, know-how, technology, and policy have made it possible for global building energy use to decline significantly. A number of low-energy and passive buildings, both retrofitted and newly constructed, already exist, demonstrating that low level of building energy performance is achievable. With the application of on-site and community-scale renewable energy sources, several buildings and communities could become zero-net-energy users and zero-greenhouse gas (GHG) emitters, or net energy suppliers.

Recent advances in materials and know-how make new buildings that use 10–40% of the final heating and cooling energy of conventional new buildings cost-effective in all world regions and climate zones. Holistic retrofits[2] can achieve 50–90% final energy savings in thermal energy use in existing buildings, with the cost savings typically exceeding investments. The remaining energy needs can be met at the building- and community-level from distributed energy sources or by imported sustainable energy supply. The mix of energy-demand reductions, on-site renewable energy generation, and off-site renewable energy supply that corresponds to the most sustainable solution and minimizes the total cost needs to be evaluated case by case, applying a full system life cycle assessment. Net zero-energy buildings and communities[3] are possible only for select building types and settlement patterns, mainly low-rise buildings and less densely populated residential areas. However, their economics are presently typically unfavorable, as opposed to high-efficiency buildings. Meanwhile, compact medium-rise and high-rise developments offer many advantages, such as reduced surface-to-volume ratios and typically lower energy service demands due to the higher density and concentration of building uses.

The scenarios constructed by the GEA buildings expert team, in concert with the GEA main pathways, demonstrate that a reduction of approximately 46% of the global final heating and cooling energy use in 2005 is possible by 2050 (see Figure 10.1). This is attainable through the proliferation of today's best practices in building design, construction, and operation, as well as accelerated state-of-the-art retrofits. This is achievable while increasing amenity and comfort and without interceding in economic and population growth trends and the applicable thermal comfort and living space increase. It goes hand in hand with the eradication of fuel poverty – i.e., supplying everyone with sufficient thermal

1 The GEA refers to energy use in the buildings sector as all direct energy use in buildings, including appliances and other plug loads, and accounting for all electricity consumption for which activities in buildings are responsible. Embodied energy use, emissions of the production of building materials, and their transport to the construction site, and other equipment are not included.

2 Holistic retrofit refers to a major renovation of a building involving a complex of various energy efficiency measures. It is the opposite to a stepwise renovation, when, first, some parts of the building are renovated (e.g., windows), later other parts (e.g., insulation), etc.

3 Net zero energy buildings (communities) are buildings (communities) that consume as much energy as they produce from renewable energy sources within a certain period of time (usually one year)

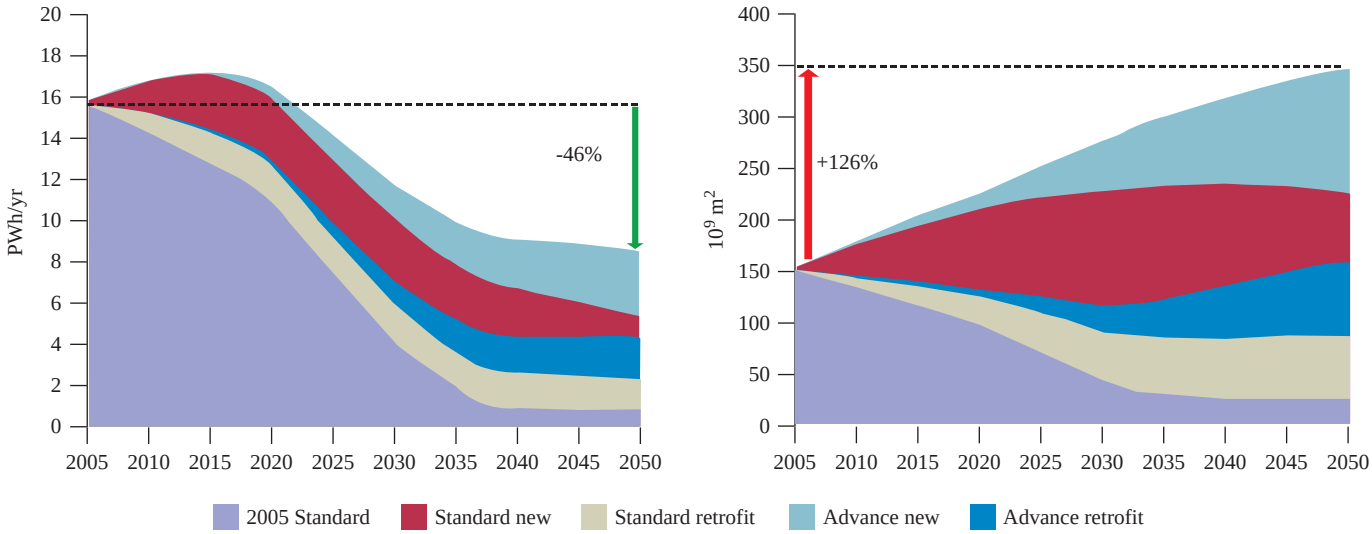

Figure 10.1 | Global final building heating and cooling energy use[4] until 2050 in the state-of-the-art scenario (corresponding roughly to the "GEA Efficiency" set of pathways) (left), contrasted to global floor area (on the right) projections.

comfort. Reaching these state-of-the-art energy efficiency levels in buildings requires approximately US$14.2 trillion in undiscounted additional cumulative investments (US$18.6 trillion with no technology learning) until 2050. However, these investments return substantially higher benefits, e.g., approximately US$58 trillion in undiscounted energy cost savings alone during the same period.

Present and foreseen cutting-edge technologies can reduce energy use of new appliances, information and communication technology (ICT), and other electricity-using equipment in buildings by 65% by 2020, as compared to the baseline. Longer-term projections of technology improvements are speculative, but likely to provide significant additional improvement. Through lifestyle, cultural, and behavioral changes, further significant reductions could be possible.

However, the scenario work also demonstrates that there is a significant lock-in risk. If building codes are introduced universally and energy retrofits accelerate, but policies do not mandate state-of-the-art efficiency levels, substantial energy use and corresponding GHG emissions will be "locked in" for many decades. Such a scenario results in an approximately 33% increase in global building energy use by 2050 compared to 2005, as opposed to a 46% decrease – i.e., an approximately 79% lock-in effect relative to 2005. This points to the importance of building shell-related policies being ambitious about the efficiency levels they mandate (or encourage). Figure 10.2 illustrates opportunities offered by a state-of-the-art scenario as well as the lock-in risk for the 11 GEA regions.

A future involving highly energy-efficient buildings can result in significant associated benefits, typically with monetizable benefits at least twice the operating cost savings, in addition to non-quantifiable or non-monetizable benefits now and avoided impacts of climatic change in the future. One of the most important future benefits is mitigation of the building sector's contribution to climate change. Other benefits include: improvements in energy security and sovereignty; net job creation; elimination of or reduction in indoor air pollution-related mortality and

4 In Chapter 10 energy use is measured in kWh, as it is the most commonly used metrics for the buildings sector. In order to convert kWh to kJ, please, follow the rule: 1 kWh = 3600 kJ.

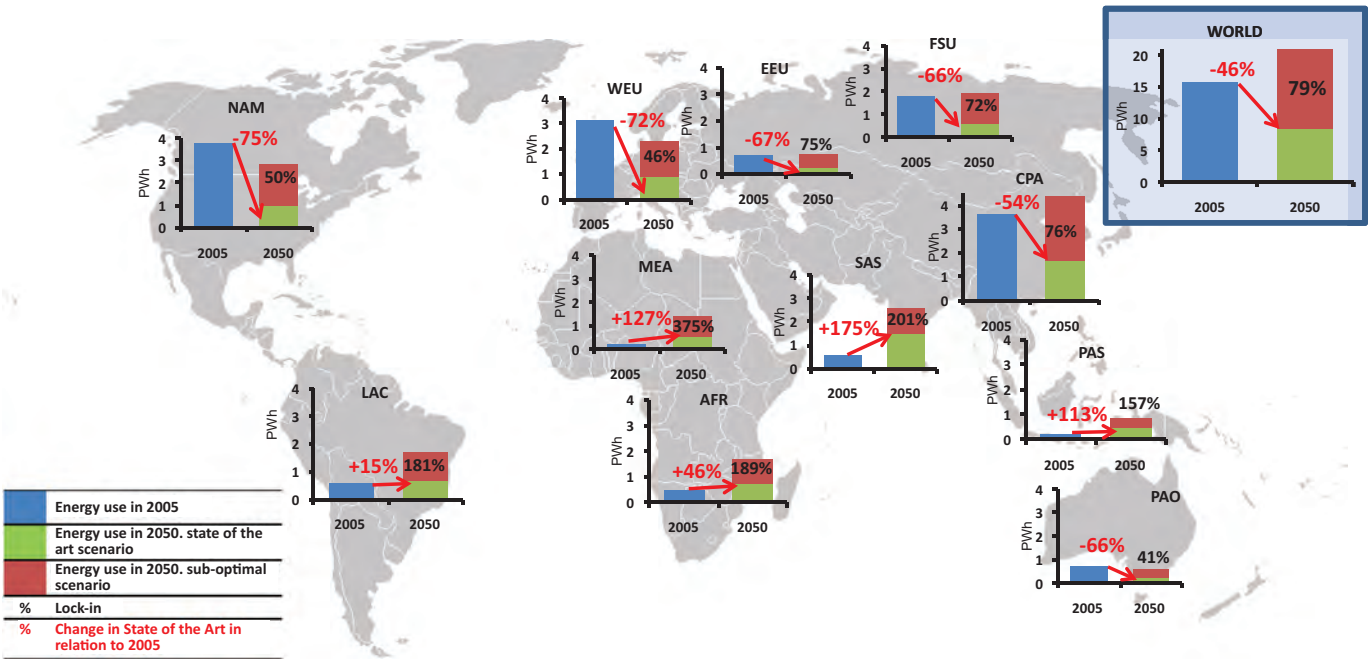

Figure 10.2 | Final building heating and cooling energy demand scenarios until 2050: state-of-the-art (~corresponding roughly to the GEA Efficiency set of pathways) and sub-optimal (~corresponding roughly to the GEA Supply set of pathways) scenarios, with the lock-in risk (difference).

Note: *Green bars, indicated by red arrows and numbers*, represent the opportunities through the state-of-the-art scenario, while the red bars with black numbers show the size of the lock-in risk (difference between the two scenarios). Percent figures are relative to 2005 values.

morbidity; other health improvements and benefits; alleviation of energy poverty and improvement of social welfare; new business opportunities, mostly at the local level; stimulation of higher skill levels in building professions and trades; improved values for real estate and enhanced ability to rent; and increased comfort, well-being, and productivity.

A survey of quantitative evaluations of such multiple benefits shows that even a single energy efficiency initiative in buildings in individual countries or regions has resulted in benefits with values ranging in the billions of dollars annually, such as health improvement-related productivity gains and cost aversions. At the same time, the market-based realization of significant, mostly cost-effective efficiency opportunities in buildings is hampered by a wide range of strong barriers. These barriers are highly variable by location, building type, and culture, as well as by stakeholder groups, such as planners, architects, craftsmen, investors, house and building users, and supervisors. Technological and human capacities of change need to be considered together, as it is through individual and organizational decisions that technologies are provided, adopted, and used. Analysis and examples in this chapter show that most of these barriers can be overcome or mitigated through policies, measures, and innovative financing schemes. A broad portfolio of instruments is available and has been increasingly applied worldwide to capture cost-effective efficiency and conservation potential and to tap other sustainable energy opportunities. Due to the large number and diversity of barriers, single instruments such as a carbon price will not unlock the large efficiency potential, but policy portfolios, tailored to different target groups and tailored to a specific set of barriers, are necessary to optimize results.

Among policy instruments, stringent, continuously updated, and well-enforced building and appliance standards, codes, and labeling – applied also to retrofits – are particularly effective in achieving large energy savings, mostly highly cost-effectively. In order to achieve the major building energy use reductions that have been shown to be possible in this chapter, an urgent introduction of strong building codes mandating near-zero-energy performance levels and progressively improving appliance standards, as well as the strong promotion of state-of-the-art efficiency levels in

accelerated retrofits in existing building stocks, are crucial. In contrast, net-zero-energy building mandates are not the most sustainable, cost-effective, or even feasible solutions in many cases, such as dense urban zones or large commercial buildings, and may only encourage urban sprawl. Thus the introduction of such mandates and commitments should be carefully analyzed and, in some cases, re-examined.

For ICT and entertainment appliances, regulation also needs to tackle the durability of the equipment in addition to its operational energy use due to the high-embodied GHG emissions. Appropriate energy pricing is fundamental, and taxation provides the impetus for a more rational use of energy sources. In poor regions or population segments, subsidies enabling a highly energy efficient capital stock can be more effective in tackling energy poverty than energy price subsidies. Carefully designed subsidies enabling investments may be needed to bridge the discount rate gap between society and private decision-makers, and the availability of financing for building owners and users is often a crucial precondition. Innovative financing schemes, such as performance contracting, are paramount for groups with limited access to financing. Carbon prices need to be very high (above US\$60/tCO_2) and sustained over a long period to achieve noticeable demand effects in the buildings sector. However, in order for energy price signals to be effective and sensible, energy price subsidies need to be removed so that the technology and fuel pricing environment provides a level playing field for sustainable energy options to be feasible. Awareness campaigns, education, and the provision of more detailed and direct information, including smart metering, enhance the effectiveness of other policies and enable behavioral changes.

A combination of sticks (regulations), carrots (incentives), and tambourines (measures to attract attention such as information or public leadership programs) has the greatest potential to increase energy efficiency in buildings by addressing a broader set of barriers. Achieving a transformation in the buildings sector that is in concert with ambitious climate stabilization targets by the mid-century entails massive capacity building efforts to retrain all trades involved in the design and construction process, as well as consumers, building owners, operators, and dwellers.

A transition into a very low building energy future requires a shift in focus of energy sector investment from the supply-side to end-use capital stocks, as well as the cultivation of new innovative business models, such as performance contracting and Energy Service Companies.

Novelties in this chapter, as compared to previous assessments, include (1) a focus on energy services, as well as life cycle approaches accounting for trade-offs in embodied vs. operational energy and emissions; (2) applying a holistic framework toward building energy use that recognizes buildings as complex, integrated systems; (3) presenting new global and regional building energy use scenarios until 2050, using a novel performance-based global building thermal energy model; (4) recognizing the importance of the lock-in effect and quantifying it; (5) in-depth attention to non-technological opportunities and challenges; (6) a large database on quantified and monetized co-benefits; and (7) a critical assessment of zero-energy buildings and related policies.

10.1 Setting the Scene: Energy Use in Buildings

10.1.1 Key Messages

Almost 60% of the world's electricity is consumed in residential and commercial buildings. At the national level, energy use in buildings typically accounts for 20–40% of individual country total final energy use, with the world average being around 30%. Per capita final energy use in buildings in a cold or temperate climate in an affluent country, such as the United States and Canada, can be 5–10 times higher than in warm, low-income regions, such as Africa or Latin America.

10.1.2 The Role of Buildings in Global and National Energy Use

Energy services in buildings – the provision of thermal comfort, refrigeration, illumination, communication and entertainment, sanitation and hygiene, and nutrition, as well as other amenities – are responsible for a significant share of energy use worldwide. The exact figure depends on where system boundaries are drawn. The global direct total final energy use in buildings was 108 EJ in 2007 and resulted in emitting 8.6 $GtCO_2e$ (IPCC, 2007), 33% of global energy-related CO_2 emissions (IEA, 2008a). Globally, biomass is the most important energy carrier for energy use in buildings, followed by electricity, natural gas, and petroleum products. Almost 60% of the world's electricity is consumed in residential and commercial buildings (IEA 2008a). In addition to the energy consumed directly in buildings, primary energy is lost in the conversion to electricity and heat and petroleum products, and the transport and transmission of energy carriers cost energy. In addition, the construction, maintenance and demolition of buildings requires energy, as do the manufacturing of furniture, appliances, and the provision of infrastructure services such as water and sanitation. The use of this indirect or embodied energy is influenced by the level and design of energy service provision in buildings. While comprehensive global statistics on indirect energy cost of buildings do not exist, regional data are presented below.

At the national level, direct energy use in buildings typically accounts for 20–40% of individual country's total final energy use (see Table 10.1), with the world average being 31%. In terms of absolute amounts, there is a significant variance among different world regions. Per capita final energy use in buildings in a cold or temperate climate in affluent countries, such as the United States and Canada, can be 5–10 times higher than in warm, low-income regions, such as Africa or Latin America (Table 10.1). Figure 10.A.1 in the online appendix and Figure 10.3 provide further information on the characteristics of building energy use by region or representative countries. Figure 10.4 shows total final energy use in buildings per capita in different world regions, according to the International Energy Agency (IEA) statistics. Figure 10.5 shows final energy use per square meter for thermal comfort by world region and building type, according to input data collected from different sources for the model presented in Section 10.6. Because sources of building energy vary greatly, e.g., significant amounts of coal and biomass burned on site in China and India and a much higher share of electricity in other countries, this results in large differences in primary energy use because of the additional energy demands of power generation and distribution.

However, policies to address sustainability challenges of energy services rendered in buildings can often only be designed optimally if a life cycle approach is used for energy accounting and not only the direct energy use is optimized. For instance, there are trade-offs between minimizing operational energy use and embodied energy in building materials; these trade-offs in greenhouse gas emissions can be even larger. For example, reducing CO_2 emissions through increased Styrofoam insulation increases hydrochlorofluorocarbon (HCFC) emissions, potentially resulting in increased rather than decreased overall greenhouse gas emissions when measured in CO_2 equivalents. Further trade-offs exist in cooking energy use and embodied energy in foodstuffs. Reduction in certain energy service demands in buildings results in the reduction of energy use of other sectors, such as electricity transformation losses, transportation (such as for building materials, water, food, etc.), or industrial energy use (needed for products and appliances in buildings). Therefore, building-related energy services can only be optimized if a systemic, life cycle approach is used to reduce associated total primary energy use and associated environmental impacts. Unfortunately, global building energy use and emission data using a life cycle approach do not exist, but smaller-scale data on life cycle building energy use is presented below. As buildings are the end-point of a large share of our energy using activities – for example, a large share of products manufactured in industry are ultimately for the purpose of providing various services in buildings and many goods being transported are being used in buildings – reducing service needs requiring energy input in buildings is key to achieve a reduction in overall primary energy use. When a life cycle approach is applied to understand the energy services demanded, the importance of buildings grows substantially.

10.1.3 The Demand For Different Energy Services In Buildings And Their Drivers

10.1.3.1 Key Messages

Energy is used in buildings to provide a variety of services, including comfort and hygiene, food preparation and preservation, entertainment, and communications. The type and level of service and the quantity and type of energy required depend on the level of development, culture, technologies, and individual behavior. Global trends are toward electrification and urbanization, including toward multi-family from single-family dwellings. At all levels, large variations in cultural attitudes, individual behaviors, and the selection of construction materials and practices, fuels, and technologies contribute to a wide range of energy services and energy use.

Table 10.1 | Contribution of the buildings sector to the total final energy demand globally and in selected regions in 2007.

World regions	Share of the residential sector in %	Share of the commercial sector in %	Share of the total buildings sector in %	Residential and commercial energy demand per capita, MWh/capita-yr.
USA and Canada	17%	13%	31%	18.6
Middle East	21%	6%	27%	5.75
Latin America	17%	5%	22%	2.32
Former Soviet Union	26%	7%	33%	8.92
European Union-27	23%	11%	34%	9.64
China	25%	4%	29%	3.20
Asia excluding China	36%	4%	40%	2.07
Africa	54%	3%	57%	3.19
World	**23%**	**8%**	**31%**	**4.57**

Source: IEA online statistics, 2007.

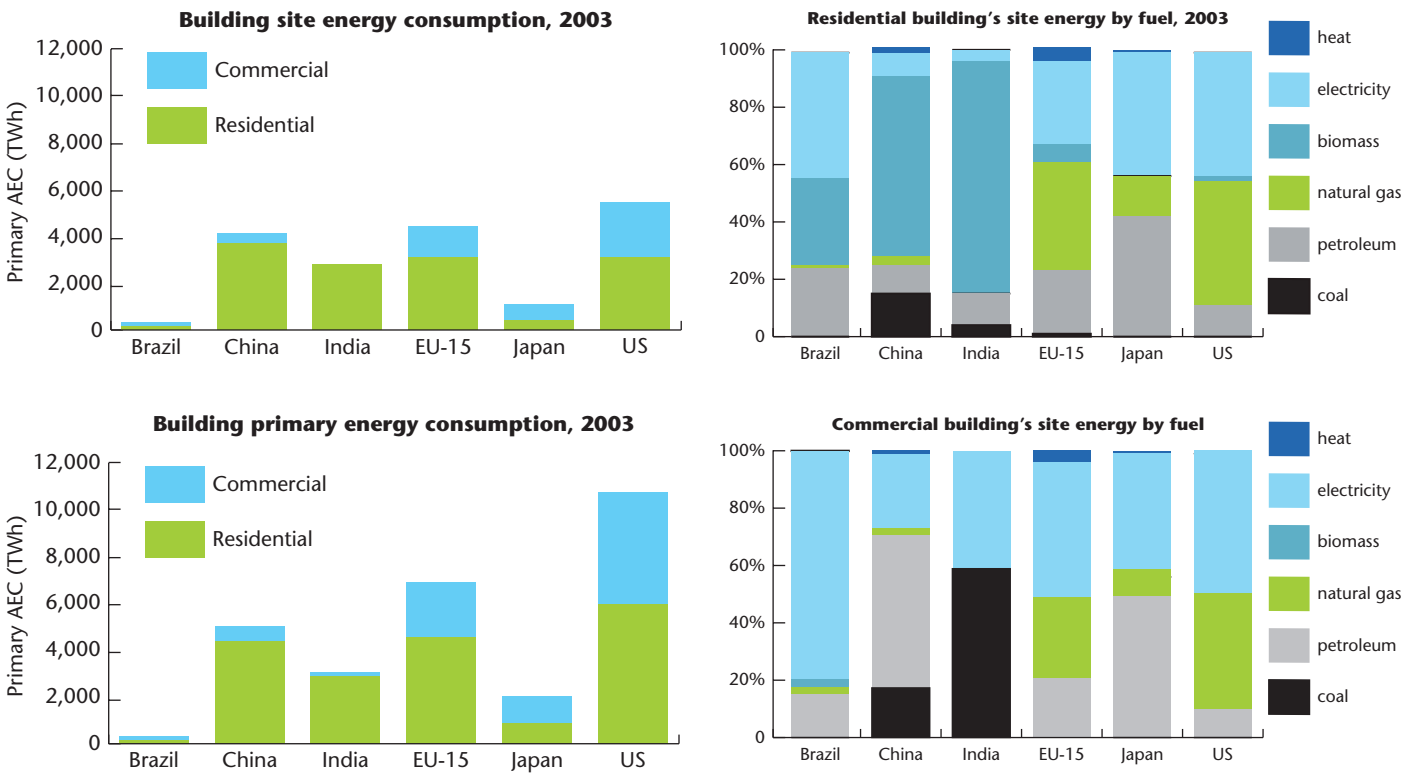

Figure 10.3 | Building final and primary energy use in selected countries in 2003; AEC = annual energy consumption. Source: WBCSD, 2008.

10.1.3.2 Building Energy Demand by Service Type

The type and level of service and quantity and type of energy required depend on a large number of factors, including culture, technologies, and individual behavior. This section includes a review of national and regional assessments conducted to understand the importance of different energy services in buildings. No global systematic studies have been performed to understand the importance of different energy services in buildings or other sectors, and therefore this section covers a selection of national and regional assessments. Figure 10.6 shows the breakdown of primary energy use in commercial and residential buildings by end-use services in the United States. The figure demonstrates that five energy services accounted for 86% of primary energy use in buildings in 2006. These were: (1) thermal comfort – space conditioning that includes space heating, cooling and ventilation – 36%; (2) illumination – 18%; (3) sanitation and hygiene, including water heating, washing and drying clothes, and dishwashing – 13%; (4) communication and entertainment – electronics including televisions, computers, and office equipment – 10%;

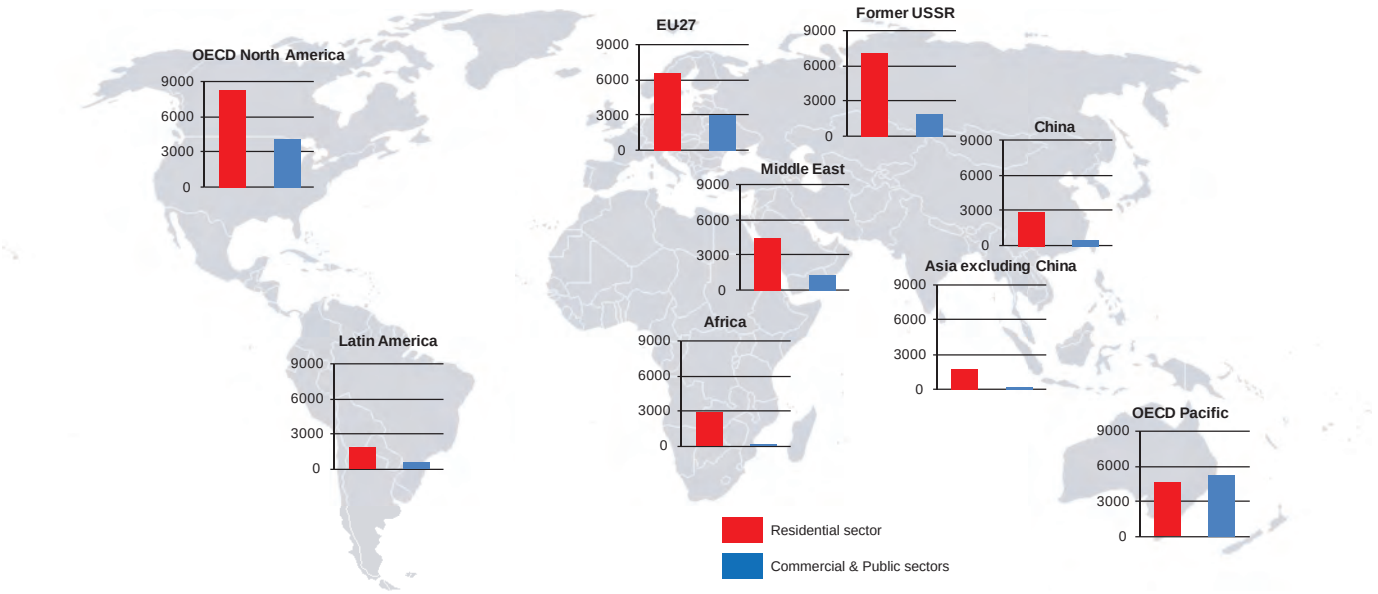

Figure 10.4 | Total annual final energy use in the residential and commercial/public sectors, building energy use per capita by region and building type in 2007 (kWh/capita/yr). Source: data from IEA Online Statistics, 2007.

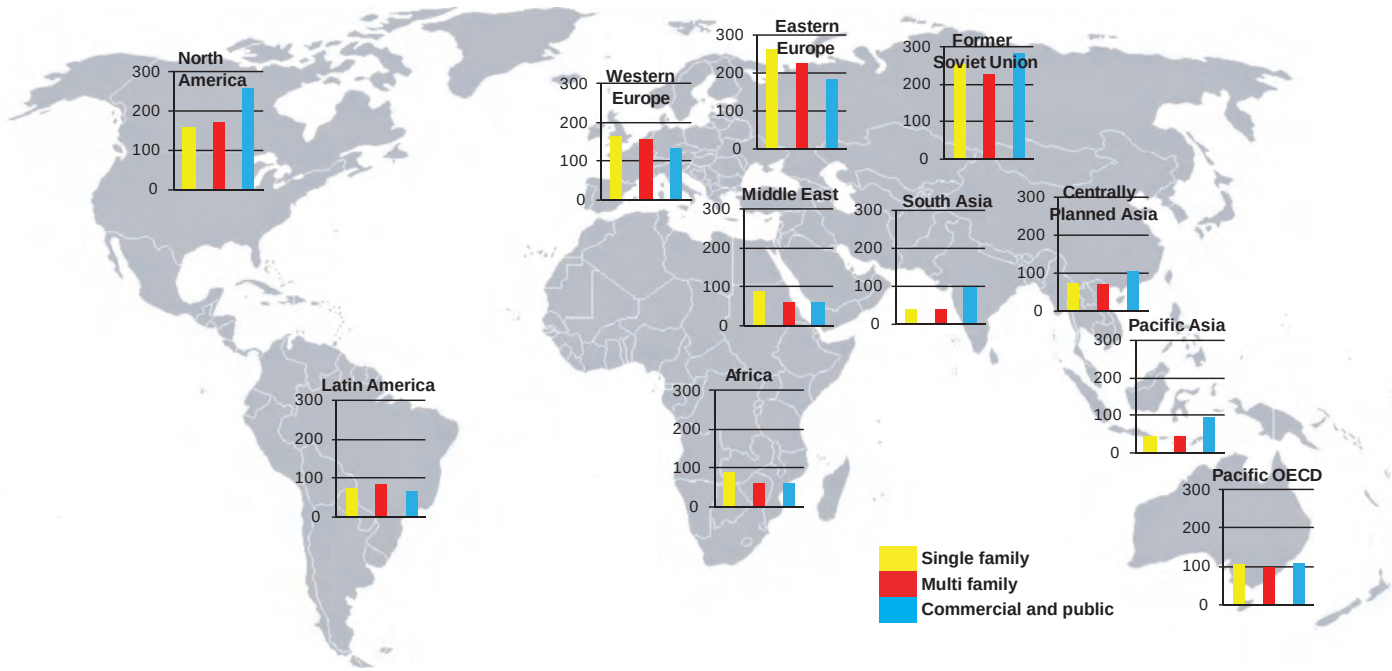

Figure 10.5 | Final heating and cooling specific energy consumption by region and building type in 2005 (kWh/m²/yr). Source: Model estimations (see Section 10.7).

and (5) provision of food, refrigeration and cooking – 9% (US DOE, 2008). The remaining 14% includes residential small electric devices, heating elements, motors, natural gas outdoor lighting, and commercial service station equipment, telecommunications equipment, medical equipment, pumps, and combined heat and power in commercial buildings.

Recently, McNeil et al. (2008) made an estimate of the current and projected end-use energy demand in buildings for ten separate regions covering the world. In the OECD member states, it was found that the five energy services listed above use 76% of the electricity and 69% of the fuel final energy[5] in buildings. In developing countries (non-OECD member states), they account for 93% of site electricity and 78% of fuel use, respectively. According to the best available figures (IEA, 2006), household energy use in developing countries contribute almost 10% of the world primary energy demand. Household use of biomass in developing countries alone accounts for almost 7% of world primary energy demand.

5 Includes natural gas, bottled gas (LPG), and fuel oil. Does not include coal or biomass, and excludes district heating, which is significant in China, Europe, and the Former Soviet Union.

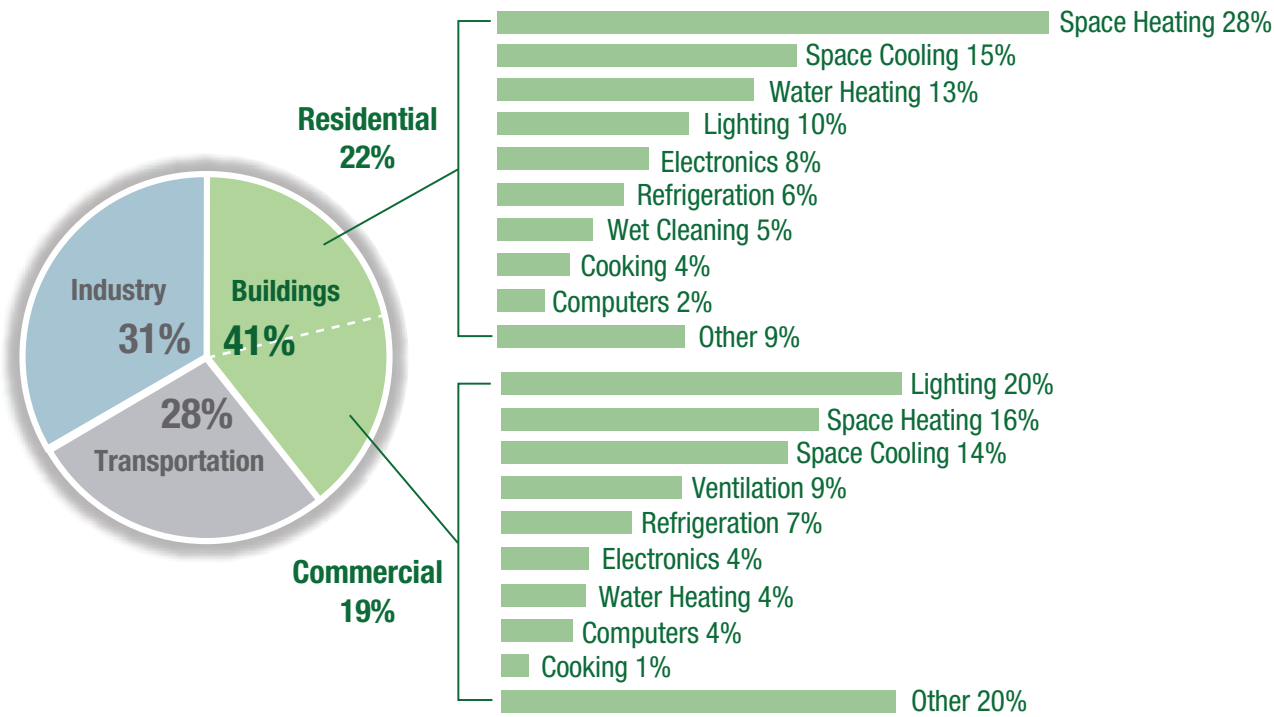

Figure 10.6 | Primary energy use in US commercial and residential buildings in 2010. Source: US EIA, 2011; 2012.

Valuable time and effort are devoted to fuel collection instead of education or income generation. While a precise breakdown is difficult, the main use of energy in households in developing countries is for cooking, followed by heating and lighting. Because of geography and climate, household space- and water-heating needs are small in these countries.

A review of national level studies of household energy services, analyzed on a life cycle basis, is presented in Figure 10.7. Buildings-related energy use contributes 60–70% of the total household energy use in OECD countries (Hertwich, 2005b) and up to 90% in India (Pachauri and Spreng, 2002; see also Box 10.1 and Figure 10.8). The remainder of household energy use is mostly related to mobility. On average across studies for a selected number of countries where data was available, buildings-related energy use, including the primary energy required to produce the energy carriers used in the household, accounts for 32% of the total household energy requirements. "Other shelter," which includes water and waste treatment utilities and construction and maintenance of buildings and furniture, accounts for 11%. Mobility accounts for 24%, food for 14%, recreation for 7%, clothing for 4%, and other for 9%. Variation in the importance of different categories, however, is substantial. Additional life cycle effects of building energy use are considered in Section 10.1.4.

10.1.3.3 Variations in Energy Service Needs and Key Drivers

The following factors are major contributors to changing energy service demands: (1) population growth; (2) urbanization; (3) shift from biomass to commercially available energy carriers, especially electrification (percent of population having access to electricity); and (4) income, which is a strong determinant of the set of services and end-uses for which commercial energy is used and the quantity and size of energy-using equipment; (5) level of development; (6) cultural features; (7) level of technological development; and (8) individual behavior. Availability and financial aspects of technologies and energy carriers are also important.

The demand for energy services in buildings varies among regions according to geography, culture, lifestyle, climate, and the level of economic development. It also varies by the type of use, type of ownership, age, and location of buildings (e.g., residential or commercial, new or existing buildings, private or public, rural or urban, leased or owner-occupied) (Chakravarty et al., 2009). There are also significant differences in energy services among commercial subsectors – such as offices, retail, restaurants, hotels, and schools – and between single- and multifamily residential buildings. Different approaches, standards and technologies to how the buildings are sited, designed, constructed, operated, and utilized strongly affect the amount of energy used within buildings.

The level of economic development is a main driver of the global differences in energy use in buildings as set out in the previous sections. Table 10.1 shows that energy use per capita in buildings is up to an order of magnitude higher in North America than in most of Asia, Africa, and Latin America. This section sets out some more detailed differences, and their drivers, among countries as well as within individual countries.

Figure 10.9 shows there are differences in per capita energy use among six developed countries, at similar affluence levels (IEA, 2007b). The data

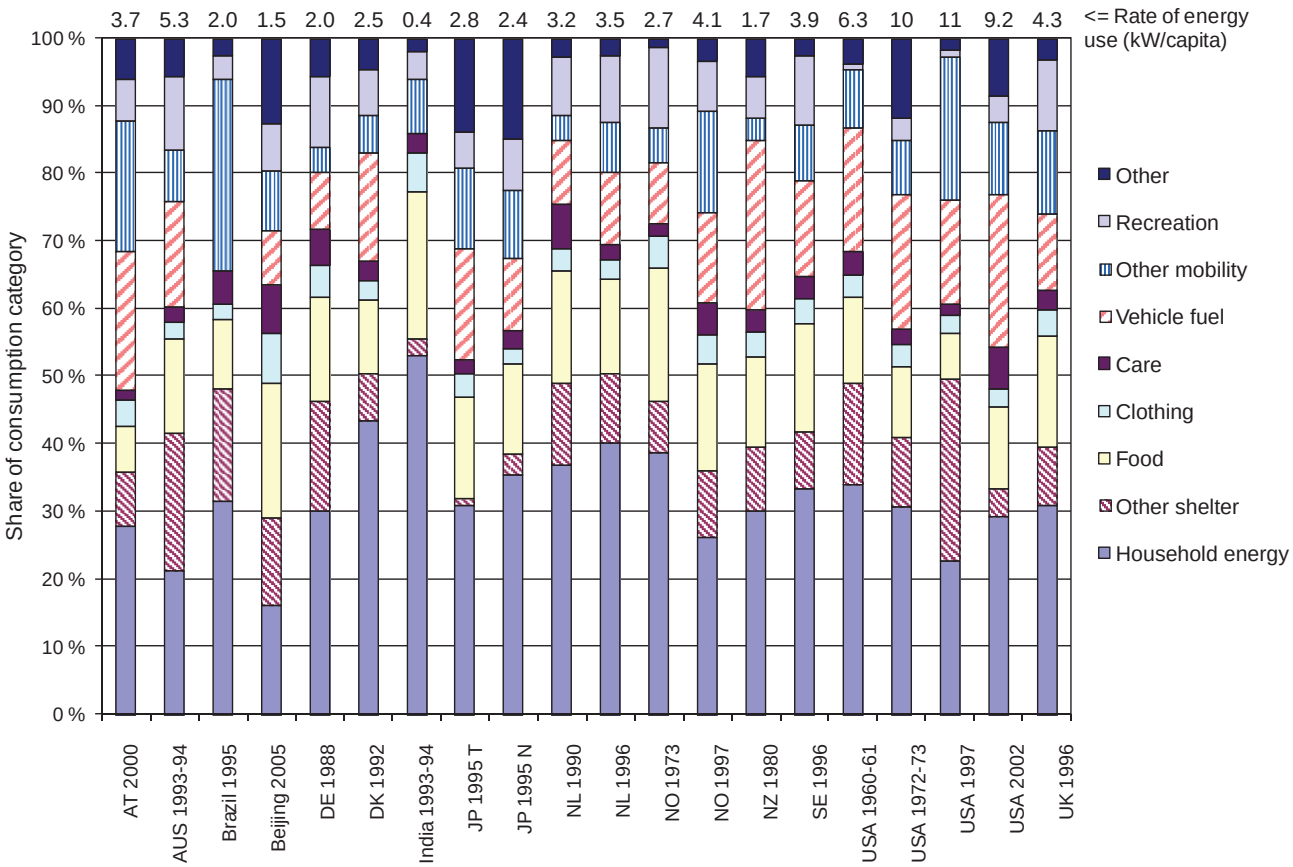

Figure 10.7 | Share of consumption categories in total energy use based on life-cycle analysis or input-output calculation and rate of annual energy use in kilowatt per capita (numbers on top of the columns). Source: Hertwich, 2011.

are "degree day normalized," i.e., corrected for the key climatic driver of heating demand. The overall energy use is higher in the United States, even by developed country standards, but lower in Japan, and intermediate in Europe and Canada. The variation between end-uses is large. For instance, space-heating demand follows the same broad pattern as the total use and is driven largely by per capita floor area and building internal temperatures (IEA, 2007b). Other end-uses are relatively less important, but there are substantial differences, notably the higher energy use in lighting and appliances in North America. The figure also illustrates the role of culture in determining energy efficiency. Japan uses less than a third of the energy used in the United States for space heating, even when normalized for climate. This is due to more compact living, as well as focusing on providing thermal comfort through alternative means rather than universal heating of all living space. The Japanese *kotatsu*, a table frame heat source which is combined with blankets and adaptive clothing, is still a common alternative despite high affluence levels.

10.1.3.4 Cultural, Social and Behavioral Drivers

Culture, values, and individual habits significantly influence consumption, as does the choice of technologies. The section above provided an example for heating energy use determined by culture in Japan. This section provides more examples and highlights further issues. For instance, cooking energy demand varies largely with dietary choices. The use of refrigerated, packed, and tinned food is very limited in developing countries which leads to larger energy use for cooking. In rural China, similar to many other developing countries, cooking is the largest energy demand item for 60% of families.

A major source of variation in energy services and energy use is the impact of habits and behavior (see Section 10.4.8), irrespective of level of development. Within all countries, high-income groups contribute disproportionately to energy demand (Chakravarty et al., 2009). However, income is not the only factor. Lenzen et al. (2006) investigated the variation of energy use with household income and size, type of house, urban versus rural location, education, employment status, and age of the householder in several countries. Higher income social groups use more energy per capita, with the elasticity of energy expenditure ranging from 0.64 in Japan to 1.0 in Brazil. Lenzen et al. (2006) also found that energy use differs across countries even after controlling for the main socioeconomic and demographic variables, including income. This result confirms previous findings that the characteristics of personal energy use are partly determined by distinctive features such as historical events – for example, energy supply shortages or the introduction of taxes, socio-cultural norms, behavior, and present market conditions, as well as energy and environmental policy measures.

Box 10.1 | Energy Use in Buildings in India

In India, energy end use in buildings varies largely across income groups, building construction typology, climate, and several other factors. The energy sources utilized by the residential sector in India mainly include electricity, kerosene, liquefied petroleum gas (LPG or propane), firewood, crop residue, dung, and other renewable sources such as solar energy. The per capita energy use in the residential sector is as low as 2560 kWh/yr for India.

Traditional fuels are predominantly used for cooking. In the rural areas of the country, the three primary sources of energy for cooking are firewood and chips, dung cake, and LPG. In urban areas, cooking energy sources are primarily LPG and piped natural gas in select cities. Figure 10.9 shows seasonal differences in energy demand for Delhi, India (Manisha et al., 2007). In summer months, air-conditioners and refrigerators each account for about 28% of total monthly electricity consumption, while lighting accounts for about 8–14% of annual electricity consumption. In winter, major uses of electricity are refrigerators (44%), water heating ("Geyser" 18%), and lighting (14%).

Based on CPWD (2004), in India's commercial sector 60% of the total electricity is consumed for lighting, 32% for space conditioning, and 8% for refrigeration. End use consumption varies largely with space conditioning needs. In a fully air conditioned office building, about 60% of the total electricity consumption is accounted for by air conditioning followed by 20% for lighting.

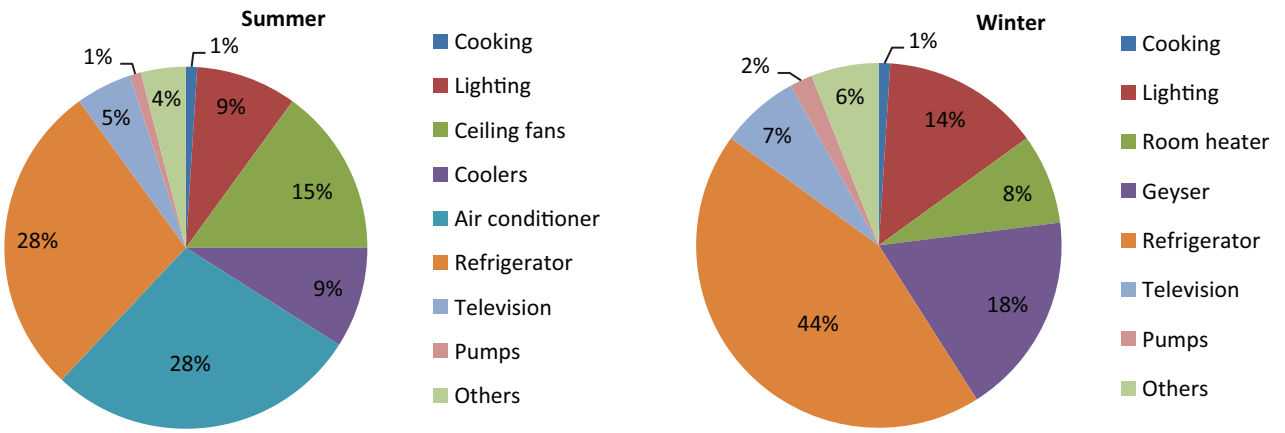

Figure 10.8 | Share of end-uses (by appliance) in electricity consumption in Delhi, India. Source: Manisha et al., 2007.

Note: "Others" include washing machine, computer and irons.

A study carried out by Socolow (1978) demonstrated energy use variations of more than a factor of two between houses that were identical but had different occupants. Gram-Hanssen (2004) found a similar variation of household electricity use in much larger sample of identical flats in Denmark. This is consistent with the findings of the World Business Council for Sustainable Development/Energy Efficiency in Buildings (WBCSD/EEB) that show that people can improve energy efficiency in buildings by around 30% by behavioral changes without any extra costs, or they can compromise a building's performance by up to 60% by behavioral effects (WBCSD, 2009).

A similar result is illustrated by a study of energy use for home air conditioning in a residential building in Beijing (Zhang et al., 2010). The building consists of 25 home units, all with similar income characteristics. Although each flat is fully occupied, the difference in energy use can be as large as a factor of 40 (see Figure 10.10). While the average is 2.3kWh/m^2, the range is from near zero to over 14 kWh/m^2. The real income of the high-energy users is lower than those of the low-energy users.

Social choices about cooling technology will prove increasingly important. For instance, a very large stock of residential, institutional, and commercial buildings in India is still designed to be non-air-conditioned and to use only ceiling fans to provide thermal comfort during hotter periods, while in other countries electric chilling is the standard in commercial buildings. Occupants of Indian buildings are acclimatized to higher temperature and humidity conditions without feeling uncomfortable. This translates to very low energy usage in such buildings, with a very limited scope for enhancing energy efficiency, but with a high potential for reducing future air conditioning needs.

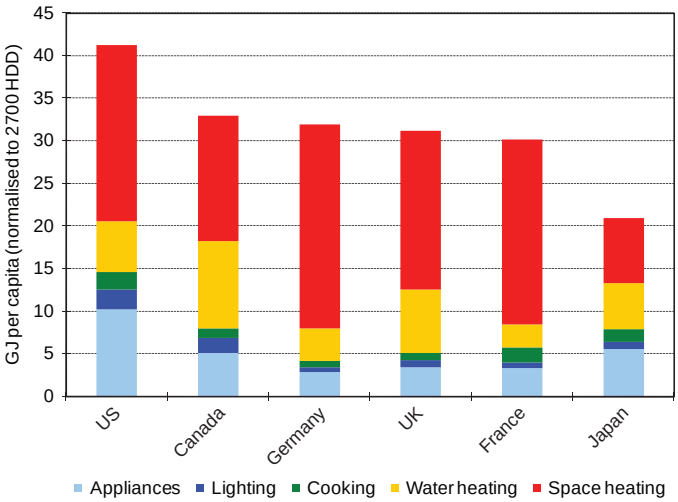

Figure 10.9 | Residential energy use in different developed countries. Source: adapted from IEA, 2007b. HDD = heating degree day.

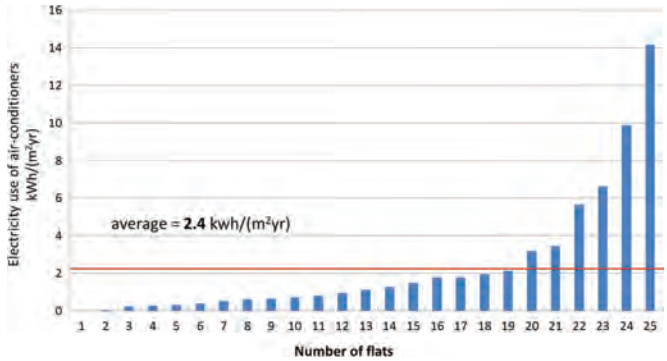

Figure 10.10 | Electricity consumption of air-conditioning in 25 flats of a residential building in Beijing. Source: based on Zhang et al., 2010.

10.1.3.5 The Drivers of Changing Demand for Building Energy Services

The share of energy use in buildings in the total energy use increases with the level of economic development. In India, with a near-consistent 8% annual rise in annual energy demand in the residential and commercial sectors, building energy use has seen an increase from 14% in the 1970s to nearly 33% of total primary energy use in 2004–2005 (authors' calculation based on the data from IndiaStat, 2010).

In addition to the determinants of building energy services discussed above, additional factors are major contributors to changing energy service demands: (1) population growth; (2) urbanization; (3) shift from biomass to commercially available energy carriers, especially electrification (percent of population having access to electricity); and (4) income, which is a strong determinant of the set of services and end-uses for which commercial energy is used and the quantity and size of energy-using equipment; (5) level of development; (6) cultural features; (7) level of technological development; and (8) individual behavior. Availability and financial aspects of technologies and energy carriers are also important.

While energy use in buildings is influenced by income, specific energy use does not necessarily continue growing at an equal rate at higher income levels. For instance, Figure 10.11 shows the trend of specific building energy use in the United States during the second half of the twentieth century, for Japan since 1970, and the trend for China since the mid-1990s. The most significant increase can be observed during the first two decades in this period. While gross domestic product (GDP) continued to increase in the second part of the period, improvements in technological efficiency have kept energy growth trends at bay. Chinese-specific building energy demand figures currently are in the same range as the United States in the 1950s. Whether China will follow trends of the United States or will be able to decouple the increase in wealth from specific building energy use at an earlier stage is an important determinant of global future energy use.

Building location, form, and orientation are integrally related to urban/rural design, which, in turn, also influences energy use necessary for transporting people and products to buildings, as well as the feasibility of certain sustainable energy supply options such as district heating and cooling, and community-scale renewable energy generation. Therefore, urban design, building energy use, and urban transport energy use are integrally related (see Chapter 9 and Chapter 18).

In India and China, urban households tend to have higher energy requirements than rural households (Lenzen et al., 2006; Peters et al., 2007). In China, moving from a rural to an urban life currently increases household demand for energy by about a factor of three (Table 10.2), while in developed countries, urban households tend to have lower energy requirements. By 2020, both rural and urban demand for energy will increase due to a combination of urbanization, a shift from biomass to commercial energy carriers, and increased income. Thus, Chinese urban energy use per household in 2020 is expected to be five times the amount of rural energy per household today.

Building size and building floor space per person are also important factors that depend upon income and demographics. Households with more occupants tend to have lower per capita energy use. Older and wealthier individuals are more likely to occupy larger dwellings with fewer occupants. Often, improved energy efficiency is offset over time by bigger floor space per person or per household.

In sum, population growth, urbanization, the shift from biomass to commercial fuel carriers including electricity, and income growth are contributing to increasing demand for energy services. Technologies, practices, and policies toward increasing energy efficiency are offsetting growth in some locations and offer large future potential for reducing the quantity of energy required for energy services. Individual choices of lifestyle and specific behavior may greatly increase or decrease the demand for energy services.

Table 10.2 | Increasing energy intensities when moving from rural to urban life in China.

	China annual energy per household in the North China (kWh)						
	Year 2000		Year 2020		Ratio as percent		
	Rural	Urban	Rural	Urban	Urban/Rural 2000	Urban/Rural 2020	2020 Urban/ 2000 Rural
Space heating	631	4990	4638	9027	791%	195%	1431%
Water heating	1108	1001	1499	1579	90%	105%	143%
Lighting	155	189	220	488	122%	222%	315%
Cooking	277	250	375	395	90%	105%	143%
Other	50	100	150	420	200%	280%	840%
TOTAL	2221	6530	6882	11909	294%	173%	536%

Source: Zhou et al., 2007.

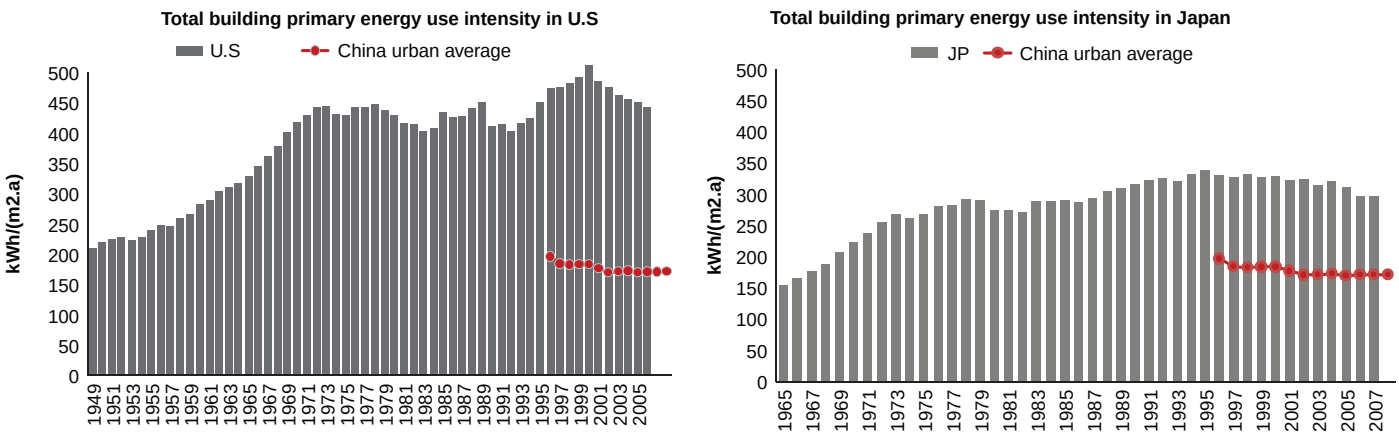

Figure 10.11 | Trend of total building final energy use per m^2 in the United States (1949–2006) and in Japan (1965–2007) (kWh/m^2/yr) as compared to China. Sources: US Census Bureau, 2000; US Census Bureau, 2008; Energy Data and Modeling Center, 2008; US DOE, 2008; Building Energy Research Center, 2010.

10.1.3.6 Energy Carriers Used to Satisfy Energy Service Needs in Buildings

In developing countries, biomass, coal, oil products, and natural gas are mostly used to satisfy energy service needs in buildings because in rural areas people have easier access to biomass compared to people living in cities, and because even many urban building occupants do not have access to electricity, (Shepherd and Zacharakis, 2001; Melichar et al., 2004; see also Chapter 2). The progression from traditional biomass fuels to more convenient and cleaner fuels has traditionally been explained by the "energy ladder" model, suggesting that increasing affluence is the key to the transition.

More recently, the multiple fuel model was developed to explain household decision making in developing countries under conditions of resource scarcity or uncertainty taking into account the following factors: (1) economics of fuel and stove type and access to fuels; (2) technical characteristics of cookstoves and cooking practices; (3) cultural preferences; and (4) health impacts (Masera et al., 2000). In addition to urbanization, Pachauri and Jiang have identified income, energy prices, energy access, and local fuel availability as key drivers of the transition from traditional to modern fuels in China and India (Pachauri and Jiang, 2008).

In developed countries, electricity and natural gas are the most frequently used energy carriers, with electricity taking an increasing share. For instance, while buildings in the United States use only 39% of the country's primary energy, they use 71% of electricity and 54% of the natural gas supply.

Figure 10.12 presents the distribution of fuels in total final energy use in the residential and commercial sectors worldwide. Note that residential energy use (81.3 EJ) exceeds commercial and public sector energy use (27.5 EJ) by a factor of three.

10.1.4 Indirect Energy Use from Activities in Buildings in Detail Using the Life Cycle Assessment Approach

10.1.4.1 Key Messages

The life cycle approach is necessary to optimize the total energy required to provide energy services in buildings because the importance of indirect energy use can increase as more energy efficient technologies are applied. Depending on climate and energy efficiency, the construction of a building contributes as much as 25% to total indirect energy use, with

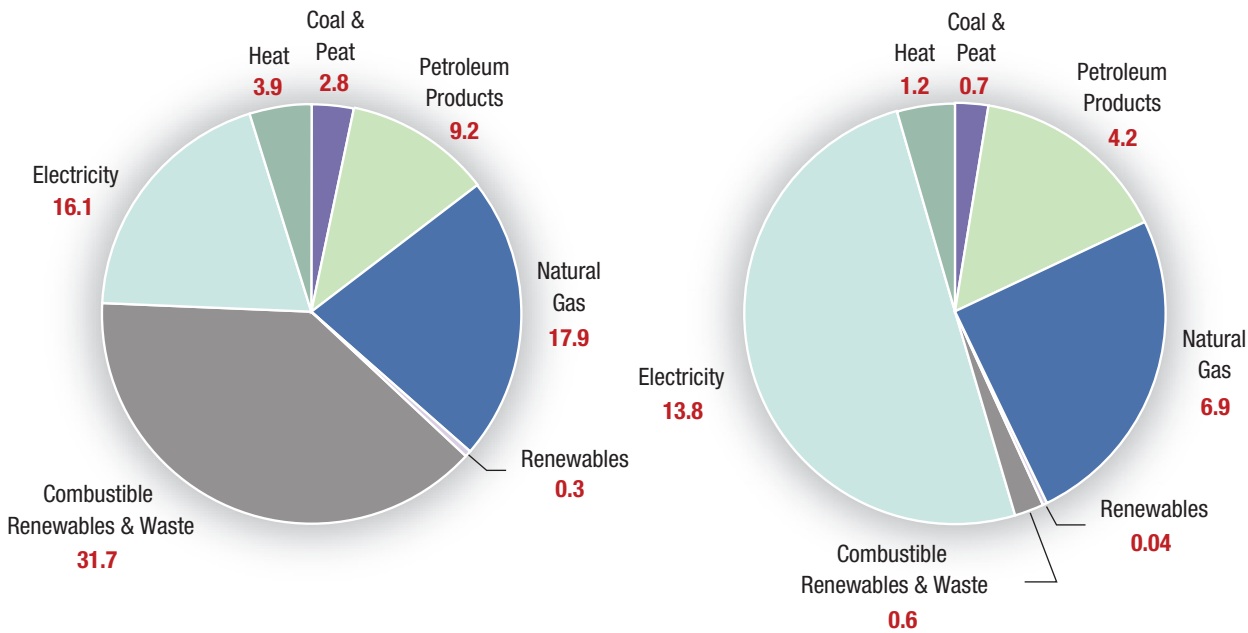

Figure 10.12 | World total final energy consumption by fuel in the residential (left) and commercial and public (right) sectors in 2007 (EJ). Source: IEA Online Statistics, 2007.

higher values for very high efficiency or energy self-sufficient buildings. Even though commonly pursued efficiency strategies increase the energy embodied in the building, in cold and temperate climates this invested energy is typically recovered with an energy payback time below one year. Building-integrated PV systems, however, require at least five years to recover the energy invested in their construction and may, from a life cycle perspective, not be the cleanest option of supplying electricity. The environmental impacts of different building materials and designs depend on a number of factors with wood offering an advantage in terms of carbon storage and potential energy recovery after demolition. A refurbishment of existing buildings to increase efficiency can offer savings in total life cycle energy use compared to demolition and new construction. While optimal solutions will be site- and case-dependent, in general significant reductions in environmental impacts can be obtained with energy efficient building designs, a wise choice of building materials, and renewable energy sources integrated in buildings.

10.1.4.2 Introduction to the Life Cycle Approach

A life cycle approach is necessary to optimize the total energy use required to provide energy services in buildings, because, for instance, the importance of indirect energy use can increase as more energy-efficient technologies are applied (see also earlier sections). In addition to direct energy use, a life cycle approach takes into account the energy used to produce the materials for constructing the buildings, energy losses associated with the provision of electricity and fuels to the buildings, energy used in the construction and maintenance of a building, and energy used in manufacturing and supplying building equipment – ranging from lighting and TV sets to heating and cooling equipment (Treloar et al., 2000). This indirect energy use has been variously referred to as embodied, grey, or upstream energy.

This section provides an overview of embodied energy, including the trade-offs between embodied and operational energy, and examines it in detail for important cases: construction, heating, and energy embodied in water consumption in buildings. Indirect energy use is strongly affected by choices made during building construction, operation and/or use, as well as dietary choices.[6]

10.1.4.3 Embodied Energy

This section provides some general insights from life cycle assessment (LCA), and presents results of life cycle studies for building materials and buildings. Section 10.1.3 presented the direct use of energy for different energy services in the US residential sector. Figure 10.13 provides an overview of the direct and indirect energy use of the average household in the United States in 2002, from the life cycle perspective. Indirect energy use is split into energy losses and indirect energy connected to the purchase of all other goods and services. The largest category is private transport. The second largest category is "utilities," which includes direct energy use and the provision of water and wastewater treatment. The third largest category is the indirect energy embodied in food purchased by households.

6 Embodied GHG emissions cover a broader set of issues than just embodied energy. They also include process-based CO_2 emissions from clinker production, carbon storage in wood, and the non-CO_2 GHGs (mainly fluorinated gases) used in the production of certain construction materials and in the operation of some equipment, such as chillers. IPCC (2007) discussed non-CO_2 emissions related to buildings in detail, and thus this section focuses on indirect energy use.

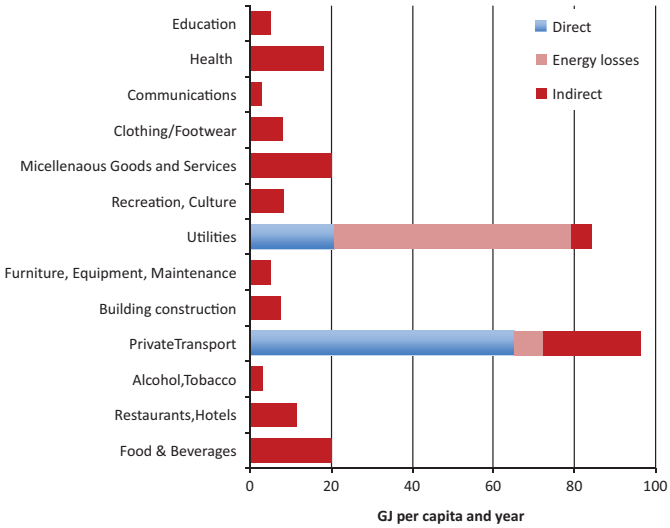

Figure 10.13 | Direct and indirect primary energy use of the average US citizen in 2002 for different consumption purposes. Source: based on Weber, 2009.

There is a trade-off between direct and indirect energy use in a number of areas, for example in thermal comfort and handling of foods. In the United States about 50% of direct energy use in buildings goes to ensuring thermal comfort (see section 10.1.3). While the building structure itself has other functions as well, its main energetic function is to provide thermal comfort. Clothing also functions partially to provide thermal comfort. Overall, however, the energy use in buildings and the cost of providing that energy dominate the total energy cost of providing thermal comfort in the United States. This issue is revisited in the remainder of Section 10.1.4.

Refrigeration and cooking requires about 10% of the direct household energy use, which is clearly less than the indirect energy required to grow and process the food. The importance of indirect energy used for manufactured goods used in buildings increases with increasing wealth, and hence overtime (Lenzen et al., 2006).

10.1.4.4 The Life Cycle Impact of Building Materials and Design

There is a distinction between the construction, operations and maintenance, and demolition of buildings. For most buildings, the bulk of energy use is in the operations phase, and energy conservation efforts have appropriately focused on reducing this energy use through smarter design, better insulation material, and improved building technology. However, for short-lived or highly efficient buildings, construction is responsible for a substantial share of the total energy use. Demolition offers an opportunity to recover some of the energy, either by combusting elements with high heating value or by reusing building materials and components, thus avoiding energy-intensive primary production of new materials. In construction, and especially demolition, energy for transport is an important consideration, constraining remanufacturing and recycling of building components and materials.

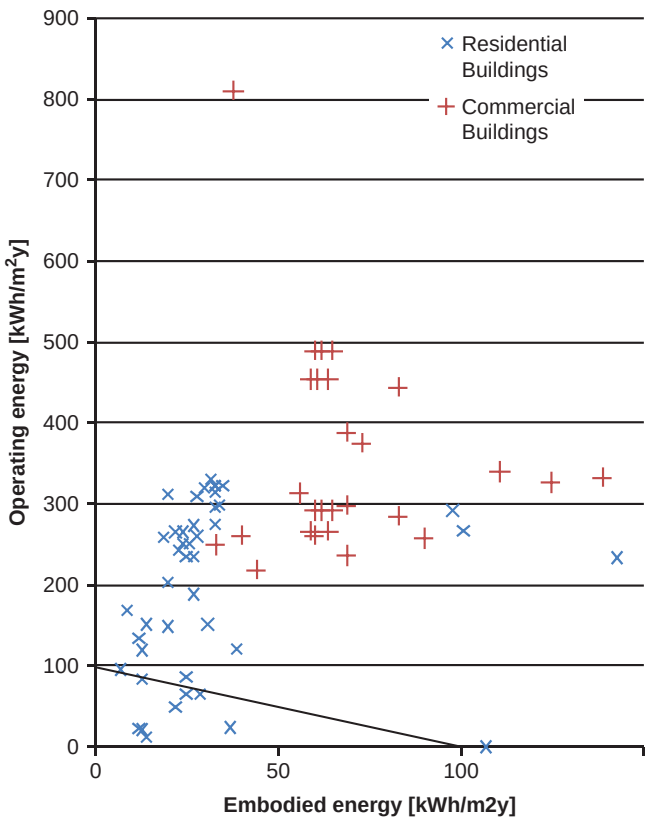

Figure 10.14 | Primary embodied and operating energy of buildings from a review of case studies mostly from northern/central Europe and Asia, including most efficient designs. Source: Sartori and Hestnes, 2007; Ramesh et al., 2010.

Note: the lines indicate points of equal life-cycle primary energy use.

Ramesh et al. (2010) reviewed life cycle energy studies of 73 buildings, including 60 buildings in OECD countries from Sartori and Hestnes (2007). The operating and embodied energy are presented in Figure 10.14. The embodied energy dominates only in three cases, two in climates not requiring heating or cooling and the other a self-sufficient solar home in a Nordic country. In most cases, the embodied energy contributes to 5–25% of the total energy over the lifecycle. The embodied energy, however, varies between 9 and 140 kWh/m^{2}y, given building lifetimes of 30–100 years. Similar results have been obtained for the United Kingdom (Monahan and Powell, 2011).

An analysis of different alternatives for the main building material in Sweden demonstrated that wood is preferable over concrete, especially if the wood is used as fuel after demolition or reused in buildings (Borjesson and Gustavsson, 2000; Lenzen and Treloar, 2002; Gustavsson and Sathre, 2006). Using a detailed input-output analysis of the entire Swedish construction sector, Nässen et al. (2007) show that building materials account for a little more than half of the energy use in the production of new detached and multifamily buildings. The energy use for excavation of the site and transport is important, as is the sum of construction and service inputs. This sector-wide study estimates energy use in the production phase of buildings for Sweden at about 25% of the total energy used for buildings (Nässen et al., 2007). Studies usually only account for energy, not

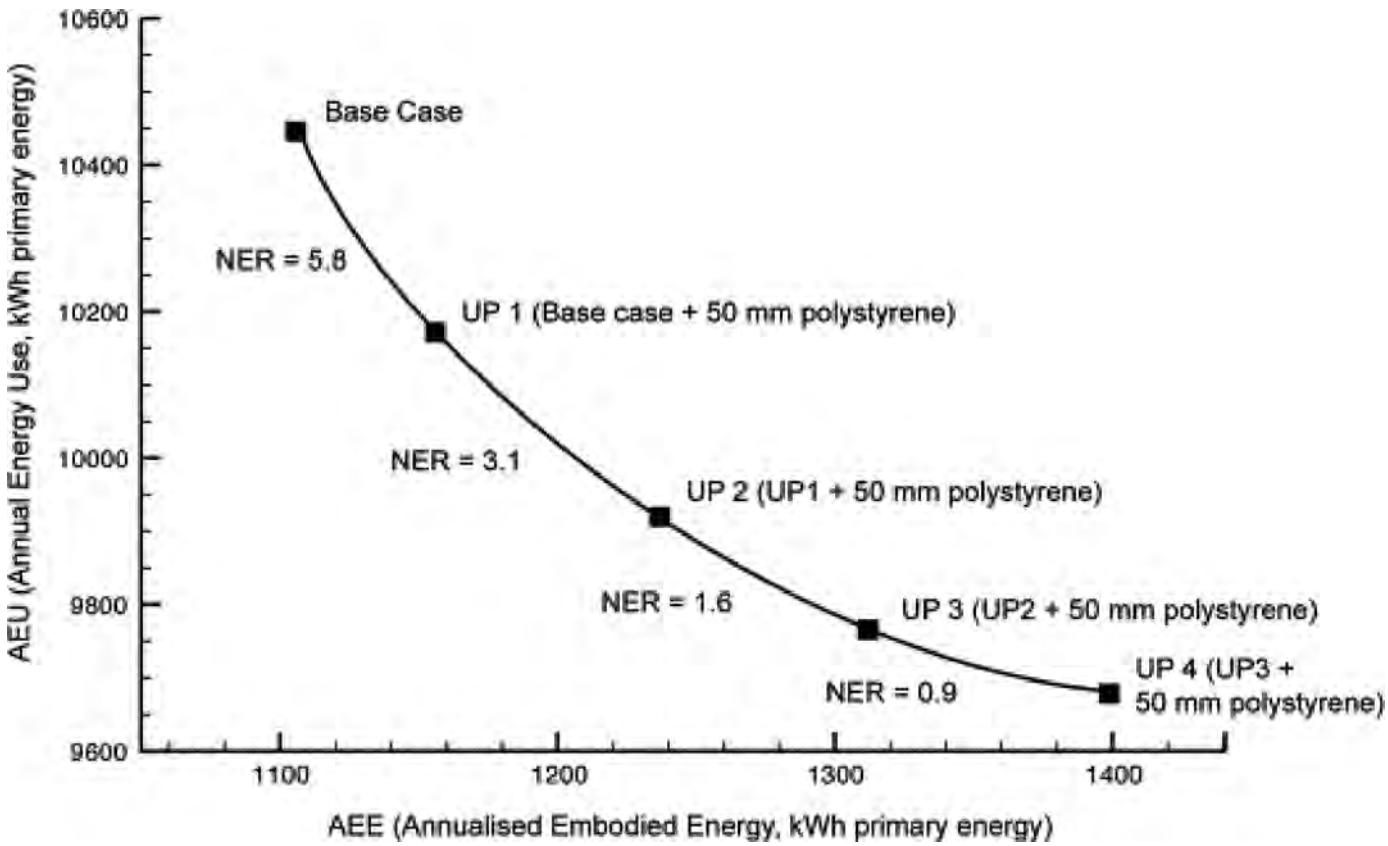

Figure 10.15 | Annualized operational energy use vs. annualized embodied energy use for polystyrene insulation of differing thickness for a case study of low-energy residential building in a maritime climate. Source: Hernandez and Kenny, 2010.

Note: The Net Energy Ratio (NER; also called the return on energy investment) indicates the benefit of each step of additional insulation.

environmental impacts. Depending on the energy mix chosen by various actors along the life cycle, a lower life cycle energy use does not necessarily result in lower environmental impacts (Brunklaus et al., 2010).

10.1.4.5 Highly Efficient Buildings and Active Components

For highly energy efficient buildings and the use of active[7] building technology, the trade-offs between embodied energy and environmental impacts and operational energy and environmental impacts becomes critical and requires a life cycle assessment to ensure that measures are not counterproductive.

Figure 10.15 illustrates an investigation of the trade-off between embodied energy and operating energy. Increasing the thickness of a fairly energy-intensive insulation material (polystyrene) in a house that already has a passive design (15 kWh/m^{2}y) reduces energy use up to a point. The last step, from UP3 to UP4, leads to an increase of life cycle energy use, because the net energy ratio (energy return on investment) is smaller than one (Hernandez and Kenny, 2010).

Reviewed case studies of highly efficient buildings indicate that efficient design depends on higher initial investments of embodied energy. The embodied energy cost of efficiency, however, is small and the energy payback period is on the order of months (Feist, 1996; Winther and Hestnes, 1999). Similar gains can be made by retrofitting existing buildings in a cold climate (Dodoo et al., 2010). An environmental assessment of a passive house in France indicates that the passive design leads to a reduction in environmental impacts in 10 out of 12 impact categories investigated, by 28% on average over a conventional design (Thiers and Peuportier, 2008). Blengini and Di Carlo (2010) report similar results for a passive house in Italy. Environmental gains, however, significantly depend on the energy source and conversion technology for heat and electricity. A study in Sweden indicates that a passive house supplied entirely by electricity can lead to higher environmental impacts than a standard building supplied by district heat (Brunklaus et al., 2010). No comparable studies for hot and dry or hot and humid climates were found.

The introduction of active energy-generating components such as solar collectors and photovoltaic (PV) modules leads to a substantial increase in embodied energy and environmental impacts (Winther and Hestnes, 1999). Published net energy analyses indicate an energy payback time of solar hot water heaters from half a year to two years (Crawford and

7 By active building technology this section refers to components that generate energy, mostly power.

Treloar, 2004), while the energy payback time of building-integrated PV systems is five years and up (Lu and Yang, 2010; Leckner and Zmeureanu, 2011). Local circumstances, such as insolation at the site and orientation of the cells, as well as electric grid properties, determine whether building-integrated PV cells are beneficial from an environmental perspective. A solar building in Spain featuring solar collectors, an absorption cooling tower, and PV arrays was found to lead to substantial reductions in emissions of greenhouse gases, acidifying gases, and ozone precursors, while causing substantial increases in water use and the emissions of human toxicants and no change in other life cycle impacts (Batlles et al., 2010).

10.1.4.6 Demolition vs. Retrofitting

The question often arises about how far it is worth pursuing the retrofitting of existing poor quality buildings from a sustainable energy perspective rather than demolishing them and replacing them with state-of-the-art new construction. There is no single answer. Various aspects of building renovation, replacement, and demolition have been investigated. Building lifetime and the choice of demolition technique are important for the life cycle energy use of different building materials. If the building structure can be made to fit new purposes, retrofitting is often the more environmentally friendly option, because it preserves material and reduces transport needs. Itard and Klunder (2007) have investigated the case of two larger residential projects using life cycle assessment. According to their results, maintenance or transformation of the existing stock has lower impacts in both cases than demolition and new construction. These results are confirmed by studies of individual building components. Retrofitting to high energy efficiency standards is fully possible and often environmentally desirable (Dodoo et al., 2010). If a demolition is necessary, the embodied energy in the building material can be preserved through the reuse of building components or recycling of the material, or it may be recovered through incineration. The environmentally preferable option depends on local circumstances, and transportation required for alternative solutions is an important factor (Bohne et al., 2008).

10.1.4.7 Life Cycle Energy and Emissions of Residential Appliances

The electricity used by electric and electronic products used in buildings is ultimately converted to heat and either contributes to heating the building or needs to be removed through a cooling system, depending on the climate, building, and heat load. Such energy use in office buildings can be up to several 100kWh/m^2/yr, while appliance-related electricity consumption in residential buildings in OECD countries is typically around 50kWh/m^2/yr.

Life cycle assessments of large appliances indicate that operations-phase electricity use is the dominant source of environmental impacts (Cullen and Allwood, 2009). For personal computers, however, the production causes significant impacts (Williams, 2004). In what is to our knowledge the first study of life cycle impacts of household appliances and

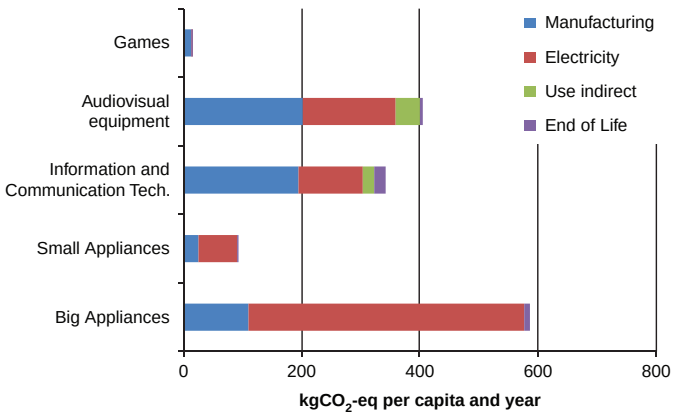

Figure 10.16 | GHG emissions associated with the purchase, use and disposal of electric and electronic equipment in Norwegian households, assuming 0.56 kgCO_2-eq/kWh for use-phase electricity (EU average). Source: Roux, 2010.

Note: Big appliances comprise cold appliances, wet appliances and big cooking appliances; small appliances include vacuum cleaners and microwaves; ICT includes computers, phones and peripherals; and audiovisual equipment include TVs, video equipment and audio equipment.

electronic equipment, Roux (2010) shows that the greenhouse gas emissions caused by the production of information and communication technology and audiovisual equipment purchased by Norwegian households is larger than the emissions caused by the electricity this equipment uses, even assuming a relatively polluting electricity mix (Figure 10.16). Taking the manufacturing of the equipment and the use of networks and content of ICT and audiovisual equipment into account, the GHG emissions caused by this equipment are equal to or larger than those caused by washing machines, driers, refrigerators, and freezers taken together. While these research results cannot be generalized, they indicate that the growing, rapid turnover of household electronics is an emerging problem that comes on top of the energy use of traditional household appliances. It may also stress the importance of regulating the durability of such equipment as a key energy- and GHG-saving strategy for residential emissions, potentially with comparable reductions as direct energy-saving policies.

10.1.4.8 Energy Embodied in Buildings-Related Water Use

Another commodity through which energy is embodied in buildings is water. The trade-offs between energy and the environment are discussed in detail in Chapter 20; however, this section narrows its focus only to the significant interactions of water and energy associated with their usage in buildings. These interactions are (1) water use for energy supply that is later used in buildings; (2) energy use to produce water consumed later in buildings; and (3) water used in energy consuming equipment and appliances installed in buildings as a special subcategory of interaction number two.

First, energy supply requires water. For instance, in the United States around 40% of freshwater withdrawals are used as cooling water for thermal power plants that are generating electricity (Huston et al., 2004).

Thus, reducing electricity demand in buildings has the potential to reduce freshwater withdrawals and associated environmental impacts. Second, water used in buildings[8] requires energy to extract, pump, transport, treat, and dispose the potable water and wastewater and to heat water for the final domestic and commercial use. For example, in California, these water-related energy uses for all sectors (buildings, industry, and agriculture) account for about 19% of the state's electricity, 32% of its natural gas, and 88 million gallons (3%) of diesel fuel every year (John et al., 2005). Barry (2007) estimated that 2–3% of the world's energy use is used only on pumping and treating water for civil and industrial supply. Water losses increase the amount of energy required to deliver water to the consumer. Barry (2007) provides case studies from Mexico, Brazil, and South Africa that exemplify that water loss ranges from one-third to one-half of the volume of water produced due to leaks and system inefficiencies.

Energy can be saved through water consumed in buildings by technologically reducing water demand at the point of its final use – such as through efficient washing machines, low flow faucets, toilets, and shower heads, increasing efficiency of water heating (see Section 10.4 for details), and eliminating water losses during the process of water extraction, treatment, transportation, distribution, and wastewater cleaning. Another cost-effective opportunity is the promotion of water-saving habits and lifestyles. Use of treated wastewater for other applications, such as for landscaping and flushing, is also predominant and even mandatory in India for several building typologies under environmental clearance norms. This, in turn, saves energy for pumping and transportation of water. The Alliance to Save Energy (2008) estimated that municipalities can cost-effectively save at least 25% of energy and money through water systems alone.

Finally, a special subcategory of energy saving measures is associated with water use in energy-using appliances, such as water heaters, cooking devices, and dish- and clothes-washing machines and in cooling and chilling applications. Energy savings can occur by means of water saving considerations in this equipment. Evaporative cooling is still largely used in India, for example, and provides a low-energy means of providing cool air in many parts of the world. For air conditioning applications, water-cooled chillers are more energy efficient than air-cooled ones. There is a dichotomy of choice between the use of water-efficient vis-à-vis energy-efficient chilling machines. Use of potable fresh water for space conditioning is prohibited in several states of India, especially where fresh water supplies are constrained. Also, existing environmental clearance norms for large-scale building projects in India encourage the use of recycled and treated wastewater or harvested rain water for space conditioning purposes. These measures not only address an environmental challenge – clean water conservation – but also reduce water-related energy use in connection with cooling.

8 According to UNEP, the global environmental footprint of the building sector represents 25% of total water use (UNEP SBCI, 2009).

10.1.5 The Impact of a Changing Climate on Building Energy Service Demand

A warming and changing climate has a strong influence on energy use in the building sector worldwide. While cooling demand increases as the climate warms, passive cooling approaches (e.g., overnight ventilation, shadowing) become less effective or do not achieve acceptable indoor temperatures. On the other hand, heating demand decreases in cold zones and allows acceptable winter comfort to be achieved more easily. In temperate climate areas such as much of Europe, Japan, South Africa, or the United States, both impacts on winter heating and summer cooling demand can be observed.

The net impact of warming depends on a complex set of factors. These include the choice of fuel and conversion efficiencies for heating fuels and power generation, building design, efficiency, and operation. Cooling loads will depend strongly on the market penetration of air conditioning, which itself will be dependent on income, building design, culture, and increasing internal loads of buildings by office automation, as well as external temperature. In addition, the cooling demand is exacerbated by the urban heat island effect (see Section 10.2.6) and the escalation of service demand for cooling. In some moderate climate regions, by contrast, heating loads may decrease substantially, or may even become unnecessary due to the combined effect of advanced know-how in building construction, building insulation performance, and an increase in internal heat loads. In contrast, the load on refrigeration equipment increases and its efficiency decreases with rising internal temperatures. The overall global effect is very likely to be an increase in electricity use, due to additional cooling demand in warmer continents and regions, despite a reduction in direct heating fuel use, with a net impact on primary energy that depends on a range of factors (Hunt and Watkiss 2011).

Changes in summer temperatures will also tend to increase the maximum load on electricity systems that already have summer peak demand, and therefore increase the need for power generation capacity. There are also implications for cooling strategies in buildings in some regions. In those regions with cold moderate climates where residential building over-heating is currently not a significant issue, it may become so, and passive cooling techniques currently associated with warmer climates will need to be incorporated into building design. On the other hand, in some arid climates, as diurnal average temperatures rise, existing passive cooling techniques may become inadequate, leading to greater reliance on active cooling. In general, buildings will need to be designed to allow comfortable conditions to be maintained in the range of climates they are expected to face over a building's lifetime. To the extent this is not done, there are increased mortality and morbidity risks from heat stress, although health impacts of cold will fall.

For much of Europe, increases in electricity demand for air conditioning and cooling will be outweighed by reductions in the need for heating energy up to 2050 (Jochem et al., 2009) while warming is moderate

and no thermally advanced buildings are considered. The individual changes may be quite large: for example, 10% per degree change in winter temperature for residential space heating in the United Kingdom (Summerfield, 2010). The aggregate impact of the different effects is smaller. The net result in a 4°C scenario[9], for instance, is a reduction in final energy demand by 2050 of 3.3% (Jochem et al., 2009) for the European Union-27 plus Norway and Switzerland. However, electricity used in space cooling is presently more carbon intensive in many countries than energy used for heating (e.g., gas, heating oil, wood fuels) in Europe and other countries in moderate climates. Depending on the final energy mix for heating and cooling, and the mix of primary energy for electricity supply, net CO_2 emissions in quite a few countries could still slightly increase even though overall energy demand decreases (Cartalsi et al., 2001; Frank, 2005; Aebischer et al., 2007; Rivière et al.; 2008).

The total electricity demand in the buildings sector is projected to slightly decrease in Nordic and Baltic countries (0.5%) by 2050. However, a 7% increase in the electricity demand by 2050 is expected in southern Greece, Malta, Cyprus, Southern Italy, Spain, Bulgaria, and Romania in a 4°C Scenario (Mirasgedis et al., 2007; Jochem et al, 2009). This points to distributional issues regarding adaptation or mitigation policies between northern and southern European countries. It may also lead to a greater need to balance summer electricity flows via the trans-European electricity grid, particularly during extreme heat waves. Similar effects can also be assumed for northern and southern states in the United States, Russia, or provinces in China.

According to Mansur et al. (2005), the combination of climate warming and fuel switching – from fuels to electricity – in buildings in the United States results in increases in the overall primary energy demand. There is likely to be a significant growth in the installation of air conditioning, but, with low utilization, additional energy demand may remain modest (Henderson, 2005), as confirmed by Jochem et al. (2009) for European countries north of the Alps.

There will be smaller impacts on other uses of energy in buildings. While the energy required to supply the same amount of hot water slightly decreases in a warmer climate, any increased demand for showers and bathing in warmer weather and additional heat waves will offset this reduction.

Climate change will increase electricity and primary energy demand in most emerging and developing countries, in contrast to a small or even beneficial effect in more temperate industrialized countries of the developed world such as Scandinavian countries, Russia, or Canada.

If left to the market alone, i.e., in the absence of specific government interventions, the responses to these climate changes are likely to be based on incremental short-term considerations – for example, the purchase of inefficient types of room air conditioning during hot summers. This may lock in the existing set of inefficient technologies (Unruh, 2000) in situations where innovative solutions would be more desirable (e.g., passive ventilation, passive buildings, cooling by absorption technology, shadowing by building elements and trees, white roofs and surfaces, vegetation in urban areas). Given the long life of building stock, it is clearly a priority that policies consider climate mitigation and adaptation of the building stock together.

10.2 Specific Sustainability Challenges Related to Energy Services in Buildings

10.2.1 Key Messages

This section focuses on major cross-cutting, building-specific issues that often present challenges and require trade-offs when pursuing sustainable energy goals; additional to those covered by other chapters in GEA. The key message that is valid across various subsections is that most of such challenges can be overcome by a high-efficiency, state-of-the-art building (from new and retrofits) and energy using equipment stock. The section on fuel poverty shows that high-efficiency buildings may eradicate fuel poverty and through this can also improve general social welfare.

10.2.2 Indoor Air Quality and Health Impacts of Air Tightness

Improving air tightness is an important method to reduce heating and cooling energy demand. However, it is also important to secure adequate ventilation, so as to maintain a healthy indoor environment due to the variety of chemicals used in interior materials, furniture, and daily goods. While this is not an issue with advanced buildings described in this chapter, since by design they operate with ventilation rates that result in very high indoor air quality, this is still an issue with existing or sub-optimally designed, inefficient future buildings.

One way to improve indoor air quality in increasingly airtight buildings is to reduce the use of materials emitting high levels of volatile organic compounds and ensure adequate ventilation. Health problems caused by airtight buildings without adequate ventilation, the so-called sick building syndrome,[10] were first identified as a result of reducing air change rate as an energy conservation measure. In order to ensure proper air quality, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) proposed a range of allowable CO_2 concentrations from 1000 ppm to 2500 ppm, as well as ventilation requirements of 10 liters/sec per person for office spaces. In addition,

9 The 4°C scenario assumes that global average temperature will rise by 4°C compared to pre-industrial levels (van Vuuren et al., 2008).

10 Sick building syndrome describes the situations in which building occupants experience health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified (US EPA, 1991).

case control studies of allergy symptoms in 390 Swedish households (Bornehag et al., 2004) showed that the air change rate of the case group that had allergy symptoms was lower than 0.5/h[11], the same value under which the sick building syndrome and other air infectious diseases have also been shown to increase (Seppanen et al., 1999). In Japan, measurement of the concentration of chemicals in 2800 households (Osawa and Hayashi, 2009) showed that concentrations of formaldehyde in 27.3% of the households were higher than the guideline value. As a result, the revised Building Standard Law stipulates that air change rate in the living rooms of new constructed buildings must be secured at at least 0.5/h.

10.2.3 Household Fuels vs. Environmental Health

As discussed in Chapter 4 and other Chapters of the GEA, indoor air pollution arising from poor quality fuels burnt in inefficient devices has a health toll of mortality and morbidity measured by hundreds of millions each year. Since the issue is treated in detail throughout this document (including, but not limited to, Chapters 2, 3, 4, 11, and 19), this section only brings the importance of the issue to the fore and highlights some key relevant aspects.

Traditional biomass fuels have been the single most important energy source in buildings for centuries. They still account for approximately 10% of global total primary energy use concentrated primarily in developing countries. Approximately 60% of all biomass is used in solid unprocessed forms such as firewood, agricultural waste, and dried animal dung burnt in crude and inefficient stoves and open fires for cooking and heating (IEA, 2008b). Chronic Obstructive Pulmonary Diseases, to which pollution from poor combustion of biofuels indoors contribute, are predicted to become the world's third largest cause of death by 2030 (WHO Statistics, 2008).

Women and children in rural and urban areas of developing countries are most at risk due to their daily, close proximity exposure. Providing chimneys and efficient wood-burning stoves have been shown to reduce health risks by up to 50% in some areas (Romieu et al., 2009). Facilitating access to clean fuels such as biogas, solar thermal energy, liquefied petroleum gas, or electricity could reduce health risks, particularly in urban areas where commercial energy is more widely available. Facilitating a "multiple fuel and clean technology" by simultaneously making a more efficient and cleaner use of biomass for cooking and increasing access to other modern fuels has wider potential ecological and economic benefits due to reduced forest degradation and the time spent, mostly by women, in collecting fuel (García-Frapolli et al., 2010). This challenge is explored in more detail in Section 10.7.3 and new developments on advanced stoves are reported in Section 10.4.3.

11 Exchange rate of the total room air volume per hour.

10.2.4 Fuel and Energy Poverty

Even if access to modern energy carriers has been enabled, many population segments still may not be able to afford sufficient amounts of energy to meet their basic needs. The problem exists even in the most affluent countries, in many of which significant shares of the population cannot afford adequate heating, or are forced to spend disproportionate shares of their income on meeting basic thermal comfort needs. Since, as the section below argues in detail, this is often not due to generic poverty; or is in cases cause of other poverty, this problem is intimately related to the sustainable development goals of GEA.

While there are several definitions of fuel poverty, this document's use of the term is broader than that in many other sources. According to Tirado Herrero (in preparation), "A household is in fuel/energy poverty when it is unable to afford an adequate amount of energy services to satisfy its basic domestic needs – particularly sufficient thermal comfort – or is forced to spend a disproportionate share of its income on them". This phenomenon, called "energy poverty" and "fuel poverty," was introduced in Chapter 2, and its health impacts were discussed in Chapter 4. This chapter elaborates further on these health and social consequences, and discusses how the solution to the problem goes hand in hand with sustainable energy goals in buildings.

Fuel poverty originates from a combination of three main causes: household income, energy prices, and domestic energy efficiency. In many cases the problem can be substantially alleviated, sometimes even eliminated, by significantly improved efficiency – thus providing a strong synergy with sustainable energy goals. Box 10.A.1(see the GEA Chapter 10 online appendix) provides a case study in India of a project to provide solar lighting for approximately 886 million rural residents.

Fuel poverty is often the long-term consequence of measures that were introduced to provide sufficient access: i.e., subsidized energy prices for the poor. Artificially low energy tariffs provide the wrong economic signals and thus result in the acquisition of inefficient equipment and occupation of energetically poor buildings. When consumers are weaned from the subsidized prices, they find themselves locked into disproportionally high energy expenditures. An example of this is the formerly communist countries of Central and Eastern Europe and the former Soviet Union, where highly subsidized energy pricing policies have resulted in a very poor efficiency building stock and highly inefficient infrastructure. After the fall of communism, the introduction of market-based energy pricing resulted in significant shares of the population now living in fuel poverty and not being able to afford adequate heating. Since they can especially not afford investments in improving the efficiency of their energy using stock or buildings, poor population segments may turn out to pay significantly more for lower levels of energy services than the more affluent who can afford higher levels of efficiency.

Fuel poverty is an insufficiently researched and reported problem, especially in certain regions like the former Soviet Union and Central and

Table 10.3 | Incidence of fuel poverty in selected countries and regions.

Country/Region	Main estimates	Reference
UK	- Number of fuel poverty households in the UK ranging between 2 and 6.5 million (1996/2007)	DECC (2009a)
Ireland	- 17.4% of households unable to adequately heat the home (2001)	Healy and Clinch (2002)
EU	- Average percentage of households unable to heat home adequately (1994/97) in EU14: 16.9% [max: 74.4% in Portugal; min. 1.6% in Germany]	Healy (2004)
CzechRepublic	- Less than 10% of households suffering from domestic energy deprivation	Buzar (2007)
Macedonia	- More than 50% of households suffering from domestic energy deprivation	Buzar (2007)
New Zealand	- Between 10% and 14% of households in fuel poverty using the UK definition of adequate indoor temperatures (2001).	Lloyd (2006)
Hungary	- The average Hungarian household allocated 9.7% of its net income to energy expenses (2000/07) - 15% of the population (1.5 million) declared to be unable to afford to keep their homes adequately warm (2005/07)	Tirado Herrero and Ürge-Vorsatz (2010)

Source: own elaboration after references consulted.

Eastern Europe, where it is suspected to be widespread (Buzar, 2007; Boardman, 2010). Though slowly gaining priority in some policy and research agendas (Friel, 2007), it is still far from being a common issue of concern (see Table 10.3). Even in economically and socially advanced regions like the European Union, few Member States have come up with specific strategies or policy frameworks to address the issue. In fact, few countries – only the United Kingdom (BERR, 2001; DEFRA/BERR, 2008), Ireland (MacAvoy, 1997), the United States (Power, 2006) and New Zealand (Chapman et al., 2009) – have started any significant action to tackle fuel poverty. In the United Kingdom, the government has set as a goal that by 2018 no British household should be spending more than 10% of its income on energy (DEFRA/BERR, 2008). The likely failure in meeting this target in the United Kingdom, as foreseen by Boardman (2010), evidences the scale of the challenge and provides arguments for jointly tackling fuel poverty, climate change mitigation, and energy security challenges. In fact, since domestic energy efficiency solutions allow bringing households out of fuel poverty while capping or reducing their energy use levels (Milne and Boardman, 2000), eradicating fuel poverty will certainly have positive effects on those related challenges.

There is evidence that inadequate indoor temperatures cause excess winter mortality (EWM) (Eurowinter Group, 1997), with most western countries reporting relative EWM rates ranging from 5% to 30% (Healy, 2004) (see Table 10.4). Based on a cross-country comparison, taking Norway as a control case, it is estimated that 44% of the cardiovascular- and respiratory-disease excess winter deaths registered in Ireland in 1986–1995 can be associated with poor housing standards (Clinch and Healy, 1999). Fuel poverty is also linked to certain illnesses (Morrison and Shortt, 2008; Roberts, 2008), with particularly negative physical and mental health effects being recorded for vulnerable populations, such as the elderly and children (de Garbino, 2004; Howieson, 2005; Liddell and Morris, 2010).

A common policy tool for alleviating fuel poverty has been subsidies aimed at reducing the energy bills or increasing the disposable income of low income households (DEFRA/BERR, 2008; Scott et al., 2008; Tirado Herrero and Ürge-Vorsatz, 2010). Such support schemes have, however, been criticized because, even though they succeed in reducing fuel poverty temporarily, in the long run they lock these households into fuel poverty by creating disincentives to improving the efficiency of energy using equipment and buildings. Healy (2004) has argued that the saved income most likely will be spent on more energy rather than invested in improving the quality of the dwellings. In addition, direct support schemes are often poorly targeted, distort the market, and constrain government budgets (Scott, 1996; IEA, 2007b; Fülöp, 2009).

A more sustainable and long-term solution is the retrofitting or replacement of inefficient equipment and building stock of these populations by high-efficiency ones. As this requires substantial investments that those experiencing fuel poverty themselves will not be able to afford, it may be necessary to (re)allocate public funds and financing to such purposes. For instance, since large sums of public funds, comparable to the investment costs of high energy efficiency retrofit programs that may fully eliminate the fuel poverty problem are devoted yearly to social energy price subsidies and temporary fuel poverty alleviation measures, a progressive substitution of the latter by the former can substantially contribute to the solution of the problem.

In addition, since a high-efficiency building and appliance stock contributes to the solution of many other problems – such as GHG and other environmental emissions, energy security, and employment – policy integration can result in the availability of funds that can more effectively reach those goals through improved efficiency, especially if sources from these several fields are combined. For instance, Ürge-Vorsatz et al.

Table 10.4 | Incidence of excess winter mortality (EWM) in selected countries.

Country	Period	EWM		Reference
		Relative[1]	Absolute	
Austria	1988–1997	14%	n.a	Healy, 2004
Belgium	1988–1997	13%	n.a	Healy, 2004
Denmark	1988–1997	12%	n.a	Healy, 2004
Finland	1988–1997	10%	n.a	Healy, 2004
France	1988–1997	13%	n.a	Healy, 2004
Germany	1988–1997	11%	n.a	Healy, 2004
Greece	1988–1997	18%	n.a	Healy, 2004
Hungary	1995–2007	12.71%	5566 deaths	Tirado Herrero and Ürge-Vorsatz, 2010
Ireland	1988–1997	21%	n.a	Healy, 2004
Italy	1988–1997	16%	n.a	Healy, 2004
Luxembourg	1988–1997	12%	n.a	Healy, 2004
Macedonia	1995–2004	n.a	885deaths	WHO, 2007
Netherlands	1988–1997	11%	n.a	Healy, 2004
New Zealand	1980–2000	18%	1,600	Davie et al., 2007
Poland	1991–2002	n.a	14,680deaths	Morgan, 2008
Portugal	1988–1997	28%	n.a	Healy, 2004
Romania	1991–2004	n.a	17,358deaths	Morgan, 2008
Spain	1988–1997	21%	n.a	Healy, 2004
UK	1988–1997	18%	n.a	Healy, 2004

Source: own elaboration after references consulted.

Notes: 1) Percentage of additional deaths in the cold season in comparison with the warm season

(2010) have suggested that Hungary could cover the bill of deep renovation of its entire inefficient building stock, and thus the complete elimination of its fuel poverty, from the redirection of existing budgets, while still reaching the objectives of those budget items.

10.2.5 Health Problems Caused by Intermittent Local Heating

Household heating in some cold regions, including Japan and parts of Europe, is often limited to the occupied space, causing large temperature differences between heated and unheated spaces.

In Japan, measurements of indoor air temperatures in residential buildings located in cold regions indicate that indoor air temperatures are maintained around 20ºC in the heated rooms, while the temperatures of bedrooms, bathrooms, and toilets without heating can be as low as outdoor air temperatures (Yoshino et al., 1985). The average temperature difference between heated rooms and not heated rooms is often about 20ºC. It is thought that blood pressure overshoots caused by such large temperature differences are one of the causes of high death rates from apoplexy in these districts. Moreover, a large percentage of deaths from accidental drowning in bathtubs in Japan is due to the low temperatures in unheated bathrooms (Tochihara, 1999): the sudden change in blood pressure before and after bath might also be the cause of death from apoplexy or anemia. High-efficiency, state-of-the-art buildings advocated in this chapter could help overcome this problem. With minimal or no energy investments, they can provide full thermal comfort and thus reduce such mortality and morbidity.

10.2.6 Urban Heat Islands vs. Resilient Buildings

The outdoor air temperature in hot weather in thermally massive built environments with surfaces of low albedo is increasing due to the urban heat island phenomenon (Oke, 1982; Akbari et al., 1990; inter alia). It is becoming a major reason for the increase in energy use, and is exacerbated by the measure that is supposed to reduce the impact: the air conditioning of buildings. Air conditioners transport indoor heat to the outdoors, adding to the heat generated by air conditioners themselves, thereby contributing to the urban heat island effect in areas with mechanical cooling. The heat island effect occurs when surfaces of the built environment absorb sunlight, which is released as heat during cooler periods, such as nighttime, and keeps the air temperature warm. It can raise a city's temperature by up to 3–4°C and catalyzes smog formation and other health hazards (US EPA, 2007).

Table 10.5 | Energy saving for HVAC loads due to green roofs in different regions[12].

Percentage Energy Savings for HVAC loads (rounded to the nearest integer)	Number of Floors	City, Country, Latitude
73%	1	Toronto, Canada, Latitude: 43°41′ N
29%	2	
18%	3	
50%	5	Singapore, Latitude: 1°22′ N
26%	2	Athens, Greece, Latitude: 37°58′ N
25%	1	Madrid, Spain, Latitude: 40°23′ N
6%	8	
32% (non-insulated)	2 1 (top floor only)	Athens, Greece, Latitude: 37°58′ N
14% (insulated)		
48% (non-insulated)		
32% (insulated)		

Source: adapted from Ahrestani, 2010; based on Martens et al., 2008; Wong et al., 2003; Spala et al., 2008; Saiz et al., 2006; Santamouris et al., 2007.

Chapter 4 reviews some health impacts of heat stress. This section presents a few further examples. Narumi et al. (2007) carried out investigations on the relationship between infection and air temperature in Osaka, Japan. The number of daily reports of disease increased when the average outdoor temperature was higher than 22°C. Six out of fifteen types of infections: (1) hand-foot-and-mouth disease; (2) herpangina; (3) pharyngoconjunctival fever; (4) enterohemorrhagic escherichia coli; (5) infectious gastroenteritis; and (6) epidemic keratoconjunctivitis – showed a positive correlation with temperature.

Genchi et al. (2007) studied the increase of tropical nighttime temperatures caused by the urban heat island phenomenon, and quantified the impact on sleep disorders. The results show that when the temperature is higher than 26.7°C, about 10% of residents suffer from sleep disorders, with 1°C increase of air temperature at midnight. It was estimated that the economic losses due to insomnia was about 305 billion yen (US$ 3.53 billion).

Among the strategies to address the urban heat island effect are "cool roofs" and roof and vertical "greening." Cool roofs are solar reflective roofs that absorb less sunlight than conventional roofs. The greater reflectivity is achieved by utilizing a light color of roof surface and special highly reflective[13] and emissive[14] materials, which can reflect at least 60% of sunlight instead of 10–20%, reflected by traditional dark-colored roofs (US EPA, 2007). Standard black asphalt roofs can reach 74–85°C at midday during the summer. The surface temperature of bare metal or metallic roofs can increase up to 66–77°C. Cool roofs reach peak temperatures of only 43–46°C, even in full summer. Conventional roofs can be 31–47°C hotter than the air on any given day, while cool roofs tend to stay within 6–11°C of the background temperature.

Cool roofing materials cost 5–20% more than conventional ones, but in the long run they can provide considerable cost and energy savings, reduce GHG emissions, and improve human health. Human health improvements include reducing heat-related illnesses and reducing deaths in buildings without air conditioning (US EPA, 2007). Energy savings vary greatly from one building to another between 10 and 70% of total cooling energy use (Wang, 2008). Preliminary estimates of the global emitted CO_2 offset potentials for cool roofs and cool pavements by Akbari et al. (2008) are in the range of 24 Gt of CO_2 and 20 Gt of CO_2, respectively, giving a total global emitted CO_2 offset potential range of 44 Gt of CO_2.

Green roofs and walls also mitigate the heat island effect, improve urban air quality (Yang et al., 2008), reduce CO_2 concentrations, and reduce the need for winter heating (Takebayashi and Moriyama, 2007; Li et al., 2010). Green roofs have also been shown to provide thermal insulation to buildings through a combination of the reduced thermal conductivity of the roof structure, and the evapotranspiration of the plants (Martens et al., 2008). A number of studies have shown that insulation provided by green roofs can reduce energy use of heating, ventilation, and air conditioning (HVAC) systems. However, the energy savings reported in the literature are usually the results of simulations rather than real measured data, therefore, the range of presented values is very wide. For example Sailor (2008) finds that for a 2-story office building in Chicago and Houston a green roof with 0.2m thick soil reduces total electricity use by 2% in both cities and reduces natural gas use by about 9% in Chicago and by about 11% in Houston compared to a conventional membrane roof. Table 10.5 demonstrates the results from several studies and shows that modeling results of HVAC energy saving from green roofs vary between 6–72% depending on the climate zone and number of floors affected.

12 All energy savings presented in the Table are the results of simulations and not measured data

13 Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface.

14 Thermal emittance is the amount of heat a surface material radiates per unit area at given temperature, i.e., how readily a surface gives up heat.

As the urban and global climate changes – and warms – the ability of buildings to continue to provide healthy and thermally-comfortable environments for inhabitants will be further challenged. A combination of efficiency (via passive solar design), bio-climatic design (where buildings are greened and integrated into their natural settings rather than set apart from them) (Yeang, 1994), and design for adaptability (when buildings are designed for simple retrofitting to enhance resilience to environmental climatic extremes) (Graham, 2005) is necessary to cope with climatic challenges (Bornstein and Lin, 1999). Designers, developers, regulators, and financiers – both government and private – urgently need to be made aware of this deteriorating situation. Occupants also need to be provided with a greater choice of strategies, including energy feedback and occupancy monitoring systems, in order to tune buildings to changing climatic conditions.

Among the primary purposes of buildings is the provision of thermal comfort. Thermal comfort is a dynamic quality based on the interaction of people's metabolism, sensory perceptions, expectations, and acclimatization experiences, as well as the human body's interaction with the surrounding interior building materials. The material nature of the urban environment is in a constant dynamic relationship with the urban climate (Santamouris, 2001), which is in turn embedded in the regional and ultimately the global climate – a relationship still little understood and appreciated. A change in any of these parameters can change perceptions and experiences of comfort, which exacerbates the demand for energy for heating or cooling. Integrating into a building the potential to naturally resist climatic extremes and especially temperature excesses in urban settings is a fundamental advantage of bio-climatically appropriate design. Both sustainability and livability are enhanced as a consequence.

10.3 Strategies Toward Energy-sustainable Buildings

This section briefly reviews the key strategies that can be applied to move towards buildings that use energy in more sustainable way. The sections to follow "unpack" these strategies, and translate them into concrete technological and non-technological options.

The key to achieving sustainability in the building stock is to reduce the energy requirements in operating buildings to the point where building energy needs can be met entirely through renewable and non-greenhouse gas emitting energy sources, while maintaining indoor air quality and avoiding hazardous chemicals. The extent to which present building energy requirements need to be lowered in order to be satiable by renewable energy depends on the overall energy demand in society and hence on the success of measures to reduce energy demands in other sectors of the economy. It also depends on the achievable and sustainable energy supply from renewable energy sources which, in the case of biomass energy, depends on a number of still uncertain biophysical and climatic factors, as well as on diet through its impact on the availability of land for bio-energy crops (see Chapter 20). The building energy intensity (annual energy use per unit of floor area) that can be regarded as sustainable depends on the human population and the floor area per person, which together determine the total building floor area. Given limits – either physical, economic, or practical – to the renewable energy supply, a larger global building floor area will require lower energy use per unit of floor area. In the GEA pathways (Chapter 17) where future energy systems meet the key environmental, social, and economic objectives, energy intensity is reduced by the factor of three to four (and even larger in some regions).

A hierarchy of options for achieving reductions in the energy intensity of buildings of this magnitude is presented in Section 10.4, beginning with urban-scale energy systems, building-scale energy systems, and finally, individual energy using devices in buildings. A least-cost approach to achieving sustainable energy use in buildings will be to implement energy saving measures – either in the construction of new buildings or the retrofitting of existing buildings – up to the point where the cost of the next measure exceeds the cost of the least expensive renewable energy supply option. The least expensive renewable energy supply option might involve the on-site generation of electricity and thermal energy, or it might entail the provision of locally produced biomass or the provision of C-free electricity from distant but high quality wind, solar, or other renewable electricity sites. The relative costs of achieving a given low building energy intensity, of on-site generation of renewable energy, and of off-site supply of renewable energy will vary regionally, over time, and with the type of building under consideration. Some forms of renewable energy supply, such as passive heating, ventilation and daylighting, can be regarded as energy demand reduction measures rather than energy supply measures, but in any case, they tend to be low cost and so will be early choices in a hierarchy of increasingly stringent demand or supply measures.

10.4 Options to Reduce Energy Use in Buildings

10.4.1 Key Messages

Deep – 75% or more – reductions in the gross energy requirements of new buildings compared to the performance of most types of recent new buildings can be achieved in most or all jurisdictions in the world through application of the Integrated Design Process and of the principles discussed here. It is also possible to achieve significant – 50% or more – reductions in the energy use of existing buildings. Once gross energy requirements have been reduced by a factor of two to four, it is sometimes possible to supply most or all of the remaining energy requirements with on-site renewable energy generation such as active solar technologies (photovoltaic, solar thermal) mounted on or integrated into the building envelope, thereby reducing the net energy requirements to zero or achieving net energy generation.

Through drastic reductions in the net energy requirements of buildings, it will be significantly easier than otherwise to eventually supply all of the remaining energy requirements from off-site renewable energy sources (such as wind, solar and biomass), whether local or distant but of high quality.

10.4.2 Urban-Scale Energy Systems, Urban Design, and Building Form, Orientation, and Size[15]

10.4.2.1 Key Messages

Urban design influences energy use by buildings in several ways. Shape, height and orientation significantly affect heating and cooling loads and opportunities for passive ventilation. The density of urban developments influences the economic viability of district heating and cooling systems.

10.4.2.2 Role of Street Orientation and Width

Traditional houses and streets in many parts of the world used to be laid out so as to provide a significant amount of self-shading. The spacing of buildings close enough to provide significant self-shading will diminish wind strength near the ground, reducing the potential for ventilation, although daytime ventilation is not always useful. Close spacing also reduces solar access in winter, but such access will not be needed in those hot-summer regions with mild winters. Bourbia and Awbi (2004) measured temperatures at the 1.5 m height in traditional (narrow) and contemporary (wide) streets in a city in Algeria. Traditional streets are about five degrees cooler than contemporary streets, whether oriented north-south or east-west. This is due both to greater shading of traditional streets, which reduces direct solar irradiance, and the smaller sky viewing angles, which reduces diffuse solar irradiance. In hot-dry desert climates of India, the urban scape is defined by narrow roads banked by tall and compact houses with thick walls and small openings – all of these strategies help keep heat out of buildings.

10.4.2.3 Role of Building Shape, Form, and Orientation

Building shape (the relative length, width, and depth), form (small-scale variations in the shape of a building), and orientation are architectural decisions that have significant impacts on heating and cooling loads, as well as on daylighting and opportunities for passive ventilation, passive solar heating and cooling, and for active solar energy systems. For instance, in temperate climates, the optimal orientation for rectangular buildings is the long axis running east-west, as this simultaneously maximizes passive solar heating in the cold season and minimizes solar heating in the warm season. Traditional houses in warm climates in India were mostly designed around courtyards and front courts (Aangan) that served as congregation spaces for families and for sleeping during nighttime, as these are naturally cool outdoor spaces. Developing countries, such as India, have a rich legacy of architecture that uses traditional low- or no-energy techniques to ensure thermal and visual comfort. Old forts and havelis (mansions) had deployed several innovative techniques of natural lighting, ventilation, and natural cooling to achieve desired comfort levels.

Roof design is another feature that can influence energy use. An unconditioned space between inhabited rooms and the roof is a traditional insulating technique, and one that allows significant improvements in thermal performance without loss of useful space, by installing additional insulation. An overhanging roof also provides passive cooling via shading, as well as protecting walls from rain and snow. A reflective (white or cool) roof reduces heat gains, as discussed earlier.

The options discussed in this section, as well as many other sections, may influence the aesthetics of the building and neighborhood. Nevertheless, by today most, if not all, sustainable energy solutions can be implemented in buildings that do not need to compromise on aesthetics.

10.4.2.4 Role of Building Size

Building size is an important factor in energy use. Increased size tends to reduce surface to volume ratio, thereby reducing thermal losses and gains relative to floor area. However, total surface area and hence total energy use will increase unless the envelope is sufficiently improved. In the United States, the living area in dwellings per family member increased by a factor of three between 1950 and 2000 (Wilson and Boehland, 2005). This is due in part to declining average family size (from an average of 3.67 to 2.62 members) and in part due to larger houses (from an average of 100 m^2 to 217 m^2). A moderately insulated 3000ft^2 (~300 m^2) house in Boston requires more heating and cooling energy than a poorly insulated 1500 ft^2 house in the same location. The larger house also requires substantially more materials. According to a designer-builder quoted by Wilson and Boehland (2005), the growth in house size is due to: (1) the loss of a sense of community and public life, so that the house becomes more of a fortress that needs to provide multiple forms of entertainment instead of basic shelter; (2) the promotion of the idea that "bigger is better" by the building industry; and (3) the diminishing craftsmanship in house construction and design, leading to a substitution of greater size to counteract the sterility of modern homes. Wilson and Boehland (2005) list various strategies to make more efficient use of space, so that smaller houses provide the same services.

10.4.2.5 Multi-unit Housing, Office and Retail Space

Multi-floor, multifamily housing is significantly more energy efficient than single-family housing, especially one-floor, single-family housing.

15 This section is a highly condensed discussion drawn from Harvey (2006, 2009, 2010).

This is due to the sharing of walls and reduction in roof area, with concomitant reduction in heat loss. Stacking housing units vertically, or designing single-family houses as two- or three-story houses rather than as one-story houses will increase the opportunities for passive ventilation in the summer by exploiting the buoyancy of warm internal air, and protects the lower floors from solar heat gain.

Analyses carried out by Smeds and Wall (2007) indicate that over twice the thickness of insulation is needed in a single-family house as in a multi-unit apartment, along with substantially better windows, in order to achieve the same reduction in heat loss. Conversely, adoption of about the same insulation levels and window performance in an apartment building as in high performance houses in Sweden reduces the annual energy use to one-third of that of the high performance house and to about one-tenth of that of conventional single-family Swedish houses.

Multifamily housing has a smaller surface to volume ratio than single-family housing, which reduces the building cost per unit of floor area by reducing the relative importance of the external envelope to the total cost. Construction material requirements are also reduced, while public transit, walking, and cycling are enhanced and land is spared because a more compact urban form can be created. Thus, multifamily and multi-unit office and retail buildings simultaneously reduce energy use and investment costs and enhance possibilities for alternatives to automobile use.

Another benefit of multi-unit housing and mixed (housing and commercial) development is that the connection to district heating and cooling grids is more likely to be economically justifiable, as explained later. However, large-scale office and retail buildings exceeding 30 meters in depth need more energy for lighting, ventilation, and cooling than small-scale office buildings. This is because natural lighting cannot reach the center of the building, so artificial lighting has to be relied upon; natural ventilation cannot provide enough outdoor air, causing a reliance on mechanical ventilation; and heat generated inside cannot be released through the envelope, so more cooling is needed. Different shapes – e.g., U-shaped or E-shaped rather than rectangular – provide better natural lighting and ventilation, but with an increase in exterior walls.

10.4.2.6 District Heating and Cooling

A district heating system consists of a network of underground pipes carrying steam or hot water from a centralized heating facility or heat source to individual buildings, while a district cooling system is a network of pipes to carry chilled water. District heating systems provide an energy savings if they make use of heat that would otherwise be wasted. The most common source of waste heat is heat produced from the generation of electricity in fossil fuel or biomass power plants. Conversely, district heating supplied entirely from centralized boilers does not save any energy, and may in fact increase energy use, compared to the use of on-site condensing boilers. System efficiency is maximized if heat from the cogeneration of electricity is supplied at the lowest possible temperature, as this minimizes the reduction in electricity generation caused by withdrawing useful heat from a steam turbine, maximizes the fraction of waste heat used, and minimizes heat losses during distribution. This, in turn, requires buildings with a high performance thermal envelope and ideally with radiant floor or ceiling heating systems, which permit low heat delivery temperatures, as discussed later. However, the heat load in this case might be so low that a district heating network cannot be economically justified unless the building density is very high.

District cooling can be supplied from large, dedicated centralized electric chillers or from absorption chillers that are driven with steam from steam turbines for electricity generation. The latter is referred to as "tri-generation," as it involves the concurrent production of electricity, hot water, and chilled water. In principle, district cooling from large, centralized chillers can provide significant (up to 45%) savings compared to the use of separate chillers in individual buildings (Dharmadhikari et al., 2000). This rate of savings is due to the larger full-load efficiency of large chillers compared to small chillers, and the ability to operate each chiller in a centralized system at, or close to, its maximum efficiency. Further savings are possible if the centralized system can make use of heat sinks, such as sewage or lake, river, or sea water that would not be available to chillers in individual buildings. However, in practice there may be no savings or even an increase in energy use if unfavorable behavioral changes – such as switching from cooling only individual rooms as needed, to cooling the entire building all of the time – accompany the switch to district cooling, as already highlighted in earlier sections of the chapter.

The total cost of district cooling systems can be less than the total cost of equipping individual buildings with their own chillers. This is due to low unit costs for large chillers, the need for less total capacity in centralized systems – because the peak cooling loads in individual buildings do not all occur at the same time – and the need for less backup capacity (IEA, 1999; Harvey, 2006). District cooling systems also eliminate the need for rooftop cooling towers, thereby freeing up roof space for other purposes, such as rooftop gardens or solar panels.

District heating networks can be coupled with the large-scale underground storage of heat that is collected from solar thermal collectors during the summer and used for space heating and hot water requirements during the winter (Schmidt et al., 2004; Harvey, 2006). Heat can also be supplied with biomass, as part of a biomass cogeneration system or from geothermal heat sources. If both heat and coldness are stored, then heat pumps can be used to recharge the thermal storage reservoirs or to directly supply heat or coldness to the district heating and cooling networks during times of excess wind energy. This, in turn, permits the sizing of wind systems to meet a larger fraction of total electricity demand without having to discard as much, or any, electricity generation potential during times of high wind and/or low demand.

10.4.3 Options Related to Building-Scale Energy Systems and to Energy Using Devices[16]

10.4.3.1 Key Messages

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

The following subsections briefly explain how extraordinary savings can be achieved. Examples are presented of exemplary buildings from around the world, spanning a wide range of climates, followed by information on the initial investment cost of low energy buildings compared to conventional buildings. Much more detailed information can be found in Harvey (2006).

10.4.3.2 Integrated Design Processes

The key to achieving deep reductions in building energy use is to analyze the building as an entire integrated system, rather than focusing on incremental improvements to individual energy using devices. This requires a new approach to building design, referred to as the Integrated Design Process (IDP) (Lewis, 2004). IDP requires setting ambitious energy efficiency goals at the very beginning of a project, and requires an early brainstorming session involving all the members of the design team to develop a number of alternative concepts for achieving the energy target. The integrated design process also entails two-way interaction between the design team and the contractors. Simulation is an important tool in an IDP process. As a building will be operated over a large range of outdoor climates and indoor states, simulation can tell what happens in a part-load situation and help the design to achieve high efficiency during part-load conditions. It often happens that the building and its system perform very well during the hot and cold season (the design states), but very poorly during transitional seasons.

As Harvey (2006) discusses, the steps in the most basic IDP are to: (i) consider building orientation, form, thermal mass; (ii) specify a high performance building envelope and other measures to reduce heating and cooling loads; (iii) maximize passive heating, cooling, ventilation, and daylighting; (iv) install efficient systems to meet remaining loads; (v) ensure that individual energy using devices are as efficient as possible and properly sized; and (iv) ensure the systems and devices are properly commissioned.

16 Subsections 10.4.3 to 10.4.9 are a condensed discussion drawn from Harvey (2006, 2009, 2010).

By focusing on building form and a high performance envelope, heating and cooling loads are minimized, daylighting opportunities are maximized, and mechanical systems can be greatly downsized. This generates cost savings that can offset the additional cost of a high performance envelope and the additional cost of installing premium (high efficiency) equipment throughout the building. These steps alone can usually achieve energy savings on the order of 35–50% in new commercial buildings, while utilization of more advanced or less conventional approaches has often achieved savings on the order of 50–80%.

10.4.3.3 Reducing Heating and Cooling Loads

The term "heat load" refers to the rate of heat loss from a building during the heating season. This heat has to be replaced by the heating system in order to maintain a steady indoor temperature, and so represents a load on the heating system. The term "cooling load" refers to the rate of unwanted heat gain during the cooling season, heat that must be removed in order to maintain a steady indoor temperature.

Heating loads can be dramatically reduced through the use of a high performance thermal envelope, consisting of: (i) high levels of insulation in the walls, ceiling, and basement; (ii) avoidance of thermal bridges; (iii) windows and doors with a very high resistance to heat loss; and (iv) a high degree of airtightness, combined with mechanical ventilation with heat exchangers to recover heat or coldness from exhaust air and possibly waste water, depending on the season.

The heating energy requirement is the difference between heat losses and useable internal and passive solar heat gains. High levels of insulation, combined with high performance windows and airtightness and coupled with mechanical ventilation and heat recovery, can readily reduce heating energy requirements by a factor of 4–10 compared to current practices in cold climate regions. In areas with mild winters where previous practice was for no insulation, rather moderate levels of insulation can substantially reduce heating energy requirements, as well as reduce summer cooling energy use by a factor of two or more (Florides et al., 2002).

Heat loss through high performance windows is so small that perimeter heating units, usually placed below windows to prevent drafts, can be eliminated, even when winter temperatures dip to -40°C (Harvey and Siddall, 2008). When perimeter heating is eliminated, ductwork or hot water piping can be made shorter, as all the radiators can be located closer to the central core of the building, with associated cost savings but also savings in fan and pump size and energy use. If the default design involves floor-mounted fan-coil units, their elimination will increase the amount of useable floor space.

Options to reduce the cooling load include:

- orienting a building to minimize the wall area facing east or west;

- clustering buildings to provide some degree of self-shading, as in many traditional communities in hot climates;
- using high reflectivity building materials; for example, Parker et al. (2002) found that houses in Florida with white reflective roofs have a cooling-energy demand about 20–25% lower and peak power demand about 30–35% lower than houses with dark shingles;
- increasing insulation; for example, Florides et al. (2002) found that for a one-story house in Cyprus, adding 5cm of polystyrene insulation to the roof reduces the cooling load by 45% and the heating load by 67%, while addition of 5cm of polystyrene insulation to the walls reduces the remaining cooling load by about 10% and the remaining heating load by 30%;
- providing fixed or adjustable shading, as external shading devices block 90% of incident solar heat, compared to 50% for internal devices (Baker and Steemers, 1999);
- using windows with a low solar heat gain – as low as 25%, compared to 70% for a clear double glazed window – and avoiding excessive window area, particularly on east- and west-facing walls;
- using highly efficient lighting and household appliances, electronics, and office equipment to reduce internal cooling loads;
- utilizing thermal mass to minimize daytime interior temperature peaks, combined with nighttime cooling; and
- using vegetation to directly shade buildings and to indirectly reduce cooling loads by reducing ambient air temperature through evapotranspiration. Vegetation integrated into building surfaces, such as walls and roofs, also contributes to cooling by reducing heat gains and through evapotranspiration.

Thermal mass does not reduce the heat gain by a building and so does not represent a reduction in cooling load (as defined here). However, a high thermal mass reduces the temperature increase for a given heat gain and, for short temperature spikes, can eliminate the need for air conditioning. Porta-Gándara et al. (2002) simulated the cooling load for housing built with traditional adobe bricks and modern hollow concrete blocks (having minimal thermal mass) in Baja California, and found the air conditioner load of the former to be one-fourth that of the latter during the hottest summer months. However, unless temperatures drop sufficiently at night to remove the heat that enters the thermal mass by day, the temperature of the thermal mass will build up over a period of days, so it will become less and less effective in limiting daytime temperatures. The nighttime removal of daytime heat can be enhanced through deliberate nighttime ventilation of the building with outside air when the outside air is sufficiently cool, as discussed in the next subsection. External insulation will inhibit daytime penetration of outside heat into the thermal mass while leaving it exposed to cool air during nighttime ventilation.

Thermal mass can also be provided through phase change materials (PCM), the most common being a paraffin wax that melts at around 25ºC. The PCM can be embedded in drywall or plaster inside 50-µm capsules. The waxes will not rise in temperature above their melting point as they melt, just as ice will not rise above 0ºC as it melts. Air in contact with the plaster or spheres will rise only a few degrees above the melting point of the wax. At night the waxes refreeze if they can be cooled to below their melting point with cool night air, releasing the heat that they absorbed during the day as they melted.

The combination of switching to a high albedo surface and planting shade trees can yield dramatic energy savings. Rosenfeld et al. (1998) calculated the impact on cooling loads in Los Angeles of increasing the roof albedo of all five million houses in the Los Angeles basin by 0.35 (a roof area of 1000 km^2), increasing the albedo of 250 km^2 of commercial roofs by 0.35, increasing the albedo of 1250 km^2 of paved surfaces to 0.25 (by using whiter, limestone-based aggregates in pavement whenever roads are resurfaced), and planting 11 million additional trees. In the residential sector, they computed a total savings of 50–60%, with a 24–33% reduction in peak air conditioning loads. Akbari et al. (2008) estimate that a net albedo increase for urban areas of about 0.1, which they consider achievable by increasing both roof and pavement albedos by about 0.25 and 0.15 respectively, can achieve the equivalent of offsetting about 44 Gt of CO_2 emissions on a global scale. At the same time, these measures would induce significant savings in cooling costs, with an estimated savings potential in excess of US$1 billion/yr in the United States. Growing vegetation on building walls can also provide important reductions in cooling energy use; simulations by Kikegawa et al. (2006) indicate a savings of 10–30% for residential buildings in Tokyo.

In hot-humid climates, the energy required to dehumidify air can represent a significant fraction of the total cooling load. This portion of the cooling load will not be reduced through measures such as shading, external insulation, or use of thermal mass and windows with low-solar heat gain, so these measures will provide a smaller percentage savings in overall cooling loads. However, materials that absorb moisture can be placed at the internal surface of rooms so as to maintain nearly constant relative humidity inside. On dry days, the moisture can be released back to the air through ventilation. This can greatly reduce the energy required for dehumidification.

Thermal mass will be less effective in reducing daytime temperature-related cooling loads in humid climates because of the smaller day-night temperature difference in hot-humid climates than in hot-dry climates. In hot-humid climates, it is more appropriate to employ urban and building forms that promote air movement between and through buildings, in order to employ low thermal mass to minimize the storage of heat so that buildings can cool quickly whenever temperatures decreases (Koch-Nielsen, 2002).

Table 10.6 | Major strategies for reducing different energy uses in buildings in different climate zones.

	Climate Zone			
	Cold Moderate	**Warm Moderate**	**Arid**	**Tropical**
Heating	• High levels of insulation and air tightness with heat-recovery ventilation • Windows with high thermal resistance and high solar heat gain	• High levels of insulation and air tightness with heat-recovery ventilation • Windows with high thermal resistance and low solar heat gain	• Modest insulation • Windows with low solar heat gain	• Minimal or no insulation • Windows with low solar heat gain
Cooling	• Earth pipe • Shading • Thermal mass	• Earth pipe • Shading • Reflective surfaces • Thermal mass with external insulation and night ventilation	• Shading • Reflective surfaces • Thermal mass with external insulation and night ventilation • Compact form and self shading • Evaporative cooling	• Shading • Open structure with plenty of ventilation • Minimal thermal mass • Solar-driven desiccant dehumidification and evaporative cooling
Ventilation	• Hybrid passive-mechanical ventilation	• Hybrid passive-mechanical ventilation		

High performance thermal envelopes can readily reduce heating energy requirements by 75–90% in cold climates, while modest levels of insulation may eliminate the need for winter heating altogether in regions with mild winters. Modest levels of insulation are also effective in reducing cooling loads by about half in hot climates. Thermal mass, combined with external insulation and nighttime ventilation, can largely eliminate cooling requirements in hot-dry climates. In hot-humid climates, the potential to reduce cooling loads is smaller, due to the greater importance of dehumidification loads and the smaller diurnal temperature range. In both hot-dry and hot-humid climates, however, the remaining cooling loads can be handled through a variety of low-energy systems.

Table 10.6 summarizes the features of low-energy buildings that depend on the climate where the building is situated. These features largely pertain to building form and envelope, and the applicability of earth pipe, evaporative, or desiccant cooling systems. These and other building features and internal energy loads are discussed in the following subsections.

10.4.3.4 Passive and Passive-low-energy Heating and Cooling

Having reduced the cooling load through the techniques described above – often by a factor of two or more – the next strategy in priority is to use passive and/or passive-low-energy cooling strategies. A purely passive cooling technique requires no mechanical energy input at all. Other techniques involve small inputs of mechanical energy to enhance what are largely passive cooling processes. Some examples of passive and passive-low-energy cooling techniques are described below.

Natural Ventilation

Natural ventilation has a cooling effect whenever the outdoor air temperature is below the indoor air temperature. It reduces the perceived temperature due to the greater ability of moving air to remove heat from a warmer body, and increases the acceptable air temperature due to enhanced psychological adaptation to warmer conditions in naturally-ventilated buildings compared to buildings with mechanical ventilation.

Natural ventilation can be achieved through:

- cross ventilation and wind, a technique that has been widely employed in traditional architecture around the world and in passive ventilation stacks that are commonly used in north European residential buildings;
- solar chimneys, which consist of a tower in which air is heated and rises, drawing cooler outside air through the building. A striking example is the Building Research Establishment offices in Garston, United Kingdom, which is illustrated in Figure 10.A.3.in the GEA Chapter 10 online appendix;
- atria, which can induce natural ventilation through proper placement of air inlets and outlets, along with shading controls or passive measures, such as the geometry of laser-cut glazing, to avoid overheating in summer;
- cool towers, in which water is pumped into a honeycomb medium at the top of a tower and allowed to evaporate, thereby cooling the air at the top of the tower, which then falls through the tower and into an adjoining building under its own weight. These have been used in the Visitor Center at Zion National Park, United States (Torcellini et al., 2002), and at the Torrent Pharmaceutical Research Centre in Ahmedabad, India (Ford et al., 1998); and
- airflow windows, which are designed to facilitate the passage of outgoing exhaust air or incoming fresh air between the glazing in a double glazed window. In the Tokyo Electric Power Company

(TEPCO) research and development (R&D) center, constructed in Tokyo in 1994, this technique reduced the inward heat transfer by one-third to two-thirds compared to double glazed windows with interior or built-in blinds, and eliminated the need for perimeter air conditioning (Yonehara, 1998).

Nighttime Passive and Mechanical Ventilation

Where the day-night temperature variation is at least 5–7 degrees, cool night air can be mechanically forced through hollow core ceilings or through the occupied space to cool the building prior to its use the next day. Where artificial air conditioning is still needed by day, external air can be pre-cooled by passing it through the ceiling that has been ventilated at night. Effective night ventilation requires a high exposed thermal mass, an airtight envelope, minimal internal heat gains, and a building configuration that induces natural airflows so that minimal fan energy is required. In such buildings in the southern United Kingdom, as well as in Kenya, cooling energy savings of 30–40% can be achieved this way, as simulations for both places have shown (Kolokotroni, 2001). External insulation should be used in order to inhibit the inward penetration of daytime outside heat while leaving the thermal mass exposed to the cooling effect of nighttime ventilation and free to absorb internal heat during the day.

For Beijing, da Graça et al. (2002) found that thermally- and wind-driven nighttime ventilation eliminates the need for air conditioning of a six-unit apartment building during most of the summer, when an extreme outdoor peak of 38°C produces a 31°C indoor peak. Simulations by Springer et al. (2000) indicate that nighttime ventilation is sufficient to prevent peak indoor temperatures from exceeding 26°C over 43% of California's geography in houses that include improved wall and ceiling insulation, high performance windows, extended window overhangs, tight construction, and modestly greater thermal mass compared to standard practice in California.

Where mechanical air conditioning is used in combination with night ventilation, the energy savings from night ventilation depend strongly on the daytime temperature setpoint. For a three-story office building in La Rochelle, France, Blondeau et al. (1997) found through computer simulation that night ventilation with a 26°C setpoint requires only 9% of the cooling energy as the case with a 22°C setpoint and no night ventilation for this particular building and climate.

The combination of external insulation, thermal mass, and night ventilation is particularly effective in hot-dry climates, as there is a large diurnal temperature variation in such climates, and placing the insulation on the outside exposes the thermal mass to cool night air while minimizing the inward penetration of heat into the thermal mass. As previously noted, low thermal mass and an open design with plenty of cross ventilation are normally recommended in hot humid climates, although Tenorio (2007) finds that in humid tropical areas of Brazil, thermal mass combined with night ventilation and selective use of air conditioning can reduce cooling energy use in a two-story house by up to 80% compared to a fully air conditioned house.

Evaporative Cooling

Evaporation can cool water down to the wet bulb temperature (T_{wb}).[17] The difference between T_{wb} and the ambient temperature is greater the lower the absolute humidity, so the potential cooling effect of evaporative cooling is greater in arid regions, although the availability of water could be limiting. Evaporative cooling can provide comfortable conditions most of the time in most parts of the world (see Harvey, 2006). A number of residential evaporative coolers are on the market in the United States. Energy is required to operate the fans, which draw outside air through the evaporative cooler and directly into the space to be cooled, or into ductwork that distributes the cooled air. Simulations for a house in a variety of California climate zones indicate savings in annual cooling energy use of 92–95%, while savings are somewhat less (89–91%) for a modular school classroom (DEG, 2004). Evaporative cooling has been widely used in western China (such as XinJiang and Gansu Provinces) and some regions in India. It can provide very good cooling for office buildings, hotels, and shopping malls with outdoor temperatures as high as 38°C. As the energy savings would be much less in humid climates, a better approach is to enhance the evaporative cooling capacity using desiccants, as described later.

Underground Earth Pipe Cooling

Outside air can be drawn through a buried coil, cooled by the ground, and used for ventilation purposes. Simulations by Lee and Strand (2008) indicate that earth pipes can meet 70% of the June-August cooling load in Illinois and 65% in Spokane, Washington. The performance of such a system can be characterized by the ratio of the rate of heat removal by the air exchange to the power used by the fans – analogous to the coefficient of performance (COP) of a heat pump or air conditioner. The measured COP of a ground loop for a building in Germany is 35–50 (Eicker et al., 2006). Argiriou et al. (2004) built and tested an earth pipe that was coupled to a photovoltaic array on a building in Greece that directly powers a 370W DC motor, thereby avoiding the need for DC to AC conversion normally associated with PV power. The fan speed increases as the incident solar radiation increases, matching the need for increased cooling. The measured average COP (based on DC power output) was about 12. In climates with warmer mean annual temperatures, the ground temperature will be warmer, so the benefits of earth pipe cooling will be smaller.

Water can also be circulated through underground pipes and pre-cooled or pre-heated. This is ideal in conjunction with radiant floor heating or radiant ceiling cooling, and has been used in Europe, usually with a heat pump to enhance the heat extraction from or transfer to the ground.

17 Wet bulb temperature is a type of temperature that reflects the physical properties of a system with a mixture of a gas and a vapor, usually air and water vapor. It is the lowest temperature that can be reached by the evaporation of water only (Hart & Cooley Inc. 2009)

Desiccant Cooling and Dehumidification

Solid or liquid desiccants[18] can be used to remove moisture from air, with the desiccant subsequently regenerated using solar thermal heat such as can be provided by flat-plate solar thermal collectors. Desiccants combined with conventional heating for regeneration are sometimes used in supermarkets today, where their substantial drying capacity is an advantage over traditional dehumidification techniques. If the air is over-dried, evaporative cooling can be used to bring the air temperature close to the desired final temperature, with only supplemental cooling with mechanical air conditioners. Heat is required to regenerate the desiccant. A great advantage of desiccant cooling systems is that they avoid overcooling the air and then reheating it for dehumidification purposes. However, the COP of a desiccant system is typically only about 1.0, compared to typical values of four to six for electric chillers, so primary energy use may increase or decrease, depending on the efficiency of the electric power plant that supplies the displaced electricity and the extent of overcooling. However, in the hot and humid climate of Hong Kong, solid desiccant systems can reduce overall energy use for cooling and dehumidification by 50% if solar thermal energy is used for regeneration of the desiccant (Niu et al., 2002).

Passive heating techniques

Passive heating refers to the simple absorption of solar radiation inside a building, preferably by elements with a high thermal mass such as stone walls or concrete walls and floors, thereby minimizing overheating during the day and providing the opportunity to slowly release heat at night. Passive heating can occur directly, through absorption of solar radiation within the space to be heated, or indirectly, through thermal mass located between the sun and living space.

10.4.3.5 Heating equipment

Commercial buildings, multi-unit residences, and many single-family residences, especially in Europe, use boilers that produce hot water or, in some exceptional cases, steam, that is circulated, generally through radiators. Efficiencies (ratio of heat supplied to fuel use) range from 75% to 95%, not including distribution losses. Modern residential furnaces, which are used primarily in North America and produce warm air that is circulated through ducts, have efficiencies ranging from 78% to 96%, again not including distribution system losses. Old equipment tends to have an efficiency in the range of 60–70%, so new equipment can provide substantial savings. Space heating and hot water for consumptive use, e.g., showers, can be supplied with heat from small wall-hung boilers with an efficiency in excess of 90%.

Heat pumps are another option for heating. They transfer heat from something that is relatively cold, such as the outdoor air, ground, or outgoing exhaust air, to the warmer ventilation air or hot water heating system. They make very effective use of electricity, as the ratio of heat supplied to electricity used (the COP) is at least three for ground source heat pumps and at least six to seven for exhaust air heat pumps (Halozan and Rieberer, 1997). Heat pumps provide one means of decarbonizing building heating, once the electric grid itself is decarbonized. If a building has a high performance thermal envelope, so that it loses heat very slowly when the heating system is turned off, heat pumps – like air conditioners – can serve as a dispatchable electricity loads that can, to some extent, be turned on and off to match variations in wind or solar generated electricity supply.

State-of-the-art biomass pellet boilers, with efficiencies of 86–94%, are another option for heating with renewable, carbon-neutral energy.

10.4.3.6 Heating, Ventilation, and Air Conditioning (HVAC) Systems

In the crudest HVAC systems, heating or cooling is provided by circulating enough air at a sufficiently warm or cold temperature to maintain the desired room temperature. The volume of air circulated in this case is normally much greater than what is needed for ventilation purposes, in order to remove contaminants and provide fresh air. The energy required to transport a given quantity of heat or coldness by circulating water is 25–100 times less than the energy required by circulating air. Thus, by using chilled or hot water for temperature control and circulating only the volume of air needed for ventilation purposes – that is, separating the ventilation and heating or cooling functions – considerable energy savings are possible. This is a system level change.

With regard to residential buildings in cold climates, distributing heat by circulating warm water rather than warm air can reduce the energy used to distribute heat by a factor of 10 to 15 and eliminates the infiltration of outside air through pressure differences induced by unbalanced airflow in ductwork (Harvey, 2006; see also Chapter 4). In radiant floor systems, the entire floor serves as a radiator by circulating warm water through pipes embedded in the floor. In this way, heat can be delivered at the coolest possible temperature – at 30°C rather than at 70–90°C – which improves the efficiency of furnaces or boilers and especially improves the efficiency of heat pumps. It would also improve the efficiency of district heating and cogeneration systems by allowing a lower temperature of the hot water provided to such systems. Ventilation requirements can then be met with a much smaller airflow that, during heating or cooling seasons when windows are closed, is circulated with fans. Heat exchangers allow 80–95% of the heat in the outgoing exhaust air to be transferred to the incoming fresh air.

In commercial buildings, three features of advanced HVAC systems with significant energy savings potential are (1) chilled ceiling cooling, (2) displacement ventilation, and (3) demand-controlled ventilation. Chilled ceiling (CC) cooling, which was pioneered in Europe in the 1980s, involves circulating water at a temperature of 16–20°C through radiant

18 A desiccant is a substance that induces or sustains a state of dryness (desiccation) in its local vicinity in a moderately well-sealed environment. In this context desiccants are used to dehumidify air in a physical or chemical way rather than through air conditioning.

panels that cover a large fraction of the ceiling area, or through hollow concrete ceiling slabs. Stetiu and Feustel (1999) carried out simulations of buildings with all-air and combined air/CC cooling systems for a variety of climates in the United States, assuming the same rate of intake of outside air for the two cases. They found that radiant cooling reduces energy use by an amount ranging from 6% in Seattle to 42% in Phoenix. The savings are smaller in hot-humid or cool-humid climates than in hot-dry climates because relatively more of the total air conditioning energy is used for dehumidification, which is not affected by the choice of all-air versus air/CC chilling.

In displacement ventilation (DV), fresh air is introduced from many holes in the floor at a temperature of 16–18°C, is heated by heat sources within the room, and continuously rises and displaces the pre-existing air. Compared with conventional ventilation systems, which rely on the turbulent mixing of air from ceiling outlets, the required airflow is reduced because of the greater ventilation effectiveness of a given air flow. DV, like CC cooling, 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). In a system where most of the cooling is done with chilled water, the airflow is reduced to that needed only for fresh air purposes, meaning that it will be completely vented to the outside and replaced with 100% fresh air after one circuit. This is referred to as dedicated outdoor air supply, or DOAS. Because the air in a DV rises from the occupants to the ceiling, and from there directly to the outside, heat picked up at ceiling level does not need to be removed by the chillers. Calculations by Loudermilk (1999) indicate that for an office in Chicago about one-third of the total heat gain – including 50% of the heat gain from electric lighting – can be directly rejected to the outside in this way. An overall savings in combined cooling and ventilation energy use of 30–60% can be achieved through a combination of DV and CC cooling (Bourassa et al., 2002; Howe et al., 2003).

Having decoupled the ventilation and heating or cooling functions of an HVAC system using some hydronic cooling method, preferably CC, one is free to vary the ventilation rate based on actual and changing ventilation requirements, rather than using a fixed ventilation rate or varying it according to some inflexible schedule. This is referred to as demand-controlled ventilation (DCV). Depending on the kind of building and occupancy schedule, DCV can save 20–30% of the combined ventilation, heating, and cooling energy use in commercial buildings (Brandemuehl and Braun, 1999).

Introducing high performance air conditioners is another way to save energy. Cooling and heating individual rooms by using air conditioners is as common in small- and medium-size non-residential buildings as in homes. The coefficient of performance (COP) – the ratio of heat removed to energy used – of package air conditioners for residential use is 4.9 for cooling, and 5.4 for heating. This COP value has significantly improved in Japan by recent technology development (Figure 10.17). In contrast,

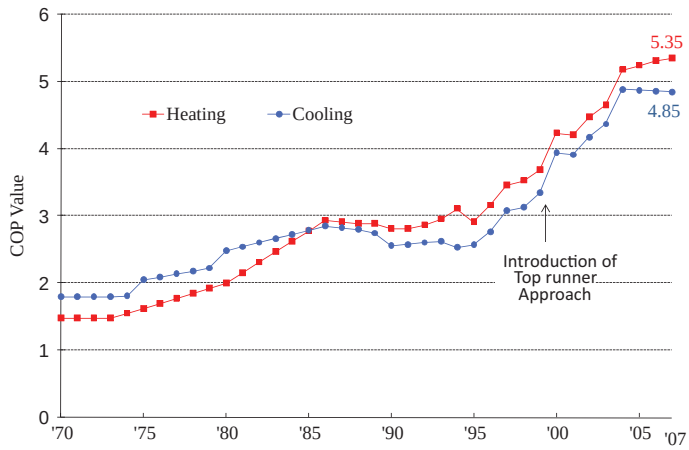

Figure 10.17 | COP values of air conditioners in Japan over time. Source: Jyukankyo Research Institute, 2007.

typical COPs of air conditioners available today in North America and Europe are 2–3.

In very humid climates, the task of air conditioning is to reduce both humidity and temperature. To remove humidity by condensing water vapor, 5–7°C chilled water is needed. However, for temperature control alone, water at 16–18°C is adequate, and this can often be obtained naturally or produced with a chiller at very high COP (up to 10). Liquid desiccants eliminate the need for producing water at 5–7°C because they can cool and dehumidify the air directly to the desired final conditions without overcooling and reheating. As noted earlier, savings of up to 50% are possible if the desiccant is regenerated with solar thermal energy.

10.4.3.7 Domestic Hot Water

The use of non-renewable energy to make hot water can be reduced by: (1) reducing the amount of hot water needed and used; (2) heating water as much as possible with solar energy using hot water panels; and (3) heating water more efficiently. Options for reducing the amount of hot water demand include using low flow showerheads (up to 50% savings), using more efficient washing machines and dishwashers, which require less water as well as less electricity, and washing using cold(er) water.

Where there are simultaneous inflows and outflows of water, as during showers, more than 50% of the heat in hot wastewater can be captured and used to preheat cold incoming water or air (Vasile, 1997).

If hot water is stored in a tank between periods when it is being used – the normal situation in North America – standby heat losses, which can account for one-third of total hot water energy use, will occur. Large losses can also occur from pipes that deliver hot water to where it is needed. These losses can be largely eliminated through

tankless point-of-use water heaters, which are common in Europe and Asia. However, electrical tankless water heaters can amplify peak electrical loads. Solar water heaters can supply 50% or more of hot water requirements in most parts of the world and require a storage tank.

Heat pumps using CO_2 as a working fluid are ideal for hot water applications, as they can more readily reach the required 55–60°C water temperature. Compared to conventional combustion type water heaters, they enable about 30% energy conservation and about 50% reduction in CO_2 emissions given the electricity mix of Japan.[19]

Finally, substantial energy savings are often possible by upgrading existing hot water boilers. Older hot water boilers have efficiencies as low as 60%, compared to 80–85% for a modern non-condensing boiler and 92–95% for a condensing boiler.

10.4.3.8 Lighting

Lighting energy use constitutes 25–50% of the total electricity use in commercial buildings in OECD countries, and about 10% in residential buildings (see Figure 10.9 and Figure 10.A.2). Lighting energy use can be reduced by 75% or more through: (1) better design of lighting systems, including provision for task lighting; (2) maximizing the use of daylight, with light and occupancy sensors to add electric lighting only as needed; and (3) use of the most efficient lighting equipment (IEA, 2006).

Advances in window technology make it possible to increase window area to up to 40–60% of wall area without increasing heat loss in winter, after accounting for solar heat gain, and with minimal impact on cooling loads in summer. Detailed measurements and/or simulations demonstrate annual savings of 30–80% from daylighting of perimeter offices in commercial buildings (Rubinstein et al., 1998; Jennings et al., 2000; Reinhart, 2002; Bodart and De Herde, 2002; Li and Lam, 2003; Atif and Galasiu, 2003). The economic benefit of daylighting is enhanced by the fact that it reduces electricity demand most strongly when the sun is strongest, which is when the daily peak in electricity demand tends to occur during summer. Daylighting can also reduce cooling loads. This is because the luminous efficacy (the ratio of light to heat) of natural light is 25–100% greater than that of electric light systems.

In retrofits of fluorescent lighting systems, 30–50% lighting electricity savings can be routinely achieved. With considerable effort, 70–75% savings in retrofits are possible. In new construction, 75% and larger savings compared to current standards can be readily achieved. These remarkable energy savings could be increased yet further through advances in the efficiency and performance of the individual components of the lighting system (described in Rubinstein and Johnson, 1998).

Light output is measured in lumens (lm), which takes into account differences in the sensitivity of our eyes to different wavelengths of light.[20] The ratio of lumens of light output to watts of energy used by a lamp is called the efficacy. At present,

- compact fluorescent lamps (CFLs) are about four times as efficacious as incandescent lamps, two to three times as efficacious as halogen infrared reflecting (HIR) lamps, and three times as efficacious as halogen lamps – all of which can be replaced in almost all applications;
- the 80-series T8 and T5 fluorescent tubes are about 60% more efficacious than T12 tubes used in old lighting and 25% more efficacious than standard (70-series) T8 tubes; and
- the ceramic metal halide lamp is about twice as efficacious as the HIR lamp, which it can replace.

Light-emitting diodes (LEDs) have the potential to be substantially more efficacious than any of the above. Commercially available LEDs currently have an efficacy of about 30 lm/W, compared to 10–17lm/W for incandescent lamps, 50 lm/W for CFLs, 105lm/W for the T5 fluorescent tubes, and up to 140lm/W for high-pressure sodium lamps. However, laboratory research LEDs have achieved an efficacy of up to 152lm/W at low current (Den Baars, 2008), and it is thought that efficacies of 150–200lm/W will be eventually achieved in commercial products. This would reduce electricity requirements by up to a factor of two compared to the best fluorescent tubes, a factor of four compared to CFLs, and a factor of 20 compared to the least efficacious incandescent lamps, which are still widely used. The effectiveness of LEDs is further improved by the fact that LEDs produce light that can be directed into only the directions where it is needed. By selective lighting, LEDs will be able to achieve energy savings compared to other lamps even before they achieve parity on a lamp-efficacy basis.

10.4.3.9 Commissioning, Control Systems, and Monitoring

Commissioning is the process of systematically checking that all of a building's systems – security, fire, life and safety, HVAC, lighting, electric, etc. – are present and function properly. It also involves adjusting the system and its controls to achieve the best possible performance. Commissioning costs about 1–3% of the HVAC construction cost, but in

19 Calculation based on 43°C quantity of hot water conversion (by Institute for Building Environment and Energy Conservation in Japan); primary energy and CO_2 emission intensity for electricity are based on Japanese Law.

20 Light is a form of energy. However, the efficiency of a lamp in producing light cannot be specified as the ratio of watts of light output to watts of electrical energy input. This is because not all watts of light are equal; our eyes are more sensitive to some wavelengths of radiation than to others.

the United States, only 5% of new buildings are commissioned (Roth et al., 2002). Consequently, the control systems never operate as intended in many buildings. Even if a building is commissioned after construction, it is important to continue adequate monitoring of the HVAC system. In a program involving over 80 buildings mentioned by Piette et al. (2001), improved controls reduced total-building energy cost by over 20% and combined heating and cooling energy costs by over 30%.

10.4.3.10 Appliances, Consumer Electronics, and Office Equipment

Residential appliances and office equipment are important uses of energy in their own right and, for office equipment and electronics in particular, can be an important source of internal heat gain that needs to be removed by the cooling system during summer from perimeter offices and year round from internal offices.

Appliances, consumer electronics, and office equipment in buildings are responsible for a large share of a building's electricity consumption and a share of natural gas use. In the United States they account for 40% of the electricity consumption and 12% of the natural gas use of buildings (US DOE, 2008; see also Chapter 1).

The energy use of most appliances used in buildings can be significantly reduced through increased equipment efficiency. Energy efficiency has increased gradually over time, as manufacturers develop new efficiency design options and incorporate them into their products as an enhancement of quality and performance.

New systems designs will reduce the energy requirements of energy services. For example, daylighting and controls or passive building shell design measures reduce the energy required for thermal comfort. Further significant reductions in energy requirements for energy services can be identified by examining specific technologies (IEA, 2008a; National Research Council, 2009). Some cross-cutting technologies offer significant promise for reducing energy use for devices providing a range of energy services. Examples include: electronics, computing and office equipment, display technologies (e.g., organic LEDs), motors (e.g., brushless DC permanent magnet rotors or variable reluctance motors), domestic refrigeration, and ceiling fans (Garbesi and Descroches, 2010). Sensors and controls for energy using devices deserve special attention, since they have many applications that can eliminate waste by limiting energy use to times and places when occupants are present and in need of the specific energy service.

Electronics and Computing and Office Equipment

Since the product life cycles of electronic products are typically months to years, much shorter than appliances or HVAC equipment, rapid improvements in energy efficiency of these products is possible. Currently, large amounts of energy are consumed while only a small capacity of devices is being utilized. Power management can reduce energy use by turning off unneeded capacity. For example, implementing sleep modes in computers can reduce power consumption by as much as 5W to 65W. Ultimately, energy use can be minimized by proxying, in which a variety of internet connected devices maintain an internet presence while in sleep mode, unlike the current situation where those devices are kept in a higher power mode only in order to remain connected to the internet (Nordman and Christensen, 2010). Servers are designed for maximum demand, and thus are usually underutilized. Virtualization involves software that allows one server to take on the functions of several, while the others reduce power. Virtualization seems applicable to 80% of servers, with potential energy savings of 70%. Computer components are also expected to become more efficient. Laptops are efficient in order to maximize battery life. Replacing desktop computers with laptop technology provides large energy savings. Replacing disk drives with solid state drives could reduce that component's energy use by 70% or more.

Display Technologies (e.g., televisions and monitors)

Energy savings of 50–70% are possible from active power management, such as controlling the brightness of display technologies based on ambient lighting, only operating in the presence of a viewer, and lower brightness for dark colors (color content). In plasma TVs, energy use can be reduced with new phosphors, improved cell design, improved gas mixtures, and optimized electronic circuits. In current TV designs, significant light loss occurs from the backlight to the viewer. Future designs may eliminate backlighting completely, using organic light emitting diodes (OLEDs) that produce light themselves, currently in use in some mobile phones. Prototypes larger than 50 inches (diagonal screen size) have been demonstrated. Alternative technologies under development include efficient electronic circuits, quantum dots, and laser display phosphors.

Motors

Motors come in many sizes and have many residential and commercial applications, making them one of the most ubiquitous components in energy-using equipment. Most motors are single-speed induction. The most efficient on the market are brushless DC permanent magnet motors (BDCPM), which avoid rotor magnetization losses and have lower heat losses, providing a secondary benefit of reduced cooling energy. BDCPM motors require less material and operate at higher efficiency when under low loads than single-speed motors. Major reductions in energy use by motors could be achieved with a BDCPM having interior magnets in the motor, advanced core design, low resistance conductors, and low friction bearings. Further savings would result by including variable speed in the design.

Domestic Refrigeration

From 1974 to 2006, electricity consumption per new top-mount refrigerator-freezers in the United States declined by 70% due to technological improvements and mandatory energy efficiency standards. Changes included using polyurethane foam instead of fiberglass for insulation, improved compressors, improved heat exchangers, and better controls. Notably, after each major efficiency improvement, new approaches

identified even further opportunities to reduce energy use. Today, the most efficient models available use 30% less energy than the maximum allowed. Research is underway on alternatives to vapor compression, including magnetic and thermo-acoustic refrigeration. The potential energy savings are not yet known.

Ceiling Fans

Fans suspended from the ceiling can provide thermal comfort in summer in some climates without compressor-driven air conditioning. Most fans have a light attached. A typical fan with a shaded pole motor has a power draw of 35W, with incandescent lighting requiring an additional 120W. An Energy Star[21] fan requires 30W, and its fluorescent lights require 30W. The most efficient model has a motor that requires 10W. A conceivable design with a DC motor, airfoil shaped blades and LED lights could draw as little as 5W for the fan, and 10W for the lights.

In large spaces, mostly commercial applications, substituting one large fan for several smaller ones results in higher efficiency. The same volume of air can be moved with larger blades at lower speed, and a more-than-linear decrease in energy use.

10.4.3.11 Energy and Greenhouse Gas Mitigation From Advanced Biomass-Based Cooking Technologies

Improved cookstoves have been disseminated since the 1980s to reduce demand for solid biomass fuels and to reduce health hazards related to cooking with open fire. Much experience was gained from early programs, which were generally not very successful. An exception is China, which put in place 250 million improved cookstoves as part of one of the largest social programs in the world. As a result of this learning process, a whole new generation of advanced biomass-based cookstoves, and dissemination approaches have been developed in the past ten years and the field is now bursting with innovations. An estimated 820 million people in the world are currently using some sort of improved cookstove (WHO, 2009). This new generation of cookstoves shows clear reductions in fuel use, indoor air pollution, and GHG emissions compared to open fires.

Innovations in the biomass cooking field relate to the: (1) technology (cooking devices); (2) dissemination approaches; and (3) monitoring and evaluation of the impacts.

Technology

Advanced biomass stoves (ABSs) for household cooking include: (1) direct combustion stoves; (2) gasifier stoves, (3) biogas, ethanol or other type of processed biomass fuels; and (4) hybrid models, which provide heat for cooking and water heating or other needs.

Direct combustion ABSs are cookstoves that directly burn biomass fuels. They include cookstoves designed to burn fuelwood, agricultural residues, and charcoal. The stoves fall typically into either portable, low-mass stoves (like the Rocket, which Envirofit disseminated in Africa and Asia, and the Darfur stove aimed at refugee camps in Africa) and high-mass chimney stoves (like the Patsari and Onil stoves disseminated in Latin America, and most of the Chinese models). These include improvements in the combustion chamber (such as the Rocket "elbow"), insulation materials, heat transfer ratios, stove geometry, and air flow (Still, 2009). Some models include a fan. As a result, combustion efficiency is greatly improved compared to open fires. The cost ranges between US$10 or less for the simpler models, to more than US$100 for the more sophisticated models. Fuel savings reach from 30% to 60%, measured in field conditions (Berrueta et al., 2008). Indoor air pollution levels are reduced up to 80–90% compared to the open fires in models with chimneys (Masera et al., 2007; Smith et al., 2007). Carbon mitigation has been estimated to range from 1–2 tCO_2-eq/yr for the simpler models, and have been measured in the field to range between 3–9 tCO_2eeq/yr for more sophisticated models such as the Patsari model in Mexico (Johnson et al., 2008).

Gasifier stoves have gone through a major development in the last five years. Stoves using wood-chips as fuel, with or without an electric blower, are commercially available in China and India (Bhattacharya and Leon, 2004). These stoves deliver 1–3kW of power with an efficiency of 35–40%. Major corporate enterprises have been involved in research and testing gasifier stoves – such as Shell and British Petroleum – and Philips is disseminating a model in India (Hegarty, 2006). Available data from lab testing indicates the potential for significant decreases in emissions of GHGs and health damaging pollutants. Programs are initially targeting urban areas, as the capital cost is still high and the stoves need pre-prepared fuel such as chips or pellets. A major challenge for their widespread dissemination so far is the need for standardizing currently used biomass into chips or pellets.

Biogas cookstoves, and stoves using other forms of processed biomass, provide clean combustion, and using animal dung as a feedstock have been disseminated worldwide, particularly in China, India, and Nepal on a large scale (Dutta et al., 1997). These cookstoves have the distinct co-benefits of enhancing the fertilizer value of the dung and serving to reduce the pathogen risks of human waste. Economic barriers include a high initial cost, which can run up to US$300 for some systems, including the digestion chamber unit. However, new designs of biogas digesters reduce the digestion time, increase the specific methane yield, and make use of alternate or multiple feedstocks, such as leafy material and food wastes. This substantially reduces the size and cost of the digestion unit (Lehtomäki et al., 2007).

Ethanol stoves have also been developed and tested in India, Nigeria, and other African countries (Rajvanshi et al., 2007). The Indian stove uses low-concentration ethanol (50%) and the Nigerian stove uses an ethanol-gel to minimize risks of explosion.

21 Energy Star means that products meet strict energy efficiency guidelines set by US Environmental Agency. Energy Star qualified ceiling fan/light combination units are over 50% more efficient than conventional units and use improved motor and blade designs (US EPA 2011).

Figure 10.18 | A stove with a thermoelectric unit includes a 2–4W power unit, which helps generate 100 lumens with a LED-based lantern. Source: BioLite, 2011.

Hybrid, or multiple-service, stoves serve multiple energy end-uses. There is currently a rapid development of these cookstoves. Commercially, stoves that provide both cooking and water heating are well established in Brazil (e.g., Ecofogao) and China (many models). A new exciting innovation is the development of thermo-electric modules, which will allow the stove's blower to generate electricity for lighting, either through CFLs or LED lanterns. Pilot units have been tested in Nepal. A modified Rocket model (Figure 10.18) shows significant improvements in stove performance as a result of the blower and is expected to sell for US$30 (BioLite, 2009).

Table 10.7 shows cooking costs for different types of stoves used in India. It can be seen that all the stoves are cheaper than LPG on an annualized cost basis. Some have high capital costs and thus need financial mechanisms or subsidies to foster dissemination.

Impact of Current Dissemination Programs

A second major innovation in the field of ABSs has to do with the production and marketing of the stoves. State-of-the-art manufacturing facilities are now in place that aim for disseminating stoves on a mass scale while at the same time assuring a quality product. Improved stoves, designed to appeal to consumers in various market segments and to be suitable for microfinance mechanisms, have been developed. As a result, several companies now produce over 100,000 stoves/yr. More than 70 stove programs are currently in place worldwide, with recently launched large-scale national programs in India and Mexico, as well as large donor-based programs in Africa.

The market for ABSs has also benefited from the recognition that using multiple fuels, rather than complete fuel switching to LPG or electricity, is the norm in many developing countries (Masera et al., 2000). Therefore, even households that already have access to LPG and kerosene continue using woodfuels, and many times an early-adopter market for ABS devices provide substantial benefits for the adopting families (Masera et al., 2000).

Overall, ABSs can provide substantial benefits in terms of energy, health, and climate change mitigation. Approximately 2.4 billion people, representing 600 million households, cook with solid biofuels worldwide. Assuming fuel savings from 30–60%, and energy use of 40 GJ/household/yr for cooking with open fires, the technical energy mitigation potential ranges from 7 to 14 EJ/yr. Also, using a unit GHG mitigation of one to four tCO_2-eq/stove/yr compared to traditional open fires, the global mitigation potential of ABSs reaches between 0.6–2.4 $GtCO_2$-eq/yr, without including the effect of the potential reduction in black carbon emissions. Actual figures will depend on renewability of the biomass used for fuel, the characteristics of the fuel and stove, and the actual adoption and sustained used of the ABS.

Future Needs

Critical needs for ABSs include increased R&D, particularly for new insulating materials, as well as robust designs that endure several years of rough use. More field testing and stove customizing for user needs is required. There is also the need for strict product specifications and testing and certification programs. Finally, it is important to better understand the patterns of stove adoption given multiple devices and fuels, as well as mechanisms to foster long-term use.

10.4.4 Incorporation of Active Solar Energy into Buildings

10.4.4.1 Key messages

Potential active solar energy systems include PV panels for generation of electricity, solar thermal collectors for production of domestic hot water, the production of hot water or heating of air for space heating, the production of hot water to operate desiccant or other thermally-driven cooling systems, and the active collection and concentration of sunlight for daylighting. PV panels on all suitable rooftops and façades of existing buildings in a range of developed countries could supply 15–60% of current total electricity demand in these countries.

10.4.4.2 Active solar technologies

The design of low energy buildings incorporates passive solar energy in many forms – passive solar heating, passive ventilation and cooling, and daylighting – and is part of the package that can achieve 75% or greater savings in overall space conditioning energy use compared to conventional local practice. This level of energy use is so low that much or all of the remaining energy demand, or even more, can be met through active solar energy features such as photovoltaic panels on roofs and façades and solar thermal collectors. Thermal energy from solar collectors can be used for space heating, domestic hot water, or solar air conditioning, the

Table 10.7 | A comparison of annualized cost of cooking energy per household.

	Capital cost (US$)	Fuel Price (US$/kg)	Annualized cost for cooking (US$/ household)
Traditional stoves	1.25	0.025	30
Improved combustion stoves	25	0.025	23
Gasifier stoves	40–75	0.075	40–64
Biogas (Family unit)	300	0.0	47
LPG (subsidised)	64	0.49	65
LPG (non-subsidised)	64	0.8	100

Source: Venkataraman and Maithel, 2007.

latter either driving absorption chillers or desiccant-based dehumidification and cooling systems.

Active solar energy systems, while sometimes driving the use of off-site energy by the building to zero and even making the building a net exporter of energy, tend to be expensive at present. This is in contrast to the system level measures discussed above, which can deliver the first 75% or even more of the transition to zero-energy buildings at very low cost or even with a net savings in investment cost (as discussed below).

The potential energy generation from building integrated photovoltaics (BiPV) is large. Gutschner et al. (2001) estimated the potential power production from BiPV in member countries of the International Energy Agency, taking into account architectural suitability (based on limitations due to construction, historical considerations, shading effects, and the use of the available surfaces for other purposes) and solar suitability (restricting the useable roof and façade area to those elements where the solar irradiance is at least 80% of that on the best elements in a given location, defined separately for roof and façade elements). They estimate that 15% to almost 60% of current total national electricity demand could be provided using all available roof and façade surfaces, depending on the country. Thus, systematic incorporation of BiPV into new buildings, and into old buildings when they are renovated and whenever this is feasible, can make an important contribution to electricity supply.

PV modules typically cost between below US$2 and 5 per peak watt of output (US$2–5/$W_p$, see Chapter 11.7), with total system costs including installation typically running from US$4/$W_p$ to US$9/$W_p$ (IEA, 2008c). However, a number of studies have identified ways in which the cost of modules might eventually reach US$1/$W_p$ (Hegedus, 2006; Swanson, 2006) or even US$0.2–0.3/$W_p$ (Zweibel, 2005; Green, 2006). Keshner and Arya (2004) have presented perhaps the most aggressive scenario for future cost reductions, with an installed cost of US$1/$W_p$ or less for various thin film modules. At 5% financing over 20 years, a US$1/$W_p$ installed cost translates into an electricity cost of about US¢4/kWh for 12% efficient modules in sunny locations (2000 kWh/m^2/yr irradiance) and US¢6.7/kWh for 7% efficient modules.

BiPV provides a number of benefits beyond the mere provision of electricity. This should be taken into account in deciding whether or not to incorporate PV into a building (Eiffert,2003). These benefits include the role of BiPV as a façade element, replacing conventional materials and providing protection from UV radiation; providing thermal benefits such as shading or heating; augmenting power quality by serving a dedicated load; serving as backup to an isolated load that would automatically separate from the utility grid in the event of a line outage or disturbance; and reducing power transmission bottlenecks and the need for peaking power plants. The grid and load saving benefits to the power utility are worth about US$100–200/yr/kW of peak power produced. Inasmuch as BiPV is used as part of an aesthetic design element in a building, it can replace rather expensive building materials. The cost of PV modules ranges from US$400–1300/m^2. By comparison, the costs of envelope materials in the United States that PV modules can replace range from US$250–350/m^2 for stainless steel, US$500–750/m^2 for glass wall systems, to at least US$750/m^2 for rough stone and US$2000–2500/m^2 for polished stone (AEC, 2002).

10.4.4.2 Net-zero-energy buildings

The 'net-zero-energy building' is taken here to mean a building that generates onsite and exports to the grid an amount of electricity sufficient to offset the amount of electricity drawn from the grid at other times plus other energy (such as fuels for heating) that is supplied to the building. Requiring buildings to be zero-net-energy is not likely to be the lowest cost or most sustainable approach in eliminating fossil fuel use, and is sometimes impossible. Net-zero-energy buildings are feasible only in certain locations and for certain building types and uses.

Highly energy-efficient residential and commercial buildings have a total energy intensity of 50–100 kWh per m^2 of floor area/yr (compared to a typical value of 200–400 kWh/m^2/yr today), which corresponds to an annual average energy flow of 5.7–11.4 W/m^2. Annual average solar irradiance ranges from 160 W/m^2 (middle latitudes) to 250 W/m^2 (in the sunniest regions). If 80% of the roof area is covered with PV modules and converted to electricity with a net sunlight-to-AC electricity conversion efficiency of 10%, and 20% of the roof area collects solar energy that is converted to useful heat (which can be used for space heating, production of domestic hot water, and desiccant cooling and dehumidification) with an efficiency of 50%, the overall capture of solar energy

per unit of roof area is in the order of 30–45 W/m^2. Although additional electricity could be generated from some PV panels on the equator-, east-, or west-facing façades if shading is not an issue, total building energy demand will greatly exceed the solar energy supply in buildings that are more than a few stories high, even if the buildings are highly energy efficient. It is typically single-family or low-rise, lower-density multifamily residential neighborhoods that can become zero net energy users for their energy needs, excluding transportation. Therefore, care needs to be exercised that ill-conceived, uniform, zero-energy housing mandates do not incentivize further urban sprawl that leads to further automobile dependence and growth in transport energy use.

As discussed in Chapter 11, many forms of off-site renewable energy are less expensive than on-site PV generation of electricity, and are thus able to achieve more mitigation and sustainable energy supply from the same limited resources. Although PV electricity is currently expensive, as noted above, there are good prospects for a factor of two reduction in the installed cost of PV systems in buildings. Furthermore, PV must compete against the retail rather than the wholesale cost of electricity produced off-site. On-site production of electricity also improves overall system reliability by relieving transmission bottlenecks within urban demand centers.

In aiming for zero fossil fuel energy use as quickly as possible, an economical energy strategy would implement some combination of: (1) reduced demand for energy; (2) use of available waste heat from industrial, commercial, or decentralized electricity production; (3) on-site production of energy; and 4) off-site supply of C-free energy, taking into account all the costs and benefits and the reliability of various options.

10.4.5 Worldwide Examples of Exemplary High-Efficiency and Zero-energy Buildings[22]

10.4.5.1 Key Messages

Numerous examples exist worldwide of residential and commercial buildings that have annual energy use that is up to two to four times less than that of recently-built conventional buildings in the same jurisdictions. The most dramatic energy savings are seen in heating energy use, where many buildings have been built with heating requirements that are four times less than that for recent conventional new buildings and up to ten times less than that of the existing stock average.

10.4.5.2 Advanced Residential Buildings

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

Several thousand houses that meet the Passive House Standard – a house with an annual heating requirement of no more than 15kWh/m^2/yr, irrespective of the climate – have been built in Europe (Passivehaus Institut, 2009). By comparison, the average heating load of new residential buildings is about 60–100kWh/m^2/yr in Switzerland and Germany, but about 220kWh/m^2/yr for the average of existing buildings in Germany and 250–400kWh/m^2/yr in central and eastern Europe (Enerdata, 2009). Thus, Passive Houses represent a reduction in heating energy use by a factor of four to five compared to new buildings, and by a factor of 10–25 compared to the average of existing buildings. Technical details, measured performance, design issues, and occupant response to Passive Houses in various countries can be found in Krapmeier and Drössler (2001), Feist et al. (2005), Schnieders and Hermelink (2006), and Hastings and Wall (2007a, 2007b), with full technical reports at www.cepheus.de.

Holton and Rittelmann (2002), Gamble et al. (2004), and Rudd et al. (2004) have shown how a series of modest insulation and window improvements can lead to energy savings of 30–75% in a wide variety of climates in the United States. In all three studies, alterations in building form to facilitate passive solar heating, use of thermal mass combined with night ventilation to meet cooling requirements, where applicable, or use of features such as earth pipe cooling, evaporative coolers, or exhaust air heat pumps are not considered. Thus, the full potential is considerably greater. Demirbilek et al. (2000) found, through computer simulation, that a variety of simple and modest measures can reduce heating energy requirements by 60% compared to conventional designs for two-story single-family houses in Ankara, Turkey.

For single-family houses in the hot and relatively humid climate of Florida, Parker et al. (1998) show how a handful of very simple measures – attic radiant barriers, wider and shorter return air ducts, use of the most efficient air conditioners with variable speed drives, use of solar hot water heaters, efficient refrigerators, lighting, and pool pumps – can reduce total energy use by 40–45% compared to conventional practices. These savings are achieved while still retaining black asphalt shingle roofs that produce roof surface temperatures of up to 82°C. Further significant reductions in cooling energy requirements can be achieved through increasing the albedo surface of roofs (Akbari et al., 2008).

10.4.5.3 Commercial Buildings

Many commercial buildings in North America, Europe, and Asia have achieved a reduction of 50% or greater in overall energy use compared to current local conventional practice. A recent survey of such buildings can be found in Harvey (2009). The National Renewable Energy Laboratory (NREL) in the United States extracted key energy-related parameters from a sample of 5375 buildings in a 1999 commercial

22 Sections 10.4.5–10.4.7 is a highly condensed discussion drawn from Harvey (2006, 2009, 2010).

buildings energy use survey. They then used energy models to simulate the buildings' energy performance (Torcellini and Crawley, 2006). The results of this exercise were as follows:

- Average total energy use as built (including thermal and electric loads) is 266 kWh/m^2/yr;
- Average energy use if complying with the ASHRAE 90.1–2004 standard is 157kWh/m^2/yr, a savings of 41%; and
- The potential average energy use in new buildings is 92kWh/m^2/yr with improved electrical lighting, daylight, overhangs for shading, and elongation of the buildings along an east-west axis, a savings of 65%.

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

In the United Kingdom, the energy use guidelines indicate that energy use for office buildings is about 300–330kWh/m^2/yr for standard mechanically-ventilated buildings, 173–186kWh/m^2/yr with good practice (a savings of about 40–45%), and 127–145kWh/m^2/yr for naturally-ventilated buildings with good practice (a savings of 55–60%) (Walker et al., 2007).

Voss et al. (2007) presented data on the measured energy use in 21 passively cooled commercial and educational buildings in Germany. The passive cooling techniques involve earth-to-air heat exchangers (nine cases), slab cooling directly connected to the ground via pipes in boreholes or connected to the groundwater (nine cases), and some form of night ventilation (16 cases), along with a limited window-to-wall ratio (0.27–0.43) and external sun shading. The buildings also have a high degree of insulation and many have triple glazed windows. Nine of the buildings have total onsite energy use of 25–55kWh/m^2/yr and 10 had 55–110kWh/m^2/yr energy use, compared to 175kWh/m^2/yr for conventional designs, so the rate of savings is up to a factor of seven. Three buildings have a heating energy use less than 20kWh/m^2/yr and eight have a heating energy use of 20–40kWh/m^2/yr, compared to a typical heating energy use of 125 kWh/m^2/yr.

In north China, represented by Beijing, typical energy demand of high standard office buildings is 60–80kWh/m^2/yr for heating and 30–100 kWh/m^2/yr electricity for air conditioning, lighting, and plug loads. In south China, represented by Shenzhen, energy demand is 60–120kWh/m^2/yr (all electricity) for all energy uses including office equipment. Design studies have also shown the feasibility of obtaining 50% savings through the use of relatively simple features in office buildings in Beijing (Zhen et al., 2005) and Malaysia (Roy et al., 2005). The measures in both cases involve insulation, shading, advanced windows, energy efficient lighting, and, in the Beijing case, natural ventilation. But measures such as displacement ventilation, chilled ceiling cooling, and desiccants were not considered, so the potential savings are even larger.

The Energy Base building in Vienna, illustrated in Figure 10.19, is another example of energy use in good practice. The glazing on the south façade is slightly overhanging to increase the proportion of diffuse to direct sunlight entering the room, while the incorporation of PV panels and reflective blinds enhances daylighting. In winter, the building combines solar preheating of ventilation air with heat recovery in a novel way, as illustrated in Figure 10.20. Ventilation air flows laterally from the north side to the south side of the building, then is overheated – to above the desired indoor temperature – by the space next to the glazing, which

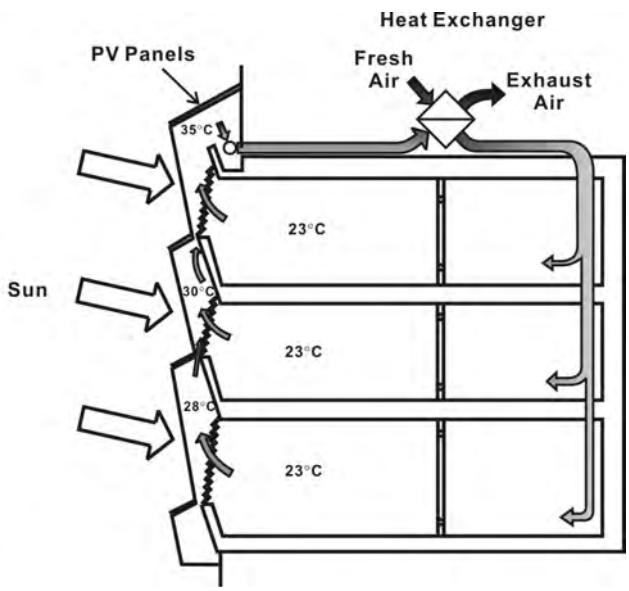

Figure 10.19 | Photograph of the energy base building in Vienna (left) and schematic diagram of the ventilation, solar-preheating, and heat recovery system (right). Source: Danny Harvey (photo); Ursula Schneider, Pos Architekton, Vienna.

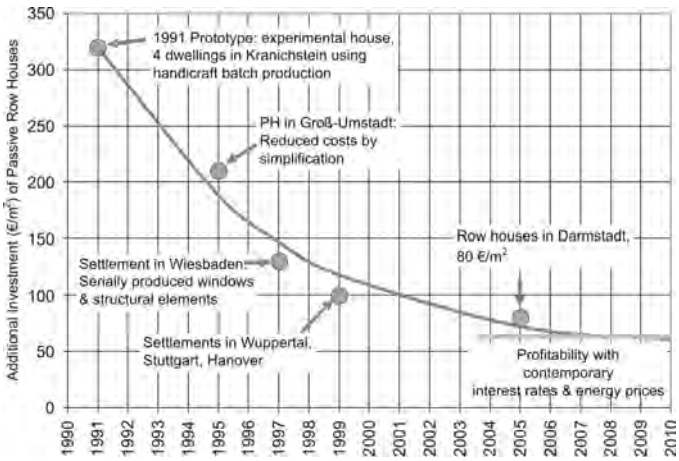

Figure 10.20 | Learning curve showing the progressive decrease in the incremental cost of meeting the passive house standard for the central unit of row houses. Source: Harvey, 2009.

functions as a solarium. This overheated air passes through a heat exchanger, where it is particularly effective in warming the incoming fresh air. At night, the system still has the benefit of heat recovery, unlike other systems for solar preheating of ventilation air. Additional heat is supplied by a ground source heat pump, which cools the ground sufficiently that the ground can be used for passive cooling (i.e., without operating a heat pump) of ventilation air during the summer. Solar regenerated desiccants are used for dehumidification during the summer.

10.4.6 Cost of New High Performance and Zero-energy Buildings

10.4.6.1 Key Messages

The additional cost of residential buildings in Central Europe that meet the Passive House standard has been steadily falling over the past two decades, and is now to the point where the additional costs are insignificant as compared to standard practice in Europe: in the range of 5–8% of the standard construction costs. In the case of high-performance commercial buildings in Europe, North America, and perhaps elsewhere, there is sometimes no additional cost or even cost savings compared to conventional buildings, because the extra cost of the high-performance envelope is offset by reduced costs for mechanical and electrical systems.

10.4.6.2 Residential Buildings

Figure 10.20 shows that in central Europe there is a progressive decline in the cost of the additional investment required to meet the Passive House standard, which uses four to eight times less heating energy than conventional new housing. Through learning, costs have fallen to the point where the incremental cost can be justified based on 2005 energy prices and interest rates. Schnieders and Hermelink (2006) report that the additional cost averaged over 13 Passive House projects in Germany, Sweden, Austria, and Switzerland is 8% of the cost of a standard house. When amortized over 25 years at 4% interest and divided by the saved energy, the cost of saved energy averages 6.2 €cent/kWh (app. 7.9 cent(US_{2005}\$)/kWh; the range is 1.1–11 €cent/kWh – 1.4–14.1 cent(US_{2005}\$)//kWh). This is somewhat more than the present cost of natural gas to residential consumers in most European countries, which ranges from 2–8 €cent/kWh (app. 2.7–11.1 cent(US_{2005}\$)/kWh) (IEA, 2004). Audenaert et al. (2008) estimate extra costs of 4% for low-energy houses and 16% for Passive Houses in Belgium, having energy savings of 35% and 72%, respectively, relative to current standard houses in Belgium.

10.4.6.3 Commercial buildings

In the case of commercial buildings, the first (initial) cost of highly efficient buildings is sometimes less than the first cost of conventional buildings. This is due to the downsizing of mechanical systems that is possible in energy efficient buildings. As an example of the cost savings with advanced, energy efficient designs (Table 10.8) gives a breakdown of capital costs for commercial buildings in Vancouver, Canada, having conventional windows (double glazed, air filled, low-e with U=2.7 W/m^2/K and SHGC=0.48) and a conventional heating/cooling system, and for buildings with moderately high-performance windows (triple glazed, low-e, argon filled with U=1.4 W/m^2/K and SHGC=0.24) and radiant slab heating and cooling. The high performance building is 9% less expensive to build than a comparable conventional building, while using about half the energy.

Larger energy savings can cost less than smaller energy savings, as indicated by a survey of the incremental cost and energy savings for 32 buildings in the United States by Kats et al. (2003). These buildings meet various levels of the Leadership in Energy and Environmental Design (LEED) standard. Summary results are given in Table 10.9. The energy savings are broken into reductions in gross energy demand and reductions in net energy demand including on-site generation – by, for example, PV modules – which tends to be expensive. The cost premium is the total cost premium required to meet the various LEED standards and so includes the cost of non-energy features as well. Nevertheless, average incremental costs are less than 2% of the cost of the reference building and are smaller on average for buildings with 50% savings in net energy use than for buildings with 30% savings.

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

The final example presented of the beneficial economics of energy efficient buildings is one of the first buildings to be built on the new Oregon

Table 10.8 | Comparison of component costs for a building with a conventional VAV mechanical system and conventional (double-glazed, low-e) windows with those for a building with radiant slab heating and cooling and high-performance (triple-glazed, low-e, argon-filled) windows, assuming a 50% glazing area/wall area ratio.Prices given in 2001 Canadian dollars.

Building Component	Conventional Building	High-performance Building
Glazing	$140/m^2	$190/m^2
Mechanical System	$220/m^2	$140/m^2
Electrical System	$160/m^2	$150/m^2
Tenant Finishings	$100/m^2	$70/m^2
Floor-to-floor Height	4.0 m	3.5 m
Total	**$620/m^2**	**$550/m^2**
Energy Use	180 kWh/m^2/yr	100 kWh/m^2/yr

Source: McDonell, 2003; 2004.

Table 10.9 | Energy savings relative to ASHRAE 90.1–1999 and cost premium for buildings meeting various levels of the LEED standard in the USA.

LEED Level	Sample Size	% Energy Savings, Based on		Cost Premium
		Gross Energy Use	Net Energy Use	
Certified	8	18	28	0.66 %
Silver	18	30	30	2.11 %
Gold	6	37	48	1.82 %

Source: Kats et al., 2003.

Health and Science University, River Campus, and completed in 2006. This 16-story building is expected to achieve an energy savings of 60%, with a reduction in total construction costs of US$3.5 million out of an original budget of US$145.4 million and an operating cost savings of US$600,000/yr (Interface Engineering, 2005).

10.4.7 Renovations and Retrofits of Existing Buildings

10.4.7.1 Key messages

Comprehensive retrofits of existing residential buildings can usually reduce energy requirements, excluding plug loads, by a factor of at least two, with savings in heating energy requirements, which is the dominant energy use in cold climates, by up to a factor of ten. There are many examples of residential buildings, especially multi-unit residential buildings, which have been retrofitted to meet the Passive House standard. Fifty to 70% or more savings in non-plug energy use have been achieved through retrofits of commercial buildings throughout the world.

10.4.7.2 Residential Buildings

Energy use of residential buildings can be reduced through, among other things, upgrading windows, adding internal insulation to walls during renovations, adding external insulation to walls, adding insulation to roofs at the time that roofs need to be replaced, and through taking measures to reduce uncontrolled exchange of inside and outside air and introducing controlled ventilation with heat recovery. Some examples of modest retrofit measures and the corresponding energy savings are:

- the sealing of ductwork alone in houses in the United States saves an average of 15–20% of annual heating and air conditioning energy use (Francisco et al., 1998);
- retrofits of 4003 homes in Louisiana, including the switch from natural gas to a ground source heat pump for space and water heating, eliminated natural gas use and still decreased electricity use by one-third (Hughes and Shonder, 1998);
- an upgrade of multi-unit housing in Germany using, among other measures, External Insulation and Finishing Systems (EIFSs) achieved a factor of eight reduction in heating energy use;
- an envelope upgrade of an apartment block in Switzerland reduced the heating requirement by almost a factor of three (Humm, 2000);
- retrofits of houses in the York region of the United Kingdom reduced heating energy use by 35% through air sealing and modest insulation upgrades, while a 70% savings was projected with more extensive measures (Bell and Lowe, 2000); and
- a comprehensive retrofit of an old apartment block in Zurich, including the replacement of the roof, achieved an 88% savings in heating energy use measured over a two-year period (Viridén et al., 2003).

There are many examples where old buildings that have been retrofitted to very high energy performance standards. Table 10.10 includes cases where 90% or more savings in heating energy use have been achieved. A striking example is the retrofit of a ten-story panel

Box 10.2 | The Solanova Project

The SOLANOVA (Solar-supported, integrated eco-efficient renovation of large residential buildings and heat-supply-systems) project of the European Commission began in January 2003 (see www.solanova.eu). The project goal was to provide best-practice examples of the renovation of large residential buildings in Eastern Europe which, at present, are being renovated with only minimal improvements in energy intensity. In 2005, one seven-story panel building in the Hungarian town of Dunaújváros was renovated as part of this project. Heating energy demand decreased from 220 kWh/m^2/yr before the retrofit to a measured demand of 30 kWh/m^2/yr over a two-year period (a reduction of 86%). Overheating in the summer was one of the worst characteristics of the original building, so triple-glazed windows with an internal Venetian blind were installed on the south- and west-facing walls, resulting in a dramatic reduction in solar heat gain through the windows. Mechanical ventilation was provided to each individual flat with a real heat recovery of 82%. The investment cost was 240 €/m^2 + VAT. The time to pay back the initial investment, based on energy-cost savings only and at current energy prices, is 17 years. However, an unattractive and uncomfortable building was turned into an attractive and comfortable building at the same time. In Eastern Europe, about 100 million people live in large panel buildings, but results demonstrated in Dunaújváros can be transferred to the large stock of Western European panel buildings as well.

Table 10.10 | Documented examples of deep savings in heating energy use through renovations of buildings.

Building and Location	Year Built	Year Renovated	Energy intensity (kWh/m^2/yr)		
			Before	*After*	*Metric*
Apartment buildings in Ludwigshafen, Germany	1950s	2001	250	30 (m)	System
Villa in Purkersdorf, Vienna, Austria	Late 19th century	2008	---	20 (m)	System
2 apartment buildings on Tevesstrasse, Frankfurt	1950s	2005	290	17 (c) 13.6 (m)[a]	Load
18-unit apartment block, Brogärden, Sweden	1970	2009	115	30 (c)	System
24-unit apartment block, Zirndorf, Germany	1974	2009	116	35 (c)	Load
Apartment block, Ludwigshafen, Germany	1965	2006	141	18 (m)	Load
50-unit apartment,Linz, Austria	1958	2006	179	13.3 (c)	Load
Apartment block on Magnusstrasse in Zurich	~1900	~2000	165	19 (m)	System
Single-family house, Pettenbach, Austria		2005	280	14.6 (c)	Load
10-story apartment block,Dunaújváros, Hungary		2005	220	20–40	System

[a] Adjusted to an indoor temperature of 20°

building in the Hungarian town of Dunaújváros, of which hundreds of thousands of this similar type building exist in Eastern Europe and the former Soviet Union (see Box 10.2). Various studies indicate that the energy demand in old buildings in western Europe (EU-15) can be reduced by more than 50% with no additional cost over a thirty-year lifetime, and by up to 85% in new countries of the EU-27 (Petersdorff et al., 2005a, 2005b). Today's advanced solutions do not even need to compromise aesthetics: for instance, several historic and heritage buildings have also been already retrofitted to passive house standards.

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

A number of single-family and multi-unit residential buildings have been upgraded to the Passive Standard in Europe. In the case of an old detached house (Haus der Zukunft, 2006) the renovation reduced the heating energy use from 280kWh/m^2/yr to 14.6 kWh/m^2/yr at 16% greater cost than a conventional renovation, but the impact of the extra cost on mortgage payments is less than the energy cost savings. In the case of a 50-unit residential building (Haus der Zukunft, 2007), heating energy use was reduced from 179kWh/m^2/yr to 13.3kWh/m^2/yr at 27% greater renovation cost.

10.4.7.3 Commercial Buildings

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

Examples of savings achieved through relatively simple measures are:

- projected savings of 30% of total energy use in 80 office buildings in Toronto through lighting upgrades alone (Larsson, 2001);
- realized savings of 40% in heating, cooling, and ventilation energy use in a Texas office building through the conversion of the ventilation system from constant airflow to variable air flow (Liu and Claridge, 1999);
- 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);
- projected savings of more than 50% of heating and cooling energy for restaurants in cities throughout the United States by optimizing the ventilation system (Fisher et al., 1999);
- projected 51% savings in cooling and ventilation energy use in an institutional building complex in Singapore through upgrades to the existing system (Sekhar and Phua, 2003);
- 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 fan, cooling, and heating energy savings of 59%, 63%, and 90%, respectively, at a university in Texas, roughly half due to a standard retrofit and half due to adjustment of the control system settings to optimal settings (Claridge et al., 2001);
- average realized savings of 68% in natural gas use after conversion of ten schools in the United States from non-condensing boilers producing low pressure steam to condensing boilers producing low temperature hot water, and an average savings of 49% after conversion of ten other schools from high to low temperature hot water and from non-condensing to condensing boilers (Durkin, 2006);
- projected savings of 30–60% in cooling loads in an existing Los Angeles office building by operating the existing HVAC system to make maximum use of night cooling opportunities (Armstrong et al., 2006);
- projected savings of 48% from a typical 1980s office building in Turkey through simple upgrades to mechanical systems and replacing existing windows with low-e windows having shading devices, with an overall economic payback of about six years (Çakmanus, 2007); and
- projected savings of 36–77% through retrofits of a variety of office types in a variety of European climates, with payback periods generally in the one to 30 year range (Hestnes and Kofoed, 1997, 2002; Dascalaki and Santamouris, 2002).

It should be emphasized that comprehensive retrofits of buildings are generally done for many reasons in addition to reducing energy costs. Thus, measures that are extensive enough to significantly reduce energy use may not pay for themselves in terms of energy cost savings alone, but may be feasible when complementing the regular renovation cycle of the building. In addition, accelerated retrofits may make economic sense if done to capture other non-energy benefits such as improved comfort or productivity, energy security, reduced greenhouse gas emissions, and increased employment (Ürge-Vorsatz et al., 2010).

A significant potential area for reduced energy use in existing buildings is through the replacement of existing curtain walls or upgrades of existing insulation and windows. Given the current trend of constructing nearly all-glass buildings, yet not using high-performance glazing, replacing existing glazing systems and curtain walls will be an essential future activity if deep reductions in heating and cooling energy use are to be achieved. Recently, the curtain walls were replaced on the 24-story 1952 Unilever building in Manhattan (SOM, 2010), which indicates that it is technically possible to completely replace curtain walls on high-rise office buildings.

In the case of brick or cement façades, one option is to construct a second, glazed façade over the first to create a double-skin façade, which opens up opportunities for passive ventilation and reduced cooling loads through the provision of adjustable external shading devices. This has often been done in Europe. A North American example of the construction of a second façade over the original façade is provided by the TELUS headquarters

building in Vancouver. In this case, the second façade was constructed as part of seismic retrofitting. Construction of a second façade can also be undertaken as a measure to preserve original façades that are deteriorating due to moisture problems related to defects in original construction.

10.4.8 Professional and Behavioral Opportunities and Challenges

As shown in previous sections, energy use is profoundly affected by building design, social norms, and occupant behavior. This section draws on socio-technical studies to focus on two dimensions of the relationship between people, energy, and buildings. It describes how organizations and individuals are central to:

- providing energy efficient buildings and technologies;
- using buildings and energy using technologies in appropriate ways.

For technical solutions to affect energy use, they must be preceded by human decisions about design, purchase, installation, and use. Reducing the amount of energy used in buildings therefore depends on these factors to varying degrees.

The broader relationship between energy service demands and socio-economic factors, particularly in developing countries, is discussed in Chapter 21. This section focuses more closely on the opportunities and challenges of reducing energy used to create comfort, visibility, cleanliness, and convenience in buildings.

Delivering a global transformation to a low energy building stock raises a number of social challenges, including in the professions responsible for the built environment, wider society, and individual building owners and users. A major effort to train the construction sector workforce will be needed in all countries. Lifestyle and management practices consistent with low energy buildings will need to be encouraged. Programs will be required to deliver appropriate education, information, and advice to building designers, constructors, and users. Better feedback to users via smart meters has an important role to play, but alone it is insufficient.

10.4.8.1 Providing Energy Efficient Buildings: a Professional Challenge

Professionals and practitioners in the building industry are essential agents of the transformation towards energy efficient new builds and refurbishments. Section 10.6 sets out scenarios for the global transformation of new and existing buildings to very high efficiency standards that are currently demonstrated but not widely used. The number of buildings requiring transformation implies a huge challenge for the construction sector. This challenge is particularly difficult in the area of housing refurbishment, which is generally fragmented in small- and medium-sized enterprises. The WBCSD (2009) suggests that a new "system integrator" profession is needed to develop the workforce capacity to save energy. The United Kingdom is training domestic energy assessors to draw up Energy Performance Certificates (Banks, 2008), while the Australian government is vigorously supporting the development of a new profession of in-home energy advisors (Berry, 2009). These efforts are essential in achieving the technical potential described above.

10.4.8.2 Using Buildings and Technologies Differently: A Personal Challenge

This section addresses how people can reduce energy by using buildings and technologies differently. It considers changing lifestyles, habits, norms, and practices, and increasing awareness.

Lifestyles

Substantial reduction, and in some cases even elimination, of energy use is possible by changing lifestyle through changing energy service demands – for example, through higher building occupancies, the use of internal temperatures closer to ambient temperatures, lower lighting levels, and the natural drying of clothes. In some cases, the change can be considered a loss of energy service (or utility), rather than providing the same service more efficiently. But levels of energy service that are considered normal, or even desirable, are a function of culture and lifestyle. Varying lifestyles require varying levels of energy service, both in different societies (Wilhite et al., 1996) and within the same society (Lutzenhiser, 1993). The variation is not only dependent on cost and income, but also on cultural practices.

The threat of climate change adds a new motivation for lifestyle change and has already generated a large number of new information sources, especially carbon footprinting web tools (Bottrill, 2007). Available evidence finds this has yet to have a major effect on most consumers (Lorenzioni et al., 2007), although there is some evidence of it providing a catalyst for community-based activity (Burgess, 2003; Darby, 2006a). However, as the thermal performance of buildings improves due to technical measures, the scope increases for occupant behavior to lead to 'in use' performance deviating (in percentage terms) from 'as designed'.

There are few quantitative studies on the impact of lifestyle change on energy demand in buildings. However, those that exist show potential for modest rates of lifestyle change to produce substantial energy use reductions in the long term, through changes in the use of energy coupled with higher propensities to adopt low energy technologies. Scenarios involving this type of lifestyle change can reduce energy use in buildings by 50% from existing levels in both Japan (Fujino et al., 2008) and the United Kingdom (UKERC, 2009). Dietz et al. (2009) examined the reasonably achievable potential for near-term reductions by altered adoption and use of available technologies in homes and non-business travel in the United States. They found that the implementation of these interventions could save an estimated

20% of household direct emissions or 7.4% of US national emissions, with little or no reduction in household well-being. Similar absolute reductions are not possible in developing countries where energy service demand will grow. However, the rate of growth of energy demand in buildings can be reduced by lower demand lifestyles (Wei et al., 2007). Although lifestyles vary across any society, lifestyle change is strongly affected by social interactions (Jackson, 2009) and therefore may be affected by policy. Chapter 21 contains a further discussion of this topic.

Changing Habits, Practices, and Norms

Even without major lifestyle changes, it is possible in high consumption societies for energy demand to be reduced through minor changes in behavior and conscious control of energy use. The reduction or elimination of wasteful behaviors generally requires increased awareness.

Behavioral changes that might take place include allowing higher/lower internal temperatures within acceptable comfort levels; the better use of shutters, blinds, or other artificial or natural shading (e.g., trees) to prevent unnecessary heat gains; reducing unnecessary air change (e.g., open windows) when heating or cooling; using showers rather than baths; using low water temperatures for clothes washing; naturally drying clothes; not overfilling pans and kettles; switching off lights in unoccupied space; using off, or other low power down states, for unused electronics. Box 10.3 gives two examples in residential and commercial buildings that further highlight social and cultural dimensions of energy use.

As shown in Section 10.1.3, conditioning living space to an acceptable temperature and humidity is generally the largest use of energy. Adaptation to higher/lower internal temperatures is therefore the most important single behavioral issue. Thermal comfort is subjective, variable, and to some extent influenced by previous experience. Recent studies have shown that people in different countries consider themselves comfortable at very different temperatures; that they will accept higher temperatures in naturally ventilated buildings than in mechanically-cooled buildings; and that indoor seasonal and diurnal temperature fluctuations may not be a bad thing. Box 10.4 discusses the concept of adaptive comfort in further detail.

Box 10.3 | Encouraging Adaptive Thermal Comfort in Japan

The importance of culture in determining buildings energy use is well demonstrated by the case of Japan. Japan is one of the most affluent countries in the world, but per capita space heating thermal energy demand per degree-day (heating degree day, or HDD) is significantly lower than in most other developed countries – about 8 GJ/capita compared to an OECD average of ~20 GJ/capita at 2700 HDD (IEA, 2007b). Japanese demand for space-heating is approximately one-third of that of other developed countries.

Beyond the typically much lower per capita floor area (29 m^2 per person compared to the OECD average of 46 m^2 per person (IEA, 2007b)), the reason is that most Japanese homes do not heat the entire living space, but use a modification of a traditional method to provide thermal comfort. In traditional Japanese homes, fire pits or charcoal braziers were generally used to warm the body. The "kotatsu," a direct body-warming apparatus unique to Japan, was common in Japanese houses. A kotatsu is a low table covered with a futon (a heavy quilted cover) placed on a tatami (floor mat). The inside of the futon is warmed by an electric heater attached to the bottom surface of the table. People sitting on the tatami put their feet under the table for direct body warmth. People can live comfortably in a room using a kotatsu even if the room air temperature is low; in many cases, rooms equipped with a kotatsu are heated only to a low temperature, or no heating is used at all. According to a detailed survey of residential energy use, the annual energy use of a house that uses a kotatsu as the main heating apparatus is approximately 40% less than the average use of all the houses studied (Sugihara et al., 2003). Over recent years, Japanese residences have been changing from a low-energy direct body-warming system such as kotatsu to a space heating system. This is one reason why energy use in the Japanese residential sector has been increasing.

Another example of a non-technological measure to reduce energy use is the Japanese "Cool Biz" program. Recognizing the fact that thermal comfort is highly dependent on clothing, which in turn is often determined by culture and dress codes, Japan attempted to change its existing dress code culture to a more sustainable one. In 2005, the Japanese Ministry of the Environment (MOE) promoted office building air conditioning settings of 28ºC during summer. As a part of this campaign, MOE has been promoting a new standard for summer dress codes, "Cool Biz," to encourage business people to wear cool and comfortable clothes to work in summer rather than the traditional multi-layered, heavy and dark standard attire that often results in air conditioners having to be set to low temperatures. MOE estimated that CO_2 emissions had been reduced by approximately 460 thousand tonnes as a result of the campaign. MOE will continue to promote Cool Biz and higher summer temperatures in offices (MOE, 2006).

Box 10.4 | Focus on Adaptive Comfort

Warmer interior temperatures are acceptable on hot days and colder interior temperatures are acceptable on cold days, if an individual knows what to expect and is accustomed to it. In fact, surveys have shown that individuals typically find acceptable indoor temperatures to be several degrees lower in the heating season than in the cooling season (de Dear and Brager, 1998). The psychological adaptation to warmer/cooler temperatures is enhanced if an individual can *control* his or her environment by being able, for example, to open or close windows, or to activate or deactivate a fan. Research in Denmark indicates that a temperature of 28°C with personal control over air speed is overwhelmingly preferred to a temperature of 26°C with a fixed air speed of 0.2 m/s (de Dear and Brager, 2002). In Thailand, Busch (1992) found that the maximum temperature accepted by 80% of survey respondents is about 28°C in air conditioned offices and 31°C in naturally ventilated offices. Despite this evidence, most air conditioned buildings are operated to maintain a temperature in the lower part of the 23–26°C range, irrespective of outdoor conditions.

Although the percentage savings from increasing the thermostat setting for air conditioning diminish the warmer the outdoor temperature, the implications are substantial. Increasing the thermostat from 24°C to 28°C in summer will reduce annual cooling energy use by more than a factor of three for a typical office building in Zurich and by more than a factor of two in Rome (Jaboyedoff, Roulet et al., 2004), and by a factor of 2–3 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).

Increasing Awareness

Many countries and regions now have energy efficiency agencies that promote "easy" behavioral actions (e.g., ADEME, 2009; Efficiency Vermont, 2009; EST, 2009). There are a number of approaches that are designed to assist energy users voluntarily to change their own energy using behavior by increasing their awareness of energy issues. The types of measures that fall within this category are: feedback, education, information, and advice.

a. Feedback – Billing and Metering

Feedback is the provision of information about personal energy use. This may be retrospectively with fuel bills, or in real time through metering and display technology. Reviews by Darby (2006a, 2006b) found that bills and other forms of indirect feedback can produce savings of 0–10%; savings from metering and direct feedback are typically in the range of 5–15%.The persistence of the effect is not well established. The use of smart metering for building energy management is growing. There is no agreed definition of smart metering. In some cases, programs of automated meter reading (AMR), i.e., remote meter reading, have been described in this way (Morch et al., 2007). These are already used extensively in some places, e.g., Italy, Sweden, and the Canadian province of Ontario (IBM, 2007; Haney et al, 2008) and provide clear benefits for energy suppliers through more timely and accurate information (Morch et al., 2007). Energy efficiency benefits within buildings are likely to be limited to those resulting from users making better decisions based on more accurate and frequent bills and incentives like dynamic pricing structure.

Greater involvement of building occupants demands two-way information flows. This is described as automatic meter management (AMM) or advanced metering infrastructure (AMI) (NETL, 2008). Information may be transferred through a range of communication channels, e.g., power lines, mobile phone text message, or radio, with results provided in real time within the building, e.g., via TV screens or internet (Wood and Newborough, 2003; Darby, 2008).

The costs of smart metering are expected to fall and the functionality to improve. Future technology will potentially use electrical harmonics, load profile data, and learn to identify, and feedback individual appliance consumption from aggregate meter data. A driver for smart metering is the need for smart grids to deal with the greater use of intermittent generation in low carbon electricity systems (see Chapter 11). These require electricity retailers and their customers to consider rescheduling of loads when possible, i.e., load switching or demand response measures(Hartway et al., 1999; Vojdani, 2008).This could be via building users responding to time-dependent price signals or by electricity supplier control over loads that are not time critical, e.g., cold appliances. In either case, smart meters potentially facilitate greater involvement of buildings in balancing electricity systems.

To effectively influence user behavior – whether to reduce demand or encourage load switching – information will need to be relevant and easy to assess. While the principle is clear, the exact format of the information that will be most effective is less obvious. Metrics could include energy, cost, or carbon and representations could be numeric or graphical, and could be based on comparisons with past use or other users. Different forms and levels of information will be required for professional users and householders, and may need to reflect other user differences, including culture and building type. More detailed research on the interaction between technology and behavior is required to maximize potential benefits.

b. Education

Education is mainly targeted at young people. The objective is to provide the knowledge and skills about energy use that will allow them to make informed choices as energy users. Energy and environment form part of

the curriculum in many countries, but not in all countries and not yet at adequate levels. A recent review of environmental programs around the world found that, although environmental education is growing, energy and energy efficiency are under-represented in national and international environmental educational programs (Harrigan and Curley, 2010). There is some evidence that education can be effective in the short term in influencing child and parent behavior (Heijne, 2003), but the lack of longitudinal studies makes firm conclusions about long-term impacts difficult.

c. Information

Information is the provision of material on energy saving opportunities via government campaigns, the media, and other means, including energy company billing. Information may be combined with motivational content design to change behavior, generally focusing on either cost savings or environmental benefits. There is some evidence that information from public and not-for-profit sources is more trusted and effective than from energy companies (DEFRA, 2005).

d. Advice

Advice differs from generally available information, as it targets the needs of the individual based on personal circumstances. There are a number of variants including face-to-face, telephone, and, more recently, internet-based advice systems. There is experience of this for energy use in businesses and households (Darby, 2003). Cost effectiveness of advice-oriented programs is generally very good. In one case, cost savings for consumers were 40 times the cost of the program (DEFRA, 2006b). Face-to-face advice is the most effective but least cost effective (Sadler, 2002). Much of the benefit resulting from advice leading to technical change persists longer than simple behavioral change.

10.5 Barriers Toward Improved Energy Efficiency and Distributed Generation in Buildings

10.5.1 Key Messages

Technologies and practices that are cost effective from an engineering-economic perspective are often not widely adopted in practice. The barriers include: lack of or imperfect information, transaction costs, limited access to capital, externalities, energy subsidies, risk aversion, principal agent situations, fragmented market and institutional structures, lack of feedback, administrative and regulatory barriers, and lack of enforcement. This section categorizes the barriers as financial costs and benefits, hidden costs and benefits, market failures, and behavioral, cognitive, and organizational barriers.

Solutions for the observed barriers must address many principal actors and their intermediaries and include increased education and training of professionals and consumers, improved information, pricing policies, and regulations (e.g., building codes and energy efficiency standards).

10.5.2 Introduction

The previous sections demonstrated that there is a broad spectrum of opportunities in buildings to significantly reduce energy demand without compromising the energy service delivered. This chapter attests that many opportunities offer net private or societal benefits. Subsidized energy prices (Kosmo, 1989; Lin and Jiang, 2010) and specific characteristics of the buildings sector – their occupants; agents who relate to construction, operation, maintenance, and use of buildings; and market characteristics – limit the "perfect" and "rational" energy efficiency function of buildings (de T'Serclaes, 2007). The IPCC (2007) concluded that the barriers that prevent many cost-effective energy efficiency and building-integrated distributed generation investments from being captured by market forces in present economic and political environments are especially strong in the built environment. Recent research identifies possible approaches to increase uptake of many of these opportunities (Brown et al., 2008; Brown et al., 2009; US DOE, 2010).

This section reviews barriers and solutions based on literature published since previous assessments, such as the IPCC (2007) and the World Energy Assessment (WEA) (2000; 2004). While the literature has been extensive in accounting for and explaining these imperfections, recent demands have become stronger for the quantification of these barriers to better inform private and public decision making. For instance, expenditure-based, climate change target setting, quantification of GHG reduction potentials at various cost levels, as well as several other policy goals require an understanding of the quantified importance of these barriers, the monetized impact of some of them, and an assessment of how much of these indirect costs can be prevented by policies. This section also aims to summarize quantitative estimates of these barriers so that their impacts can be incorporated into estimates of energy saving potential, in addition to incorporating co-benefits of energy efficiency (see Section 10.7). Different barriers are grouped according to typology as presented by the IPCC (2007) and summarized in Table 10.11.

10.5.3 Financial Costs and Benefits

Energy issues remain a low priority to most building owners and occupiers because energy is a relatively small part of the total costs in commercial and residential sectors (WBCSD, 2009). While other investments are subject to risk assessment, energy budgets for buildings are rarely analyzed (Jackson, 2008). Financial barriers to the penetration of energy efficiency and building-integrated distributed generation technologies include factors that increase the investment costs and/or decrease savings resulting from the improvement. These factors result in prolonging the payback time and downsizing the internal rate of return on investments. These factors include high initial costs of advanced technologies, costs associated with risks of implementation and financial operations (transaction costs), high discount rates for households and commerce,

Table 10.11 | 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.
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
Behavioral and organizational non-optimalities	Behavioral 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, behavior, lack of awareness, and lifestyle Corruption Lack of enforcement/implementation/monitoring

Source: Carbon Trust, 2005.

lack of or limited access to financing, cost of capital, and energy subsidies that do not allow for estimating the real energy cost savings (IPCC, 2007; de T'Serclaes, 2007).

Table 10.12 illustrates that transaction costs, high discount rates, and lack of real-time pricing are studied to the largest extent in the financial group of barriers. Based on the information available, the financial barriers are concluded to be very strong. For example, the transaction costs of energy efficiency and renewable energy projects in the buildings sector reach as high as 20% of investment costs.

Higher investment costs of efficiency technologies require significant investment in research as well as government programs to push market development further and faster. Since energy codes are relatively new in several developing nations, green products and services including insulation, CFLs and T5 lamps, efficient glass, and efficient HVAC systems – required by buildings to comply with some code requirements – are not readily and abundantly available or competitively priced.

Consolidation of the majority of global production in a handful of multinational manufacturers for each product type creates an opportunity for a well-designed set of policies, including voluntary labels, mandatory performance regulations, and financial incentives, to rapidly increase the production of energy efficient products. The energy efficiency standards and the Energy Star program for some products provide examples where most production has shifted toward higher efficiency, having several sequential updates for some products. Updating those policies and continued R&D are necessary to maintain the long-term trend in decreasing energy use and costs per product to support sustainable development in the building sector. For building retrofits, accessible mechanisms for providing information and capital are needed.

10.5.4 Market Failures

In traditional economic analysis, market failures refer to flaws in the ways that markets operate in practice compared to theoretically perfect markets. They are violations of one or more of the neoclassical economic assumptions that define an ideal market, such as rational behavior, costless transactions, and perfect information (Brown, 2001; Jaffe and Stavins, 1994). These failures are caused by misplaced incentives; administrative and regulatory barriers; imperfect information; unpriced environmental, health, social, and other external costs and benefits; fragmented market structure; and limitations of the typical building design and construction process. Decisions that result in the energy performance of buildings are fragmented, being made by building owners, architects, craftsmen, and occupants. Their motivations and opportunities for efficiency differ. Recently, social science gained new insights concerning positive drivers for efficiency and renewables – e.g., social prestige using the image of being socially responsible or "green," education, and social networking.

As Table 10.12 shows, the impacts of market failures are rarely measured, with the exception of misplaced incentives which have been covered recently by a few publications. Meier and Eide (2007) estimated that up to 100% of energy services and up to 80% of primary energy use of buildings are affected by misplaced incentives. If the barrier is removed, the energy savings, for instance for space and water heating, may reach 50–75%. The impact of administrative and regulatory barriers is difficult to measure, but researchers attest that there are a number of distorting policies against installing distributed generation (see, e.g., Brown, 2001). Methodologies exist for monetizing externalities, but final consumers have little information or incentive to undertake the level of effort required to include external costs and benefits in their decisions.

Table 10.12 | Selected barriers to GHG mitigation in the buildings sector and methodologies for their quantification in the literature.

Barriers	Case study	Methodologies used for quantification	Quantified impact of the barriers	References
Financial (including hidden) costs and benefits				
Transaction costs	World, India (IN), Sweden (SE), United Kingdom (UK), United States (US)	Empirical survey Literature review Interviews Review of official documentation Bottom-up estimates	SE: ≤ 20.5% and ≤ 14.4% of project costs for energy efficiency and renewable energy projects in buildings respectively IN: about 100 US$/t CO_2 in CDM projects targeting EE in housing sector World: ≤ 100 €/tCO_2 for CDM on EE in buildings World: €30,000 – €100,000 per JI/CDM project (almost for any project size) UK: 30% and 10% of investment costs for cavity wall insulation and CFL respectively US: information cost, vendor information cost, and consumer preferences add US$10, US$5, and US$5 respectively to the CFL price that was US$10/piece	Krey, 2005; UNFCCC, 2002;Michaelowa and Lotzo, 2005;Mundaca, 2007; Sathaye and Murtishaw, 2004; UNIDO, 2003
Limited access to capital	Australia (AU)	Case study	AU: In the case of energy efficient mortgage, stretching the credit ratio[a] by 2% allows a further 5% of loan application to succeed. However, as financial institutions frequently avoid softening the loan conditions, it may be concluded that these 5% loan application fail postponing or cancelling the intended energy efficiency projects	de T'Serclaes, 2007
Lack of real-time pricing	US, Japan (JP),Canada (CA), Netherlands (NL)	Case study on residential energy demand feedback devices Questionnaires Statistical analysis (Chi-square test)	USA: energy savings from providing real-time energy feedback is about 10–15% JP: feedback devices caused a 18% electricity saving and 9% gas saving CA: feedback displays produced electricity savings of 13% NL: daily feedback led to a 10% reduction in household gas consumption USA, CA: electricity savings totaled to 5% in Quebec and to 7% in California	Parker et al., 2006; Ueno et al., 2006; Dobson and Griffin, 1992; Van Houwelingen and Van Raaij, 1989; Hutton et al., 1986.
Behavioral: high discount rates (DR)	US, NL	Present value analyses Option value method Capital asset pricing model (CAPM) Discrete choice models Econometric models	US: DR is 5.1% – 89%/yr. in an inverse order of household income; average 20%/yr. US: DR < 15% a choice is a CFL; > 15% – an incandescent; = 15%/yr – indifferent US: DR = 21%/yr. at electricity price of 4.8 ¢/kWh; 27–28%/yr. – 6 ¢/kWh, and 30%/yr. – 7.5 ¢/kWh NL: high-efficiency durables to be bought at DR 0% – 1.4%/yr. or, in a more myopic case, 8% – 101.3%/yr.; low-efficiency durables – at DR 1.4% – 8%/yr. or, in a more myopic case,> 101.3%/yr.[b]	Hausman, 1979; Thompson, 1997; Sanstad et al., 1995; Kooreman and Steerneman, 1998

Market failures				
Market fragmentation	US	Empirical study	US: Uncaptured social returns from R&D are ≥ 50% than estimated private returns because of the fragmentation within the sector	CEA, 1995
Uncertainty in future prices	US	Economic model of irreversible investment	USA: Investment in energy efficiency under uncertainty falls from 25%/yr. to ~ 1%/yr. and is less than 5% after 20 years	Hassett and Metcalf, 1993
Misplaced incentives (principal agent problem)	US, Norway (NO), NL, AU, JP	Survey Authors' estimation Top-down analysis Case study	NO: the problem in the commercial offices affects around 80% of the energy use; energy use is ca 50 kWh/m2 higher in leased office space; the potential energy savings are 3.24 to 5.4 PJ/yr., or 15% of the total energy use in the Norwegian commercial sector US: savings from 2003 sales of water heaters would amount to 9.6 PJ/yr. of final energy and 12.6 PJ/yr. (about 7%) of primary energyuseif PA problems were solved NL: after removing the barrier, ca 20% of houses can be additionally insulated with an energy saving of 50%-75%/house for space heating (2–4 PJ/yr.) NL: The energy use affected by problems is more than 24.5 PJ per year, which accounts for over 40% of total energy use in commercial offices JP: energy use in commercial offices affected by the problem is 0–1.5% of total national electricity consumption	Meier and Eide, 2007;Ecofys, 2001;OECD/IEA, 2007
Behavioral and organizational non-optimality				
Lack of understanding	US	Case study, regression analysis, survey	US: energy savings amounted to 10% due to campaign (ca $130,000/yr.)	McMakin et al., 2002

[a] The ratio, expressed as a percentage, which results when a borrower's monthly payment obligation on long-term debts is divided by his or her net income or gross monthly income (Business Dictionary Online, 2008)

[b] Difference: more myopic consumers are more reluctant to buy EE goods (this is true for both high- and low-efficient durables). On the other hand, consumers are more myopic in case of low-efficiency durables.

Box 10.5 | Design Challenges of Efficient Buildings

In developing countries located in tropical regions, most of the residential buildings and several commercial building types are still designed as unconditioned spaces. Thus, the construction methods do not address issues of proper weather stripping, infiltration control or use of appropriate building materials, such as insulation or doubling glazing. However, changing climate and lifestyles have triggered retrofit of such buildings with window/packaged air conditioners. This leads to inefficient energy use.

Designing efficient buildings typically leads to a reduction in cooling loads and lighting loads and thus reduced sizes for installed system, with an imminent reduction of capital expenditure on systems. Typically a consultant's remuneration is a percentage of the capital cost, and thus a consultant may not be positively inclined to reduce the capital cost of a project, if there is no provision for added incentive for doing so. Designers and contractors are often slow to adopt energy efficient designs due to inertia or lack of training.

10.5.5 Behavioral and Organizational Non-optimalities

There are different behavioral and cognitive characteristics of individuals and organizational characteristics of companies that hinder energy efficiency technologies and practices in buildings. Perhaps the strongest barrier in this category is a major lack of technical, economic, and general knowledge related to low-energy buildings (see Box 10.5). This knowledge gap exists not only among building designers and architects, but also among politicians, investors, tenants, and consumers.

Beginning with the design side, there is a lack of knowledge among designers of how to best incorporate efficiency practices into building design to meet or exceed building code requirements. This is due to the novelty of energy efficiency concepts in buildings, especially in developing countries until recently. Furthermore, the capability of designers and architects to perform energy simulations to quantify the potential savings from energy efficiency is also very limited in developing countries.

Even once some efficient buildings have been designed effectively, the building construction industry is not generally prepared to apply these measures practically on site and remains largely unaware of the environmental impacts of its operations. Actual energy performance is generally not reported back to designers, builders, or contractors and they are not held accountable for inefficient designs or poor construction practices.

There are very few university programs in architecture and engineering in which curricula include energy efficiency issues in buildings. A report in the United States on workforce education and training identified 43 (of 492) higher education and/or training programs that meet minimum criteria of a specific emphasis on energy efficiency (Goldman et al., 2009). Due to the fact that courses on energy efficiency topics are not always compulsory, the number of graduates who have studied these subjects is even lower.

Insufficient education for building professionals causes the problem of ineffective communication with specialists in related fields and lower production in the construction process. Gallaher et al. (2004) estimated that the costs caused by ineffective communication between different stakeholders in the US building industry, including architects, engineers, general constructors, suppliers, owners, etc., is about US$15.8 billion. Improvement of building professionals' communication skills and ability to use modern software and electronic systems for the exchange of information can reduce such costs. In addition to the education of architects and effective communication of opportunities to consumers, an adequate trained workforce is needed to install and maintain efficient buildings and equipment. The training of a modest workforce (about 24,000 jobs) to commission non-residential buildings is expected to yield significant benefits, including US$30 billion in energy savings by year 2030 and annual greenhouse gas emissions reductions of about 340 megatonnes of carbon dioxide (Mills, 2009). Studies of energy service companies in the United States estimate the 2008 workforce to be about 120,000 person/yr equivalents (PYE), or equivalent to about 400,000 employees, and it is expected to grow by a factor of two to four by 2020, if they can overcome a number of key challenges (Goldman et al., 2010).

For designers and architects to shift their design and building practices, there needs to be a demand for efficient buildings from investors, developers, owners, and building occupants. This demand is currently low in developing countries due to several factors. There is a lack of knowledge about green investments and returns on efficient buildings. The value of energy efficient designs are underestimated by appraisers and reduced energy bills are not generally considered by mortgage lenders. Most consumers are also unaware of the comparative costs of the future operation and maintenance of buildings, and therefore they do not take building efficiency into consideration when making purchasing decisions. Because of this, most builders do not consider the future costs of operating the building during design and construction. Finally, there is a lack of awareness of the financial, environmental, and health benefits of operating buildings efficiently.

Also, many consumers are still unaware of the availability of green products and energy efficiency labeled products. With attention primarily on

purchase costs and without adequate consideration of the lifecycle costs and benefits of efficient products, the perception of higher upfront cost limits purchases of efficient products. An owner who wants to improve his or her house may find it difficult or impossible to get a proper offer from a construction firm on how to refurbish a building with a focus on the whole house and its energy efficiency.

Decisions about installing original or replacement appliances, lighting, and equipment (e.g., heating and cooling, water heating) in buildings face similar barriers. The situation is improved by the existence of energy labels, and more so by minimum energy performance standards and building codes that mandate cost-effective efficiency levels.

10.5.6 Barriers Related to Energy Efficiency Options in Buildings in Developing Countries

Table 10.12 presents an assessment of impacts of different groups of barriers on the scope or the costs of energy conservation potential. Analysis of Table 10.12 finds that the research has extensively covered only a few barriers, namely transaction costs, lack of real-time pricing, and the principal-agent problem, and only in developed countries. Table 10.12 also illustrates that studies use different indicators to measure the impacts of different barriers, making it difficult to compare these impacts or to estimate the overall aggregated effect of the barriers on energy conservation potential in the built environment and its costs and benefits. Therefore, unification of the methods is important to have a comprehensive analysis. This section attempts to look at the barriers through a regional lens.

Major barriers to energy efficiency improvements in the building sector in developing countries include lack of awareness of the importance of, and the potential for, energy efficiency improvements, lack of financing, lack of qualified personnel, and insufficient energy service levels (Ürge-Vorsatz and Koeppel, 2007). Also, negative experiences with energy efficient equipment such as in the case of some low cost CFLs that fail prematurely, can pose barriers. The biggest building market – single-family homes – is often unorganized and outside the control of local authorities. When homes are part of the informal sector, building codes or standards are not applied. In Brazil, for example, 75% of the residential sector falls under the informal category.

Subsidized energy prices are another strong barrier in many developing countries. However, these subsidies enable access to minimal energy service levels for certain population groups, which means that removing subsidies may be socially difficult and undesirable. In these cases energy efficiency programs may be especially important because improved efficiency can either reduce the need for public subsidies or enable elevated service levels and the more effective use of subsidies. In countries or regions with a lack of access to reliable energy supply, such as parts of Africa, the priority of governments may be to improve access to energy for inhabitants rather than to improve energy efficiency. In such cases, renewable energy projects and rural electrification often play a more important role for governments than energy efficiency. A scenario for implementing cost-effective efficiency for electricity in India, primarily through end-use technologies in buildings, is expected to reduce government payments of energy subsidies, to involve lower capital costs than the costs of new supply, to eliminate the chronic electricity supply shortage in a few years' time, and to improve the national economy by increasing the availability of electricity for commercial and industrial enterprises (Sathaye and Gupta, 2010).

The increased influence of western architecture, such as glass-dominant structures for commercial use, is very common in India. Being in primarily a cooling-dominant climate, this often leads to large cooling loads and hence increased energy demand. Also in developing countries, the regulatory frameworks for the implementation of energy efficiency in buildings are often inadequate. In India, for example, while there are regulations – such as environmental clearance of large construction projects by the state or central environment departments or ministries – implementation and monitoring mechanisms are inadequate.

Lack of knowledge among architects and system providers to incorporate energy efficiency is another major barrier. Energy efficiency in buildings is not taught as a part of the curriculum in most schools of architecture. Another key barrier is inadequate availability of products and services related to energy efficient buildings, which often leads to a monopoly of a few providers and thus higher costs. The absence of suitable financial products, such as low interest loans for energy efficient buildings and robust energy performance contract mechanisms to offset and/or build confidence in incremental costs, is a major barrier that hinders the penetration of energy efficiency in buildings.

10.6 Pathways for the Transition: Scenario Analyses on the Role Of Buildings in a Sustainable Energy Transition

10.6.1 Key Messages

This section presents scenarios for future regional and global energy use in the buildings sector that meet the multiple objectives outlined in the GEA. The energy demand scenarios developed here served as input to and have been harmonized with the main assumptions in the GEA transition pathways presented in Chapter 17. The scenarios demonstrate that reducing approximately 46% of final thermal energy use in buildings is possible by 2050, as compared to 2005. This is achievable through the proliferation of existing best practices in building design, construction, and operation, as well as accelerated state-of-the-art retrofits. This is attainable in concert with increases in thermal comfort, the elimination of energy poverty, economic development, and living space increases in some regions. Realization of this potential requires undiscounted

cumulative investments of approximately US$14.2 trillion (or US$18.6 trillion without technology learning) by 2050. At the same time, these costs will be substantially recovered by the approximately US$58 trillion in undiscounted energy cost savings during the same period. However, scenarios also show a great risk of lock-in effect – about 80% of thermal energy savings can be locked in the global building sector if suboptimal solutions continue to be pursued.

New appliances, IT, and other electricity using equipment also have significant potential for energy use reduction – up to 65% by 2020 in relation to the baseline – due to the worldwide utilization of present and foreseen cutting-edge technologies.

10.6.2 Description of the GEA Building Thermal Energy Use Model

Providing thermal comfort in buildings contributes significantly to global energy use, yet this energy end-use sector is also the most poorly understood one. Little data and detailed information exist related to the heating and cooling of our buildings. Consequently, few global models exist. The model in this report is a newly constructed one prepared for the GEA pathway analysis, but is built on earlier results as well as present state-of-the-art work in progress, using a novel approach.

The energy demand scenarios developed here served as input to and have been harmonized with the main assumptions in the GEA transition pathways presented in Chapter 17.

The building thermal energy use model constructed for the GEA is novel in its method, as compared to earlier global world energy analyses. It reflects a new emerging paradigm that builds on an emerging approach to building energy transformation: one that takes advantage of the fact that buildings are complex systems rather than sums of components. This holistic approach is based on a performance-oriented concept of building energy use, as opposed to a component-oriented approach. It also focuses on providing energy services rather than energy per se. Applying this approach to building energy saving potential assessment typically results in much higher energy saving potentials than earlier approaches, which do not integrate systemic opportunities or opportunities emerging through focusing on the provision of energy services. However, this approach is consistent with the empirically observed opportunities presented earlier in this report for various technologies and know-how, based on the savings that are possible by treating buildings as systems rather than as sums of separate components. Electricity use by appliances (except cooling appliances) and other plug loads is treated separately and does not require the consideration of system level savings opportunities. These energy uses (in contrast to cooling), are more complex from modeling purposes and do require the consideration of system level opportunities; thus, they have been modeled using conventional approaches in a separate module.

The following subsections describe the models of thermal energy use and electric plug loads and their results. The driving questions were:

- How large of a role can buildings play in an energy transition for sustainability?
- How far can buildings take us in mitigating climate change and addressing other energy-related challenges outlined in this report?

The scenarios presented here analyze pathways in which energy efficiency in buildings is pushed toward the state-of-the-art, but do not extend to assessing building-integrated sustainable energy generation options such as renewables, or to assessing the role of lifestyle/behavioral changes, due to time and other constraints.

They represent feasible deployment potentials (i.e., techno-economic potentials that also consider deployment constraints), assuming a very strong supporting policy framework globally. It is important to note, however, that the building scenarios share the fundamental philosophy of the GEA in that they presume the increase in the thermal energy service to satisfactory levels to all populations worldwide, i.e., they assume that fuel poverty is eliminated and sufficient thermally conditioned minimal living space is provided for all by the end of the modeling period. Originating from the nature of these end-uses, the timeframe for these projections is different. In contrast to other GEA pathways, the building scenarios only extend until 2050 since, due to the shorter lifetime and high changeability of the equipment covered, any projections beyond the midterm become extremely speculative and thus lack robustness.

10.6.2.1 Model Design and Novelty

Prior models of building energy use or mitigation opportunities have focused on individual building components or the equipment used for heating and cooling, or other end-uses and alternatives to these that can save energy. One example of a model mastering this approach is the Bottom Up Energy Analysis System (BUENAS) of the Lawrence Berkeley National Laboratory, focusing on appliance efficiency. The model projects increases in appliance – space heating and cooling systems included efficiency on total final energy use. This model was used for the plug load part of the GEA pathways. (The BUENAS model is described in more detail in Section 10.6.3.)

A new thinking has been emerging recently in building energy science and analysis that represents a shift of paradigm – a system-based, performance-based, holistic approach. This replaces the component-based, piecemeal approaches of earlier efforts. The new approach recognizes that buildings are more complex systems than just the sum of their components, and that there are many synergistic opportunities and trade-offs, too. It also recognizes that the same levels of energy performance can be obtained through different pathways – i.e., different packages of energy-efficiency measures, which gives optimal freedom

for the constructors and designer to reduce energy use in a particular set of circumstances (Laustsen, 2008).[23] This new thinking is reflected in performance-based building energy regulations – i.e., that specify building codes based on energy use per square meter useful space, or other similar complex systemic performance indicators, rather than those regulating individual building components.

Following this paradigm change, a number of countries and jurisdictions have been revising their building energy codes based on new performance-based approaches (Hui, 2002). These include building regulations in the United States, Canada, the European Union and its member states (i.e., the Energy Performance of Buildings Directive (EPBD)), and Singapore (Hui, 2002).

At the same time, building energy and climate scenario modeling related to buildings has not yet reflected this paradigm change. The GEA building pathway assessment is among the first models using the performance-based approach, and has been developed in close cooperation with the few other ongoing efforts using a similar logic for global building energy modeling (Harvey, 2010; Laustsen, forthcoming).

Another novel aspect of the present model is in that it focuses on providing energy services rather than energy per se. This is reflected in the fact that the model's end goal is to provide adequate thermal comfort for living and commercial floor spaces needed by the population, and first examines options how this can be provided with the least energy input. As a result, architectural and engineering solutions that maximize the thermal performance of buildings are emphasized, often significantly reducing, and sometimes eliminating, the heating and/or cooling load that needs to be met by energy input, even before a technological solution needs to be applied. Therefore, a focus on energy services rather than energy allows for many non-energy solutions or a larger portfolio of innovative options to reducing energy use, and thus unlocks much larger mitigation options and energy saving potential.

10.6.2.2 Modeling Logic, Structure, and Main Assumptions

As described earlier, the GEA model is grounded in a performance-based logic that considers buildings as entire complex systems and not the sum of their components. Specifically, buildings energy use is not modeled based on individual energy efficiency measures, but are computed based on marker exemplary buildings with measured, documented energy performance levels and associated investment costs. A fundamental thesis of the model is that building energy performance depends less on precise degree days (cooling and heating) and technical efficiencies of individual devices than on state-of-the-art design, construction, and operation know-how and technology packages, as well as main climate types. The total energy requirement for thermal loads is derived as the product of energy intensity and floor area, summed over all building types, vintages, regions, and climate zones. Thus, key model inputs include floor space developments and specific energy demand values for existing and replicable, economically feasible, exemplary buildings in each region and each climate zone.

The logic of the model leaves it to the creativity of the architect and energy engineers to decide how – through which technologies or design and operational measures – the state-of-the-art performance level is exactly achieved. It assumes that once the selected type of exemplary buildings have demonstrated the feasibility of a certain ambitious level of energy performance and the promise of economic viability in the respective climate and building type, such levels are broadly attainable in that particular climate zone, building type, and vintage. The model then presumes that such state-of-the-art construction and renovation becomes the standard, e.g., through strictly enforced building codes.

Each time a new building is constructed or reaches its retrofit cycle, it is assumed to reach state-of-the-art specific energy demand levels for its category and climate type, after a certain transition period. The transition period is allowed so that markets and industries have ramp-up time for large-scale deployment of exemplary building construction technologies, materials, and know-how, as well as allowing time for the needed ambitious enabling policies to be enacted and the necessary supporting institutional framework to be introduced. The model assumes ten years for this transition period, which is shown by recent literature likely to be a very conservative assumption (Ürge-Vorsatz et al., 2010; in preparation).

Separate final energy intensity levels are specified for different building types (single family (detached or attached), multifamily (four or more levels, terraced, etc.), and commercial and public buildings) in four different climate zones (warm moderate, cold moderate, tropical, and arid) in each of 11 GEA regions (North America (NAM), Western Europe (WEU), Pacific OECD (PAO), Eastern Europe (EEU), Former Soviet Union (FSU), Centrally Planned Asia (CPA), South Asia (SAS), Other Pacific Asia (PAS), Middle East and North Africa (MEA),Latin America and the Caribbean (LAC), and sub-Saharan Africa (AFR)).

The specified energy intensity levels for advanced new buildings and retrofits are based on demonstrated energy and financial performance results in each region, but energy values are adjusted upward to allow for difficulties in achieving the best-observed performance in all cases.

The model distinguishes three different categories of buildings: all three categories of buildings exist in all eleven GEA regions of the world and are then split by four climate types (for regions, climates, and the floor area model see the sections below). The model uses business-as-usual construction and demolition rates. However, as became clear in the first

23 Note that with greater flexibility for designers, the performance-based standards require using computer-based models and a deeper understanding of the building principles (Laustsen, 2008). However, there are developments in this area as well, and European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) are developing international standards founded on performance-based approaches (Laustsen, 2008).

modeling runs, retrofit dynamics fundamentally determine the attainability of ambitious sustainability goals in the mid-century, so the model assumes an approximately doubled retrofit rate (i.e., 3% as opposed to the average 1.5%). This requires policy intervention. Most of the model's non-building input data, such as on GDP and population growth, urbanization, and other key macroeconomic parameters are derived from the main GEA pathway work, and as such is consistent with its assumptions on GDP and population growth, urbanization, and other key macroeconomic parameters. These are explained in Chapter 17.

The model estimates the additional investment costs needed for energy efficient construction and retrofits assumed and an estimation of the resulting energy cost savings. The cost values are calculated based on marginal expenditures as compared to standard construction and retrofit investments, while overall energy cost savings are based on comparison with a business-as-usual scenario, taking into account policies in place or in the pipeline. The overall model logic diagram is shown in Figure 10.A.4 in the GEA Chapter 10 Online Appendix.

10.6.2.3 Description of the Analyzed Scenarios

Two scenarios have been elaborated in the presented global building energy use model: state-of-the-art and sub-optimal efficiency scenarios, which are described below.

State-of-the-art Efficiency Scenario

This scenario demonstrates how far today's state-of-the-art construction and retrofit know-how and technologies can take us in meeting the GEA objectives as far as the provision of thermal comfort in buildings is considered, were they to become standard practice after a transition period. These standards are applied to all buildings in their respective categories as they are retrofitted or constructed during the modeling period, except for the small share of heritage buildings where lower efficiency levels can be achieved in renovation.

Sub-optimal Efficiency Scenario

The rationale for this scenario is to illustrate the potential lock-in effect in building infrastructure that can be caused by accelerated major policy efforts (such as the ones currently implemented by many governments and international organizations for climate change mitigation)which do not mandate sufficiently ambitious performance levels. Specifically, the scenario assumes the same accelerated renovation rates as the state-of-the-art scenario, to reflect that many countries recognize the importance of energy-efficient retrofits and energy-efficient building codes, but these accelerated retrofits and advanced new buildings are still built and renovated to far less efficient levels than are achievable according to the state-of-art scenario; thus they are referred to as "suboptimal" levels.

New buildings in this scenario are assumed to be built to the building codes for the region. Only in Western Europe (WEU) is it assumed that highly efficient buildings are being built in relatively large numbers, but the maximum fraction of these advanced building is only 5% in this scenario. Renovations are carried out to achieve approximately 35% energy savings from the stock average, as opposed to the state-of-the-art savings, which can be as high as 95% in some climate and building types, as demonstrated by best practices.

10.6.2.4 Main Assumptions and Input Data

The model's main assumptions and data sources are briefly described in the GEA Chapter 10 Online Appendix. For a more detailed description, see Ürge-Vorsatz and Petrichenko et al. (in preparation).

The world's building stock is broken into the same eleven regions as are used elsewhere in the GEA (such as Chapter 17), which are presented in the technical appendix. These are: North America (NAM), Western Europe (WEU), Pacific OECD (PAO), Eastern Europe (EEU), Former Soviet Union (FSU), Centrally Planned Asia (CPA), South Asia (SAS), Other Pacific Asia (PAS), Middle East and North Africa (MEA),Latin America and the Caribbean (LAC), and sub-Saharan Africa (AFR).

Specific Energy Demand Assumptions

Table 10.13 shows the specific energy demand figures that are used as an input to the model. It is important to note that it has been extremely challenging to arrive at these figures. Necessary statistics are rarely available, and even if they are, they contain different groupings, and thus during the regrouping new assumptions needed to be introduced. For the majority of the regions, however, experience transfer and extrapolations, combined with interviews and expert judgments, had to be applied to derive these figures. New and retrofit data represent advanced standard practice today – i.e., reflecting new building codes and relatively ambitious energy retrofits taking place as a result of support programs. Advanced new and advanced retrofit data are based on exemplary buildings for the respective climate zones, assuming that these can become standard practice from a technological and economic perspective, after sufficient learning and deployment phases, and under mature market conditions, but with some allowance for lesser performance when scaled up to the entire building stock. Figure 10.5, shown earlier, maps these values weighted by respective floor areas.

10.6.2.5 Results of the World Building Thermal Energy use Scenario Analysis

As Figure 10.1 demonstrates, if today's existing regional best practices in building construction and retrofit proliferate and become the standard, approximately 46% of global building heating and cooling final energy use can be saved by 2050 as compared to 2005 levels. This is in spite of the approximately 126% increase in floor area during the period and a significant increase in comfort and energy service levels arising

Table 10.13 | Specific heating and cooling final energy use (kWh/m²/yr) figures assumed in the scenarios for different building types, vintages, and regions and climate zones.[24]

Region	Climate Type	Single Family					Multi-Family					Commercial and Public				
		Existing	New	Adv New	Retrofit	Adv Retrofit	Existing	New	Adv New	Retrofit	Adv Retrofit	Existing	New	Adv New	Retrofit	Adv Retrofit
NAM	Warm Mod.	150	65	15	105	20	170	65	10	119	15	220	65	15	154	17
	Cold Mod.	191	65	20	134	30	200	65	15	140	20	340	65	15	238	20
	Tropical	75	65	17	53	25	75	65	17	53	25	131	65	25	92	30
	Arid	87	65	12	61	20	87	65	12	61	20	114	65	20	80	25
WEU	Warm Mod.	160	50	12	112	15	155	50	10	109	15	130	50	10	91	17
	Cold Mod.	261	50	14	183	20	225	50	14	158	20	209	50	14	146	20
PAO	Warm Mod.	100	55	15	70	20	95	60	10	67	15	90	66	15	63	17
	Cold Mod.	150	65	20	105	30	130	80	15	91	20	90	66	15	63	20
	Tropical	65	55	17	46	25	63	55	17	44	25	131	65	25	92	30
	Arid	155	65	12	109	20	155	60	12	109	20	114	65	20	80	25
EEU	Warm Mod.	240	145	14	168	15	205	120	10	144	15	180	120	10	126	17
	Cold Mod.	280	123	20	196	20	245	150	15	172	20	280	111	14	196	20
FSU	Warm Mod.	240	150	15	168	25	205	130	15	144	20	180	120	10	126	17
	Cold Mod.	280	180	20	196	20	246	150	20	172	25	353	150	14	247	20
	Arid	210	100	12	147	20	210	100	15	147	20	210	65	18	147	25
CPA	Warm Mod.	65	42	15	46	20	65	42	10	46	15	96	62	15	67	17
	Cold Mod.	140	91	20	98	30	120	78	15	84	20	150	98	15	105	20
	Tropical	60	39	17	42	25	55	36	17	39	25	96	62	25	67	30
	Arid	70	46	12	49	20	55	36	12	39	20	96	62	20	67	25

24 NAM has the same energy demand for multi-family and single-family buildings due to the aggregation of the residential sector in US EIA's RECS data by climate but not by climate and type of dwelling.

Continued next page →

Table 10.13 | *(cont.)*

Region	Climate Type	Single Family					Multi-Family					Commercial and Public				
		Existing	New	Adv New	Retrofit	Adv Retrofit	Existing	New	Adv New	Retrofit	Adv Retrofit	Existing	New	Adv New	Retrofit	Adv Retrofit
SAS	Warm Mod.	65	42	15	46	20	65	42	10	46	15	96	55	15	75	17
	Tropical	35	23	17	25	25	35	23	17	25	25	96	65	25	75	30
	Arid	35	23	12	25	20	35	23	12	25	20	96	65	18	75	18
PAS	Warm Mod.	65	42	15	46	20	65	42	10	46	15	96	55	15	75	17
	Tropical	35	23	17	25	25	35	23	17	25	25	96	65	25	75	30
MEA	Arid	87	50	12	50	20	62	60	12	60	20	62	65	20	75	25
LAC	Warm Mod.	81	50	15	50	20	81	60	10	60	15	91	55	15	55	17
	Cold Mod.	196	50	20	50	30	170	60	15	60	20	209	65	15	65	20
	Tropical	63	50	17	50	25	63	55	17	55	25	131	65	25	65	30
	Arid	87	50	12	50	20	155	60	12	60	20	114	65	20	65	25
AFR	Warm Mod.	120	50	15	50	20	100	60	10	60	15	100	55	15	55	17
	Tropical	63	50	17	50	25	63	55	17	55	25	65	65	25	65	30
	Arid	87	50	12	50	20	62	60	12	60	20	62	65	20	65	25

Note: Sources of data are diverse, ranging from national statistics through literature review to personal interviews and expert judgments, largely by the author team of this chapter, for regions without documented data.

Source: US DOE, 2009a; 2009b; US EIA, 2003a; 2005; BMVBS, 1993; ICC, 2007; Feist et al., 2001; Schnieders, 2003; Mitthone, 2010.

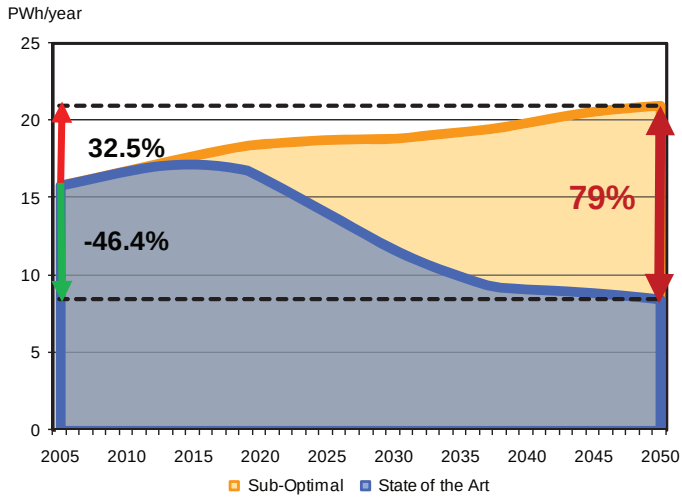

Figure 10.21 | World space heating and cooling final energy use, 2005–2050, sub-optimal and state of the art efficiency scenarios.

from a general improvement in affluence. The savings correspond to a drop from 15.8 Petawatt-hour (PWh)/yr to 8.5 PWh/yr in final heating and cooling energy use during the period. At the same time, fuel poverty is eliminated as a basic assumption, in accordance with the GEA multiple objectives.

At the same time, if similarly broad and strong efforts are invested in proliferating building codes and accelerating energy-efficient retrofits worldwide, but only suboptimal performance levels are mandated instead of the state-of-the-art ones that have been demonstrated to be feasible and economic in the particular region, global building heating and cooling final energy use will *increase* by 33% by 2050 as compared to 2005 instead of decreasing (Figure 10.21). Since buildings are constructed or renovated for very long periods, this represents a significant lock-in – 79% of 2005 total global heating and cooling final energy demand in this case – as it is not feasible or is extremely uneconomic to capture the remaining energy savings opportunities outside of renovation and construction cycles. The lock-in problem is described in more detail below.

In the state-of-the-art scenario, most regions are able to decrease final thermal energy use in buildings, with the largest drop in OECD countries (73%), followed by emerging economies (66%) (see Figure 10.22 for the five aggregate GEA regions). Even in Asia, the final energy use decreases, after an initial increase, ending 16.5% lower than in 2005. Regions in which the increase in conditioned floorspace and thermal comfort levels exceed efficiency gains are Latin America and the Caribbean, as well as the Middle East and Africa, with 15% and 71.5% increases, respectively.

The Significance of the Lock-in Effect

The model demonstrates the major risk of the lock-in effect in the building infrastructure. If present standards prevail for new construction, combined with suboptimal efficiency levels[25] for renovation, 79% of 2005 final heating and cooling energy use will be locked in by 2050, even with accelerated renovation rates. This will result in 21 PWh/yr consumption in the sub-optimal scenario – a 32.5% increase as opposed to a consumption rate of 8.5 PWh/yr in the state-of-the-art scenario.

There has not been an extensive discussion in the literature of the lock-in risk in the buildings sector. The GEA scenarios show, for the first time, the significance of strong policies that are insufficiently ambitious in efficiency targets – ones that prevail today in many developed countries. While from merely an energy savings perspective, the lock-in effect is less problematic since energy saving targets may be reached at a later stage, i.e., in the next renovation or construction cycles although some potentials will never be possible to unlock, which is more due to building structures related to urban design, plot sizing, and orientation, etc. From the climate change perspective, it is essential that buildings deliver greater energy savings in the midterm, such as 2050. Since this chapter shows that buildings are one of the lowest cost options to reach GEA objectives, including climate change, locked-in potential in buildings means that other options will need to replace building-related measures for reaching very ambitious midterm climate change goals. This may be problematic, because building-related measures come with a wide range of multiple benefits, as later sections here and Chapter 17 show, which may not be present in the case of the replacement mitigation measures at comparable costs. Also, there may not be alternative measures of such magnitude at similar cost levels.

The architecture of the suboptimal scenario is based on present efforts taking place in countries, jurisdictions, and institutions strongly committed to solving the climate problem. Many countries and multilateral international foundations and institutions recognize the importance of the building sector, and have passed improved building codes or encouraged high-efficiency or even zero-energy buildings and facilitated an acceleration of energy efficiency retrofit activities. However, in few of these cases are energy efficiency levels close to what is achievable by the state-of-the-art scenario, especially for retrofits. Therefore, the suboptimal scenario already depicts a world in which strong efforts are devoted to solving the building energy problem, and thus shows the danger with which even a well-intended path may be associated.

The lock-in problem originates from the fact that if suboptimal performance levels become the standard in new buildings or retrofits, it can either be impossible or extremely uneconomic to go back for the potentially remaining measures for many decades to come, or in some cases, for the entire remaining lifetime of the building. For instance, lower performance levels originating from suboptimal land use planning and constraints related to plot and building orientation can never be corrected in the building's life or longer. If, during a refurbishment or

25 Suboptimal renovation levels are determined for each region, climate, and building type, as shown in Table 10.2, but are typically in the 35% energy savings range where no other data were found.

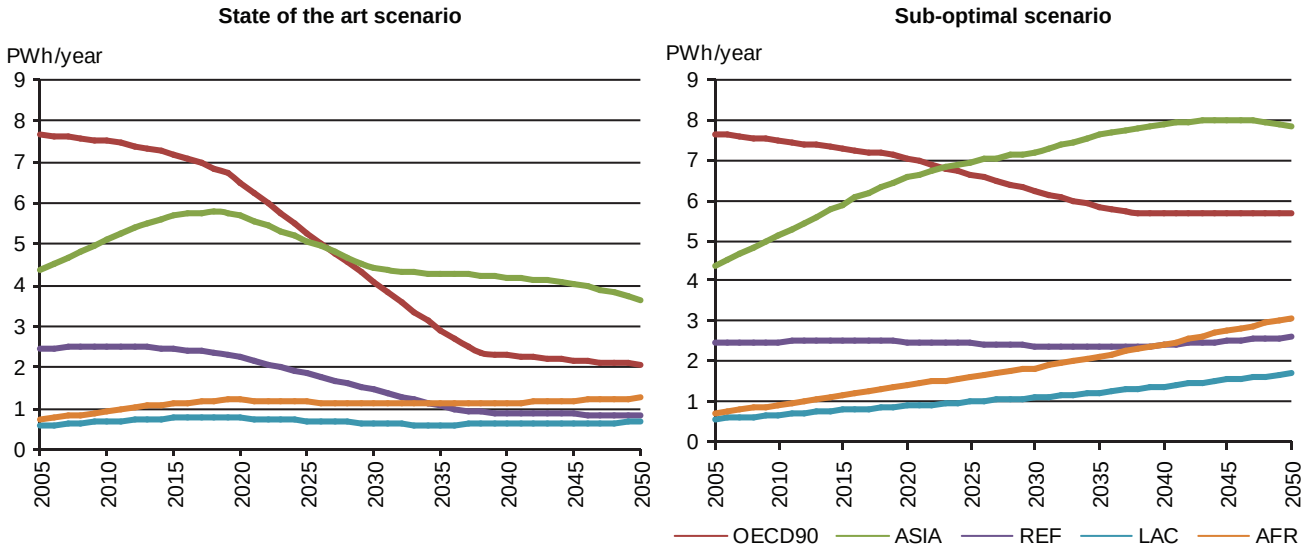

Figure 10.22 | Space heating and cooling final energy use in the five aggregate GEA regions, 2005–2050, in state-of-the-art and sub-optimal scenarios for the five regions: heating and cooling final energy use development for scenarios (i.e., assuming sub-optimal renovation and construction energy performance levels).

new construction, a holistic optimization is not followed, later installation of even the highest efficiency equipment or building materials will not be able to capture the savings otherwise attainable in a comprehensive refurbishment. For instance, heat losses and gains will still occur through other, non-optimized building parts. Finally, each retrofit is associated with significant transaction costs and inconveniences, including finding contractors, planning, preparing contracts, perhaps obtaining the financing, putting up scaffolding or other construction support structures, painting and finishing surfaces after it is done, etc. Thus, in subsequent "top-up" retrofits, energy savings are smaller and costs higher, with fixed costs comparable to those for a comprehensive, deep retrofit. As a result, going back for non-captured savings after suboptimal retrofits or new construction is typically so expensive on a specific cost, such as cost/tCO_2 saved, basis that other mitigation or sustainability measures will likely become much more attractive, whereas this is not the case if they are originally part of an integrated, deep design retrofit or construction.

Figure 10.22 shows large increases in energy demand in the suboptimal scenario for the regions of the developing world, where the ASIA region (Asia, excluding the OECD90 countries[26]) has the most pronounced increase. The results for the OECD90 countries show that there is still a decrease in total building energy demand in the sub-optimal scenario due to already gradually strengthening new building codes, less dynamically growing floor space, and actions taken toward efficient retrofits. Conversely, in ASIA there is a major increase in energy demand due to presently unsaturated thermal energy service levels and partially less ambitious building codes.

26 OECD90 comprises countries that were members of OECD in 1990.

The lock-in risk is high in all regions, in the range of 40–200% of 2050 state-of-the-art energy use, but its composition is different. The relative importance of renovation and new construction is different in each region. Figures 10.23–10.26 show state-of-the-art and sub-optimal renovation scenarios in the eleven GEA regions broken down by vintage (age) and efficiency level. In OECD, the difference in energy use is primarily due to differences in renovation efficiency levels (see Figure 10.23), while in Asia it is almost entirely due to sub-optimal performance standards in the new building stock (Figure 10.24). In regions of the world that are highly developed or had built the majority of their building stock up to 100 years ago, there is great potential to incur a future energy penalty due to the renovation lock-in effect. This occurs when there is a large part of the building stock that has been built to lower energy standards in the past and is not scheduled for demolition or a deep energy retrofit in the near term. This problem is exacerbated by the fact that buildings have a very long service life, over 150 years in some parts of Europe, and will continue to have the same energy demand until they are appropriately renovated. This points to the importance of different priorities in building-related policymaking in the different regions. In historic regions, ambitious renovation policy – consisting of accelerated renovation dynamics emphasizing state-of-the-art energy performance levels – is important, while in dynamically developing regions new building codes are paramount for achieving a low building energy future. Figure 10.23 demonstrates that retrofits are also important in the more dynamically developing regions.

The Rebound Effect and the Elimination of Fuel Poverty

The logic of the model is that when a new building is constructed it applies the average specific energy use of the new stock – either low or high efficiency – that is either based on state-of-the-art case studies or building codes, i.e., assuming full thermal comfort in the entire building. As a result,

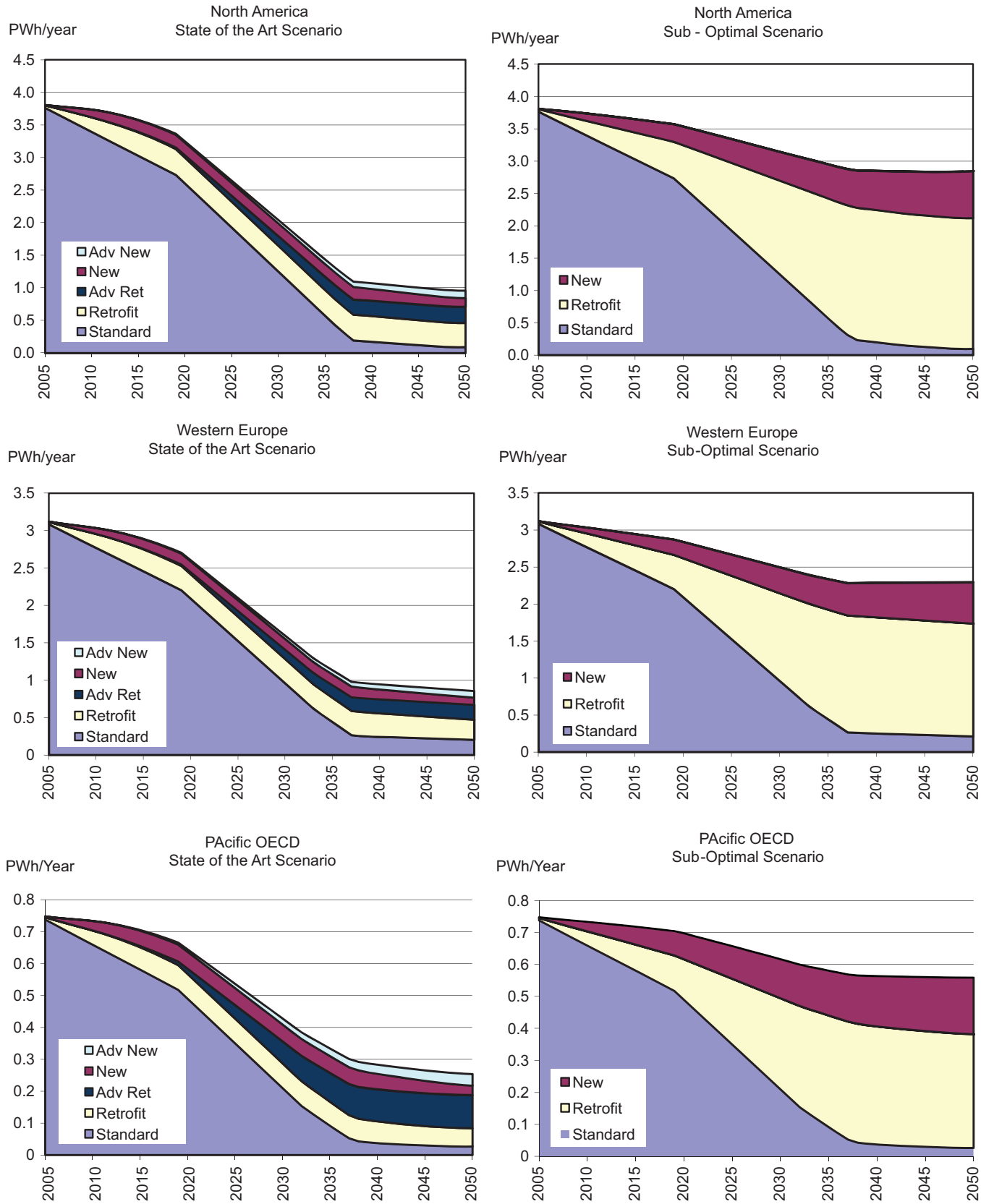

Figure 10.23 | Comparison of the two GEA building scenarios for OECD90 regions, final thermal energy use by construction type.

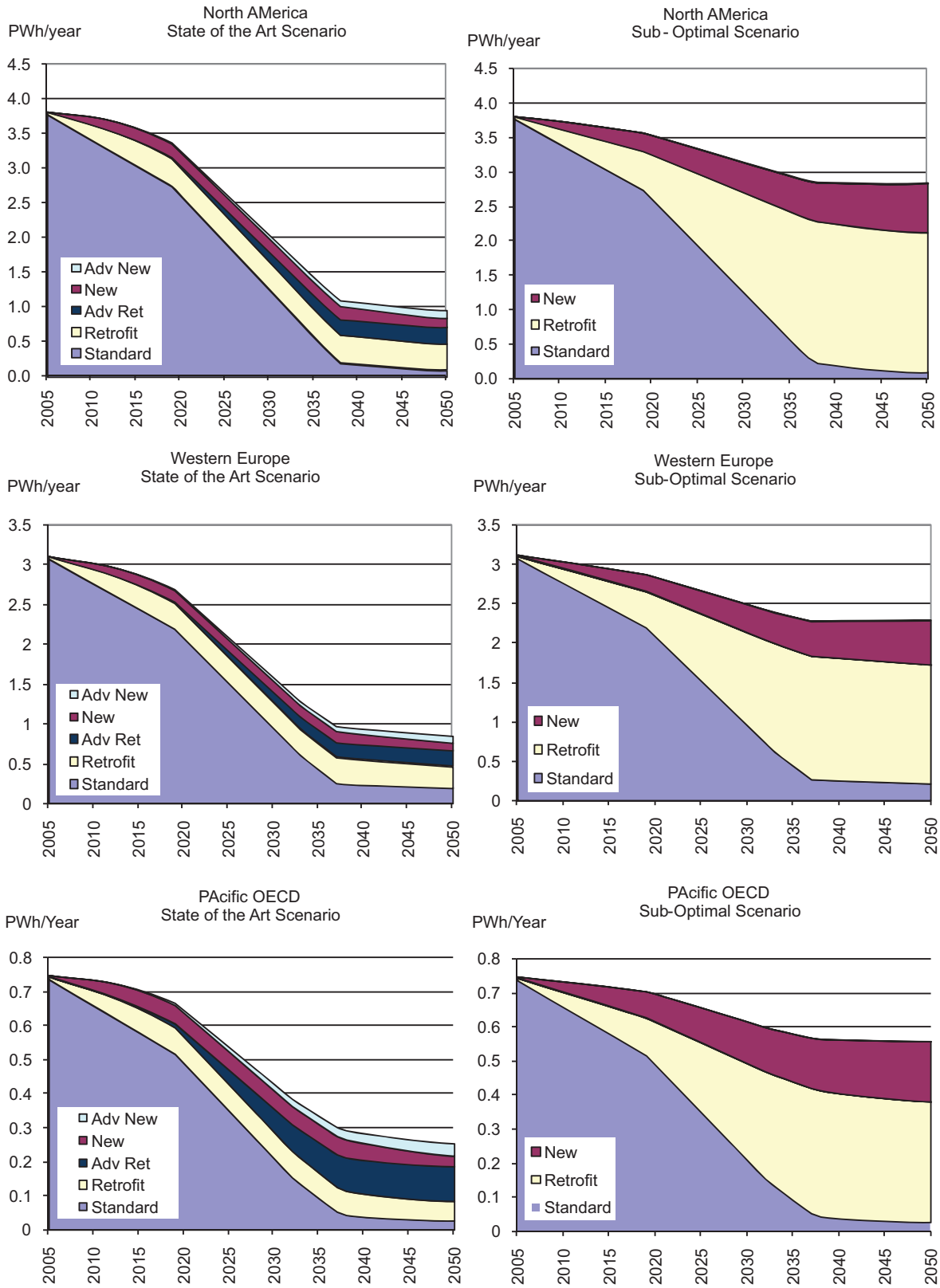

Figure 10.24 | Comparison of the two GEA building scenarios for ASIA Regions, final thermal energy use by construction type.

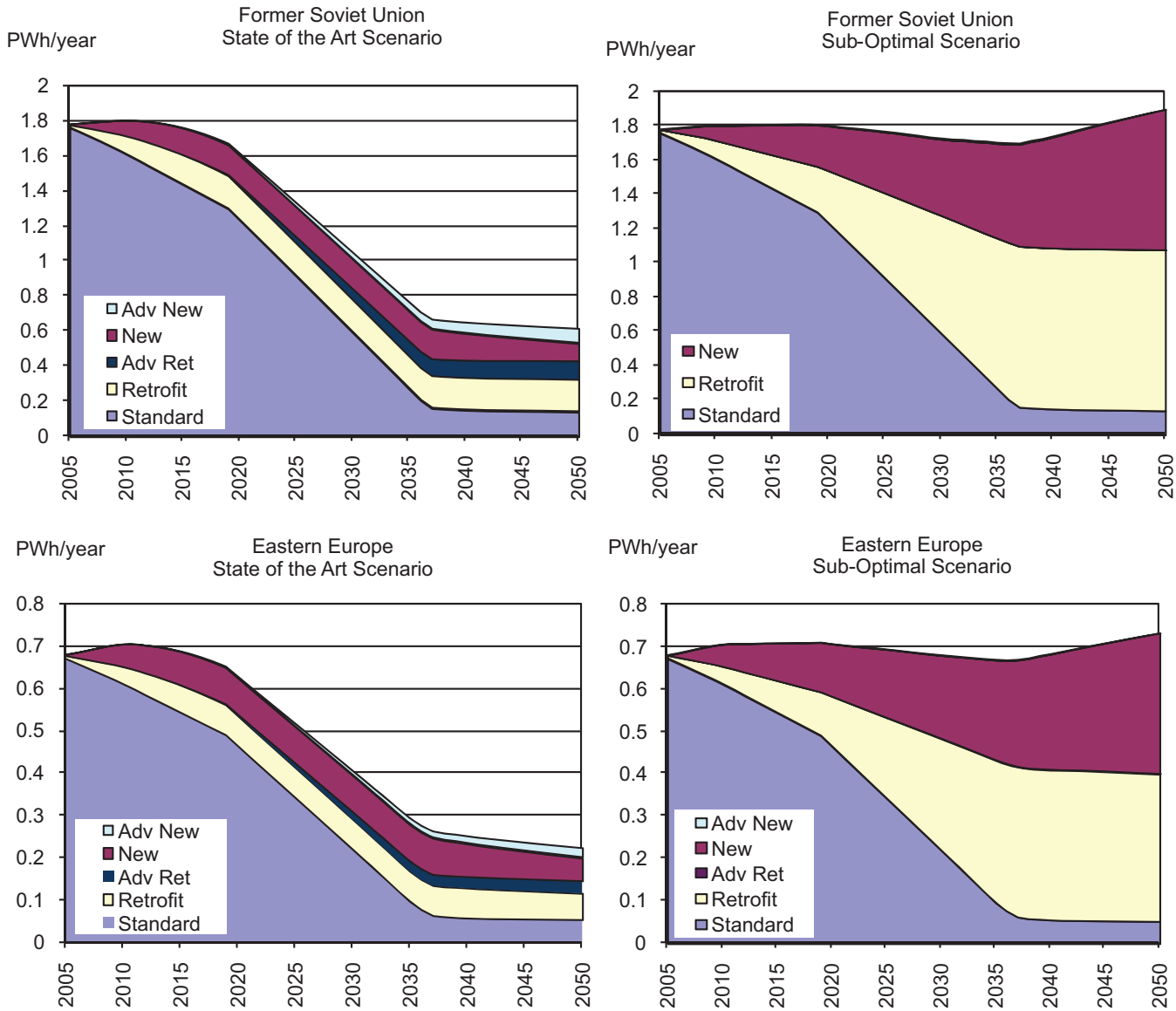

Figure 10.25 | Comparison of the two GEA building scenarios for REF regions, final thermal energy use by construction type.

fuel/energy poverty is fully eliminated by the time the entire building stock has been either replaced or renovated, i.e., before 2050 through assuming full thermal comfort to everyone. This results in significant thermal comfort increases, especially in regions having unsaturated thermal comfort levels – i.e., spaces not heated or cooled to medically acceptable levels – in all of our scenarios. As a result, it is possible that the state-of-the-art new building is actually more energy intensive than the inefficient existing ones. Traditionally, this is referred to as the rebound effect; it is important to note that the direct rebound effect has been fully considered in the scenarios. It is not possible to have more thermal comfort, since heating or cooling beyond the comfortable levels will not result in increases in well-being but rather compromises it. However, this is not considered an undesirable effect, but rather, one of the primary goals of the scenarios and an integral part of the GEA approach: to provide adequate energy service levels to those presently suffering from energy poverty or other limitations due to inadequate thermal energy services.

Investment Costs and Energy Cost Savings

Implementation of the state-of-the-art-scenario worldwide requires approximately US_{2005}\$14.2 trillion of cumulative undiscounted investments until 2050, if a 60% cost learning[27] is assumed for new technologies and know-how. This value is US_{2005}\$18.6 trillion without any cost learning. In contrast, these investments result in a US_{2005}\$57.9 trillion cumulative undiscounted energy cost saving for the same period. Figure 10.27 shows these results on cumulative investments and energy cost savings by 2050 for the different GEA regions of the world.

The cost values are calculated based on marginal expenditures as compared to standard construction and retrofit investments, and energy

27 Approximately 60% reduction in costs of low-energy buildings construction and renovation by 2030 as a result of large market size, technology learning, and optimization.

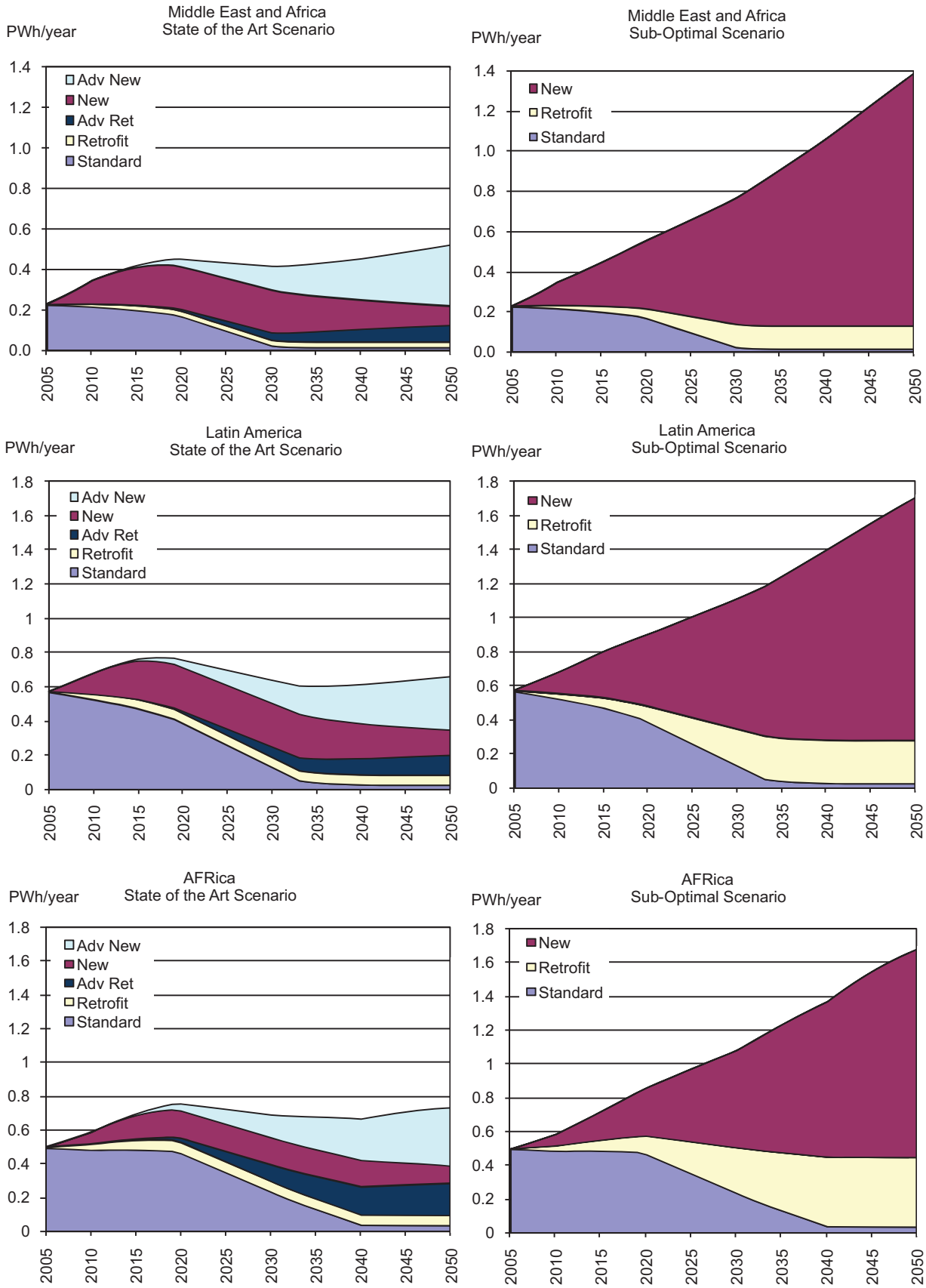

Figure 10.26 | Comparison of the two GEA building scenarios for MEA, LAC, and AFR regions, final thermal energy use by construction type.

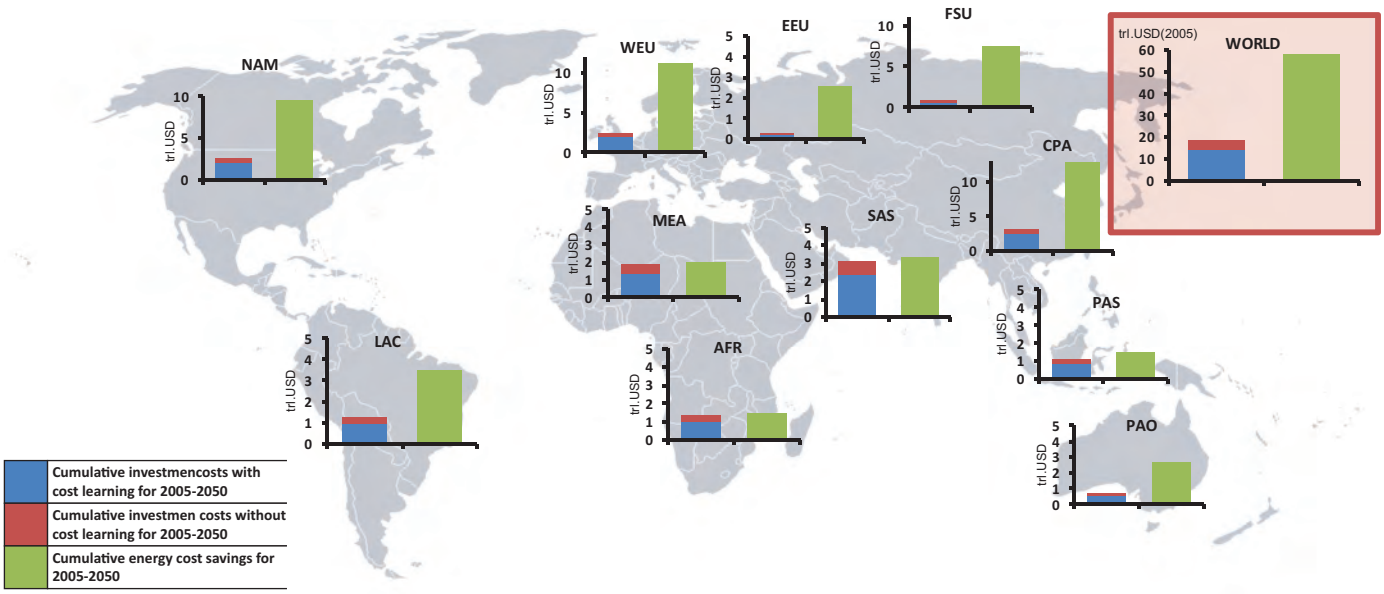

Figure 10.27 | Cumulative undiscounted investment costs and energy cost savings in different regions and worldwide, $US_{2005}$$ trillion.

cost savings as compared to a business-as-usual scenario, taking into account policies in place or in the pipeline. Energy prices and projections are based on IEA statistics and US EIA data (2010). An update of the calculations and further details of the methodology and assumptions is documented in (Ürge-Vorsatz and Petrichenko et al., in preparation).

The results presented in Figure 10.27 are comparable to other existing estimations. For example, in Laustsen (forthcoming) cumulative additional incremental investments for the period 2010–2030 in a case with considerable reduction in final energy use for heating, cooling and hot water are about $US_{2005}$$16 trillion. Cumulative investment costs for the realization of the Blue Scenario in IEA (2010a) – which assumes maximizing the deployment of energy-efficient technologies, achieving substantial renovation of three-quarters of the OECD building stock by 2050, and ensuring the widespread deployment of new technologies – are around US$12 trillion for the period 2007–2050.

Comparison of the Results with Other Existing Models

In order to verify the findings of the model, the authors have calibrated global estimations of energy use in the building sector of a few landmark and reliable recent studies. The results of the comparison are presented in detail in Ürge-Vorsatz and Petrichenko et al. (in preparation), and summarized in Figure 10.28, as well as in Table 10.14. However, it is important to note a few major points that limit how far the messages of such comparison can be interpreted. First, the GEA buildings model specifically covers the final energy use for space heating and cooling, while most other models include other end-uses – e.g., Laustsen (forthcoming) also considers domestic hot water (IEA, 2006; IIASA, 2007; IEA, 2008a; IEA, 2010a; IEA, 2010b). Moreover, methodologies, assumptions, and metrics differ among the analyzed studies. Thus, precise comparison among the models is not possible. However, the general trends can be captured. Figure 10.28 illustrates all the scenarios analyzed and Table 10.14 presents the percentage of change in thermal energy use from 2005 to 2050.

Therefore, while numbers should not be precisely compared, the figures illustrate well that most major building energy use scenarios reinforce the achievability of this sector's significant energy use reduction potential with ambitious policies, and its substantial growth without strong efforts (except WEO10 New Policy and WEO06 ALT).

The GEA Chapter 10 Online Appendix discusses, in detail, how these scenarios relate to the main GEA scenarios described in Chapter 17, and further discuss the limitations of the model.

10.6.2.6 Conclusions from the GEA Building Thermal Energy Scenarios

GEA building scenario analysis has demonstrated that building thermal energy use can significantly decrease by the mid-century despite expected growth in living space, well-being, and energy service levels, and despite the GEA assumption that fuel poverty is fully eliminated in two decades. Assuming that today's state-of-the-art becomes standard practice in new construction and retrofit, world space heating and cooling energy use can decline by 46% in 2050 from 2005 levels, in spite of the approximately 126% growth in global floor space, elimination of fuel poverty, and significant increases in thermal comfort levels. The implementation of such a scenario requires an approximately US$14.2 trillion undiscounted investment (US$18.6 trillion without technology learning), but results in US$58 trillion savings in undiscounted energy expenditures. However, while this scenario is achievable at net profit, it does require significant policy effort.

At the same time, the analysis has also demonstrated the significant risk of the lock-in effect. If policies are implemented to reduce building energy use, such as building codes and support to accelerate energy-efficient renovation, but these do not mandate the state-of-the-art,

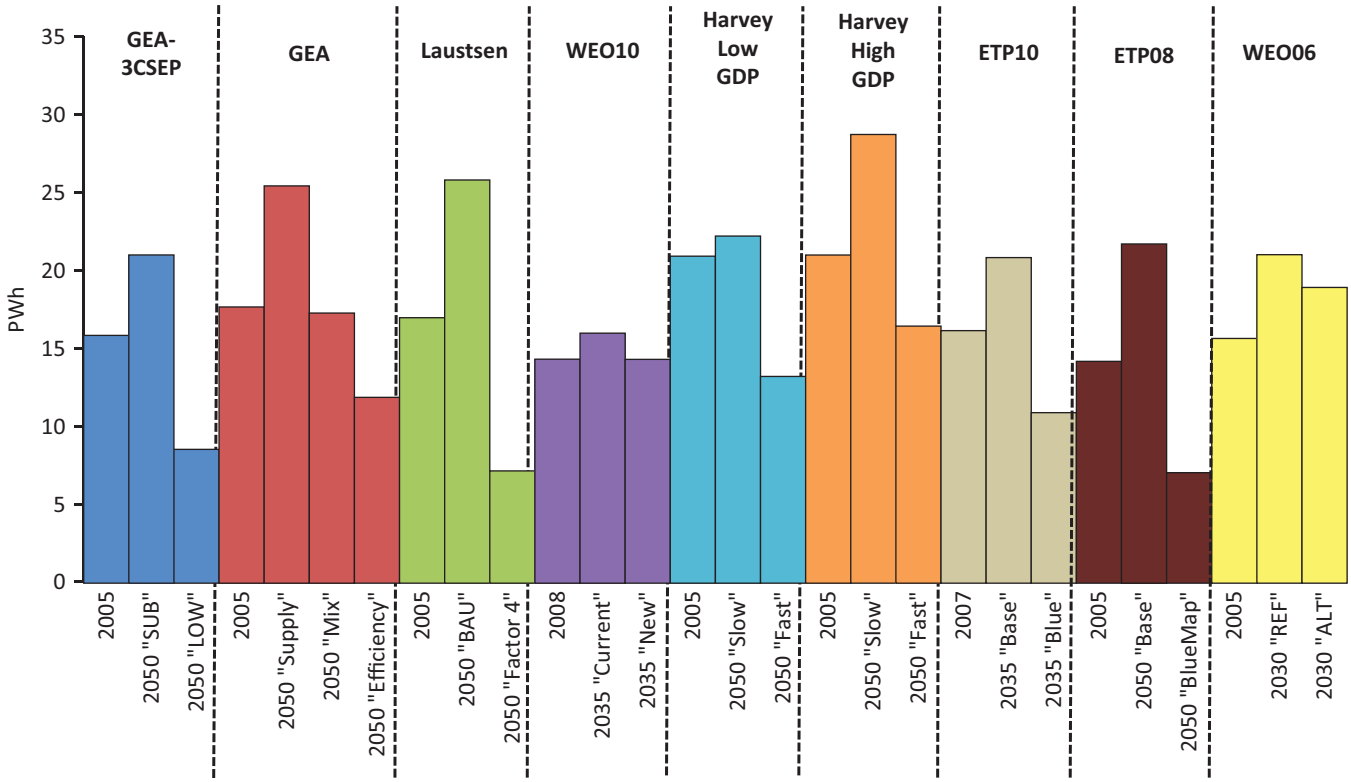

Figure 10.28 | Thermal energy use in the global building sector for different scenarios projected by different models. Source: for WEO06 ALT and WEO06 REF – IEA, 2006; for GEA Efficiency, GEA Mix, and GEA Supply – IIASA, 2007; for ETP08 ACT Map, ETP08 BlueMao, and ETP08 Base – IEA, 2008a; for Harvey Low Fast, Harvey High Fast, Harvey Low Slow, and Harvey High Slow – Harvey, 2010; for ETP10 Blue and ETP 10 Base – IEA, 2010a; for Laustsen Factor 4 and Laustsen BAU – Laustsen, forthcoming; for WEO10 New WEO 10 Current Policy – IEA, 2010b.

Note: Bars should not be compared precisely due to the reasons described in the text.

but rather only suboptimal efficiency levels, there will be substantial energy penalties; thus, energy use is locked-in for many decades due to the very long lifetime and renovation cycle of buildings. As a result, energy use increases by 32.5% by 2050 instead of a 46% decline as compared to 2005, resulting in a 79% lock-in by 2050 as expressed in terms of 2005 world building thermal energy use. Therefore, it is essential that building-related energy policies do not compromise target performance levels, and are most ambitious from as early as possible.

The state-of-the-art scenario, while extremely ambitious, can be achieved through a combination of policy instruments, of which building codes and equipment energy performance standards are the pillars. While state-of-the-art new construction is often a little more expensive than conventional new-built, it can sometimes be less expensive, and deep retrofits do incur substantial capital investments. Although these are investments that pay back well within the remaining life of the building, financing is key for renovation. Section 10.8 is devoted to exploring the policy space and the menu and effectiveness of different policy options that can take us to this more sustainable building energy future, and which are necessary for the implementation of the state-of-the-art scenario.

10.6.3 Description of Appliance Energy Scenarios

If the world embarks upon an ambitious strategy to improve the energy performance of its buildings, currently already pursued in several regions, the building energy demand toward the middle of the century may start to be dominated by electric appliances and other plug-in loads. Therefore it is paramount to also investigate the possibilities of energy savings through improved efficiency in energy-using equipment. The present section describes the potential of energy savings if very aggressive energy efficiency programs would be applied to the equipment in buildings in different world regions.

The description of the Bottom-Up Energy Analysis System (BUENAS) model, developed by LBNL, and its adoption to the GEA scenario exercise is included in the GEA Chapter 10 Online Appendix.

10.6.3.1 BUENAS Model Results

In the long term, that is, beyond 2030 and up to 2050, the efficiency improvements to the stock initiated in 2010 and enhanced in 2020

Table 10.14 | Relative change in building thermal energy use from buildings for different global scenarios.

Scenario	2005–2030	2008–2035	2005–2050
GEA-3CSEP LOW	**–26%**	**–39%**	**–46%**
GEA Efficiency	–25%		–33%
Laustsen Factor 4	–30%		–58%
WEO10 450		–8%	
WEO10 New Policy		12%	
Harvey LowFast	–9%		–37%
Harvey HighFast	–1%		–21%
ETP10 Blue		–33%	–33%
ETP08 ACT Map			–16%
ETP08 Blue Map			–51%
WEO06 ALT	21%		
GEA-3CSEP SUB	**19%**	**18%**	**32%**
GEA Mix	–2%		–2%
GEA Supply	28%		44%
Laustsen BAU	31%		52%
WEO10 Current Policy		23%	
Harvey LowSlow	23%		6%
Harvey HighSlow	40%		37%
ETP10 Base		29%	29%
ETP08 Base			53%
WEO06 REF	35%		

will have permeated the stock almost completely due to the replacement of old appliances with more efficient ones. Therefore, relative energy use of the stock after 2030 will largely scale according to the efficiency level in 2020 relative to the baseline. In order to avoid dependence on assumptions of market-driven efficiency improvements, BUENAS calculates energy savings demand versus a frozen efficiency case rather than a business-as-usual scenario. Frozen efficiency electricity demand, absolute savings, and percent savings are shown in Table 10.15.

The results show that electricity consumption for appliances studied, which is estimated at 1582 terawatt hours (TWh) in 2005, will double by 2025, and will nearly double again to 5696 TWh in 2030 in the absence of significant efficiency improvement. Much of the growth in appliance use during this period will occur in developing countries, especially in ASIA. By 2050, the OECD90 countries will still have the highest consumption for most appliances, but will be surpassed by ASIA for refrigerators, fans, and televisions, appliances that will be present in nearly all Asian households by that time.

Electricity savings will vary between appliances and regions. In absolute terms, savings in 2050 will be largest for refrigerators, with 1171 TWh, followed by standby power with 961 TWh and televisions with 842 TWh. In relative terms, standby power offers the largest opportunity for savings, with the assumption of the technical capability to reduce standby nearly to zero (0.1 W) per appliance. The total savings for all appliances is 3718 TWh, or 65% of the demand. The savings for all other appliances is 50% or greater, with the exception of washing machines in Latin America and the Caribbean. In that case, efficiency gains are expected to be largely offset by increases in capacity and market shifts from semi- to fully-automatic washing machines.

Figure 10.29 shows a graphical representation of the efficiency scenario. In this picture, appliance efficiency is currently rising rapidly, but growth will be slowed somewhat by standards in 2010, then more dramatically curtailed in 2020. From 2020 to about 2030, growth will actually be negative, and by 2030 total consumption will be roughly equivalent to 2005 levels. After that, however, the demand begins to grow again, although at a much lower rate than base case demand.

In conclusion, the scenario shows that a very significant reduction in appliance electricity demand is possible, given the current state of technologies. It is unlikely, however, that technologies common on today's market will result in energy demand that is only a small fraction of today's consumption. For that to happen, new, very high efficiency technologies must be developed, marketed, and adopted on a wider scale. Such a high tech scenario, which at this point would be somewhat speculative, is an interesting topic for further study.

Table 10.15 | Appliance electricity demand and savings in 2025 and 2050.

Appliance	Region	Demand (TWh)			Savings (TWh)		Percent Savings	
		2005	2025	2050	2025	2050	2025	2050
Refrigeration	ASIA	226	511	867	201	592	39%	68%
	OECD90	194	267	357	61	206	23%	58%
	REF	76	79	79	22	51	28%	65%
	LAC	58	100	150	40	105	40%	70%
	MEA	32	98	336	43	216	44%	64%
	Total	**586**	**1055**	**1788**	**368**	**1171**	**35%**	**65%**
Fan	ASIA	56	107	153	33	77	31%	50%
	OECD90	32	42	53	12	27	30%	50%
	REF	12	12	12	4	6	28%	50%
	LAC	16	25	36	8	18	30%	50%
	MEA	15	38	107	12	54	33%	50%
	Total	**131**	**224**	**362**	**69**	**181**	**31%**	**50%**
Washing Machine	ASIA	22	92	155	43	102	47%	66%
	OECD90	171	245	348	65	257	27%	74%
	REF	33	34	34	11	26	32%	75%
	LAC	9	16	24	3	4	18%	16%
	MEA	8	27	120	10	65	38%	54%
	Total	**243**	**414**	**682**	**132**	**455**	**32%**	**67%**
Television	ASIA	122	414	834	170	417	41%	50%
	OECD90	91	215	335	88	167	41%	50%
	REF	26	46	53	18	27	40%	50%
	LAC	24	71	124	29	62	41%	50%
	MEA	16	82	339	35	169	42%	50%
	Total	**279**	**828**	**1685**	**341**	**842**	**41%**	**50%**
Standby	ASIA	62	139	565	101	553	73%	98%
	OECD90	134	194	276	135	271	70%	98%
	REF	10	13	18	9	17	69%	98%
	LAC	15	26	46	18	45	71%	98%
	MEA	15	32	76	23	75	72%	98%
	Total	**236**	**403**	**980**	**287**	**961**	**71%**	**98%**
Oven	OECD90	96	133	181	49	98	37%	54%
	REF	10	16	18	6	10	37%	54%
	Total	**106**	**148**	**200**	**54**	**108**	**37%**	**54%**
GRAND TOTAL		**1582**	**3073**	**5696**	**1251**	**3718**	**41%**	**65%**

10.7 Co-benefits Related to Energy Use Reduction in Buildings

10.7.1 Key Messages

A future involving highly energy-efficient buildings also results in significant associated benefits – typically with monetizable benefits at least twice the operating cost savings, in addition to non-quantifiable or non-monetizable benefits now and avoided impacts of climatic change in the future. Multiple benefits beyond climate change mitigation include: improvements in energy security and sovereignty; net job creation; elimination or reduction in indoor air pollution-related mortality and morbidity; other health benefits; alleviation of energy poverty and improvement of social welfare; new business opportunities, mostly at the local level; stimulation of higher skill levels in building professions and trades; improved values for real estate and enhanced ability to rent; and increased comfort, well-being and productivity.

A survey of quantitative evaluations of such multiple benefits shows that even single energy efficiency initiatives in buildings in individual

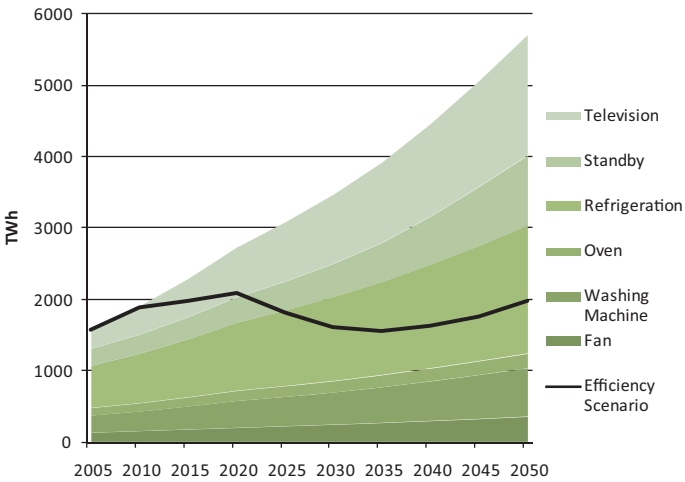

Figure 10.29 | Appliance electricity demand in base case and high efficiency scenario.

countries and regions alone have resulted in benefits with value in the range of billions of dollars annually for single benefits, such as health improvement-related productivity gains and cost aversions. Due to their significance, co-benefits can often present attractive entry points to policymaking, and point to the crucial importance of policy integration.

10.7.2 The Importance of Non-energy Benefits as Entry Points to Policymaking and Decision Making

Traditionally, energy cost savings have been regarded as a key rationale for implementing energy efficiency measures and environmental benefits for introducing policies to promote them. However, only a limited portion of such opportunities has been taken up by individuals as a result of the cost saving motivation and few policies implemented. Energy efficiency being the key strategy in climate change mitigation has provided a new rationale, giving rise to further policies that foster efficiency in developed countries. However, strong policy commitment to climate change mitigation only exists in a few countries and even there energy efficiency policies still fall very short of capturing the potential for cost-effective efficiency.

This section demonstrates that co-benefits are very significant in the building sector and offer new entry points into policy- and decision making. In jurisdictions where environmental benefits do not play a strong role in public policy, other benefits, such as poverty alleviation, employment creation, or improved energy security may be important enough to motivate such policies. For private decision makers, for whom energy cost savings are not sufficient to take steps, other benefits, such as improved comfort and health or corporate productivity gains, can unlock action.

While a single benefit, such as climate change mitigation, energy cost saving, or energy security gains, may not be sufficient to motivate action to capture saving potentials or to fare positive in a cost-benefit calculation, considering multiple benefits together may help the total benefits significantly outweigh the costs, or be sufficient motivation to enable action. However, this is only possible if public policymaking frameworks are adequately integrated to allow benefits in such otherwise disjointed areas to be combined. Private decision makers can take advantage of multiple benefits in decision making if tools are available that facilitate complex, integrated assessments of costs and benefits.

This section focuses on demonstrating the significance of co-benefits to sustainable energy action in buildings in several areas to illustrate that they are sufficient enough for offering alternative avenues for decision- and policymaking.

10.7.3 Typology of Benefits Of Energy Efficiency And Building-Integrated Renewable Energy

The co-benefits – often also called non-energy benefits – of energy efficiency and distributed energy generation in buildings are numerous. Many of the existing studies do not give an explicit classification of these benefits in the building sector. One classification is proposed by Skumatz and Dickerson (1997). They group non-energy benefits depending on the recipient: as (1) energy efficiency program participants, e.g., increased comfort, improved health; (2) society, e.g., cleaner outdoor air, employment creation, lower energy prices; or (3) a utility, e.g., lower bad debt write-off, decreased transmission costs. In addition, there are a few classifications of benefits of energy efficiency and GHG emission mitigation in general that might be applied to the benefits of energy-using sectors. For instance, Davis et al. (2000) suggest three categories of co-benefits: health, ecological, and economic and the IPCC (2007) lists co-benefits in the buildings sector in a similar way adding improved social welfare and poverty alleviation. Table 10.16 classifies co-benefits of energy efficiency in the buildings sector synthesizing these approaches. Table 10.16 also contains indicators showing how specific benefits can be measured. Once quantified, and with certain caution, many of these figures could be monetized and integrated into cost-benefit assessments of energy efficiency and saving actions. The following sections elaborate on a selection of co-benefits, avoiding repetitions of previous assessments.

10.7.4 Health Effects

The existing links between public health and the use of energy at home have been explored and quantified following two main directions: the health impacts of indoor and outdoor (regional) pollution, and the health impacts of inadequate access to energy, mostly heating in regions with a cold season. That way, it is likely that the most important health non-energy benefit of providing more energy-efficient solutions in buildings is the large number of lives that could be potentially saved through the provision of safe, clean, and energy-efficient cooking plus heating and lighting equipment in developing countries for population segments not

Table 10.16 | Typology of benefits of energy efficiency and distributed energy use in the buildings sector and selected indicators for their potential quantification.

Category	Non-energy benefits	Examples of indicators and concepts for its quantification
Health effects	Reduced mortality	Mortality risk (acute and chronic), Years of Life Lost (YLL), Loss of Life Expectancy (LLE), Value of a Life Year (VOLY), Value of a Statistical Life (VSL), hedonic wages.
	Reduced morbidity and other negative physiological effects	Avoided hospital admissions, Restricted Activity Days (RAD), Years Lived with Disability (YLD), Disability Adjusted Life Years (DALY), Quality Adjusted Life Years (QALY), Cost of Illness (COI: direct medical costs plus cost to the society from lost earnings), productivity loss and lower learning performance.
Ecological effects	Reduced impacts on ecosystems and crops	Acidification, eutrophication, exposure to tropospheric ozone, atmospheric deposition of pollutants, critical loads, number of protected hectares, Potentially Disappeared Fraction (PDF)
	Construction and demolition waste reduction	Percentage of reduction in construction and demolition wastes.
	Lower water consumption and sewage production	Percentage of reduction in water consumption and sewage production,
Economic effects	Lower energy prices[1]	Inverse price elasticity of supply.
	Employment creation[2]	Employments per unit of investment, multiplier effect, working age population relying on unemployement benefits,
	New business opportunities	New market niches
	Rate subsidies avoided[3]	Decrease in the number of subsidized units of energy sold, percentage of the energy price subsidized,
	Enhanced value of the buildings capital stock.	Higher resale and rental prices.
	Energy security	Reduced dependence on imported energy,.
	Improved productivity	Drop in absenteeism rates, reductions in voluntary terminations, GDP/income/profit generated.
Service provision benefits	Transmission and distribution loss reduction	Value of eliminated energy losses.
	Fewer emergency service calls	Saving staff time and resources necessary for attending the calls.
	Utilities' insurance savings[4]	Decrease in the insurance costs of utility companies.
	Lower bad debt write-off[5]	Decrease in the average size of bad debt written off, decline in the number of such accounts.
Social effects	Fuel poverty alleviation	Reduced expenditures on fuel and electricity; reduced fuel / electricity households debt; reduced excess winter deaths.
	Increased comfort	Mean household temperature,reduction of outdoor noise infiltration (dB).
	Safety increase (fewer fires)	Reduced number of fires and fire calls.
	Increased awareness	(Conscious) reductions in energy use, higher demand for energy efficiency measures.

Notes:
1. However, it is unlikely that initiatives at local, regional or even national scales bring sufficient reductions in the overall energy demandto affect prices set internationally.
2. To be incorporated as a benefit into cost-benefit analysis, only net employment creation can be accounted for.
3. Rate subsidies can be defined as lower, subsidized rates provided by utilities for their low-income customers (Schweitzer and Tonn 2002).
4. Reducing gas leaks and repair of faulty appliances (as a part of weatherization programs) decreases the insurance costs of utility companies.
5. Writing off the portion of a bad debt which is not paid by customers to the utilities (Schweitzer and Tonn 2002).

having access to clean energy sources. The health benefits of avoiding the inefficient indoor burning of traditional biomass and other solid fuels is thoroughly discussed in Chapter 4; it could translate into avoiding up to 1.5 million deaths/yr by 2030 (IEA, 2010d).

Providing access to cleaner fuels like LPG and more efficient stoves with enhanced ventilation systems would substantially improve in-house air quality and reduce household fuel collection and cooking time (Hutton et al., 2007). Furthermore, indoor air pollution is also a health concern in developed countries because of problems related to inadequate ventilation (Kats, 2005) and the so-called Sick Building Syndrome (SBS), discussed earlier in the chapter, which result in low work and learning performance and loss of productivity (WHO, 2000). Improving building ventilation and insulation allows the control of air exchange rates and reduces indoor air pollution and outdoor noise infiltration (Jakob, 2006). This provides opportunities for enhancing public health protection through retrofitting and weatherization programs.. In particular, state-of-the-art buildings eliminate, or significantly reduce, the health effects of indoor radon, dampness and mold, house dust mites, Volatile Organic Compounds (VOCs), NO_2, and secondhand tobacco smoke (see Chapter 4).

The buildings sector will also play a role in reducing mortality and morbidity if energy-efficiency and -saving programs are able to reduce outdoor air pollution, thus lowering end-use energy demand, especially

when emissions arise from the direct combustion of fossil fuels like coal and oil for heating and cooking (see Chapter 4). Many studies (Aunan et al., 2000; Samet et al., 2000; DEFRA, 2004; Rypdal et al., 2007; van Vuuren et al., 2008) have translated the reduction of human mortality and morbidity stemming from outdoor air quality improvements and climate policies into monetary terms. In the European Union, large research initiatives such as ExternE (Bickel and Friedrich, 2005), NEEDS (Ricci, 2009), and CASES (FEEM, 2008) have identified and put an economic value on the negative health-related externalities of the life cycle of energy provision that can also be avoided through energy demand reductions.

Additionally, connections have been established between cold and damp houses and excess winter deaths, respiratory illness, asthma, and impaired mental health (Morrison and Shortt, 2008). Therefore, improving building capital stocks for fuel poverty alleviation is also expected to generate physical health (Clinch and Healy, 2001) and psychosocial and mental health benefits related to warmer indoor environments, as discussed in Chapter 4. Such weatherization programs are especially beneficial in countries with poor housing conditions, where the problem of fuel poverty is especially acute (Clinch and Healy, 1999).

10.7.5 Ecological Effects

Reducing energy use in buildings results in a lower concentration of outdoor air pollutants (NO_x, NH_3, SO_2, VOC, or PM) that damage ecosystems and crops, which will then be better protected against acidification and eutrophication and less exposed to elevated ground level tropospheric ozone concentrations (EEA, 2006; van Vuuren et al., 2008). This includes the reductions in of various negative externalities like the impacts of acid rain and ozone in forests and the effects of acidification on recreational fisheries, as well as a reduction in noise pollution, visual amenity disruption, and major accident risks (European Commission, 1995). A growing body of literature on the economic value of ecosystem services (Costanza et al., 1997; Torras, 2000; CBD, 2001; Hein et al., 2005; Nahuelhual et al., 2007) provides a basis to establish a connection between energy efficiency and saving actions and enhanced ecosystem services provision.

Retrofitting and weatherization programs also extend the lifetime of buildings and increase resource use efficiency. For instance, Kats (2005) and SBTF (2001) estimated that building green and efficient houses could reduce construction and demolition wastes over 50%, and up to a maximum of 99%, as compared to an average practice. In the United States, Schweitzer and Tonn (2002) found significant reductions in water consumption and sewage production over the lifetime of energy-efficiency measures, i.e., low-flow showerhead and faucet aerators. Since building construction, operation, and decommissioning are energy-using activities, as is water provision and treatment (see Section 10.1.4), longer building lifetimes and lower resource consumption will bring about reduced amounts of embodied energy and GHG emissions.

10.7.6 Economic Effects

Creating employment and enhancing the overall productivity of the economy are broad macroeconomic goals that energy efficiency and saving programs can help to achieve. In underdeveloped, often rural regions the lack of modern energy is a primary cause of poverty. Improving energy efficiency would result in better energy security and less dependence on imported energy sources (IEA, 2004; Behrens and Egenhofer, 2007). Also other co-benefits, such as the increased value of real estate and lower energy prices, have welfare implications for households.

Characteristics of buildings and indoor environments significantly influence rates of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker performance (Fisk, 2000). Related to that, productivity increase at the micro level has been documented and may reach about 6–16% in efficient buildings (Lovins, 2005), which translates into direct financial benefits: a 1% increase in productivity, ~5 minutes/employee/day, is calculated at US$600–700/employee/yr or US$3/ft2/yr in the United States (Kats, 2003).

Research also indicated that investing in energy efficiency renovation in the buildings sector has positive net employment effects once job losses in energy supply sectors are accounted for. Given the distributed nature of direct, indirect, and induced employment effects, additional jobs are expected to be geographically widespread (for Hungary, see Ürge-Vorsatz et al., 2010). The experience has pointed at spatial overlaps of fuel poverty and high unemployment. Promoting energy-efficient renovations in fuel poverty affected areas will benefit fuel-poor households by also providing additional income-earning opportunities (ACE 2000).

10.7.7 Service Provision Benefits

Improvement of energy efficiency and emission reduction in the buildings sector may result in higher quality provision of a number of energy-related services. This category of co-benefits include, inter alia, transmission and distribution (T&D) loss reduction, fewer emergency service calls, utilities' insurance savings, and lower bad debt write-off (Schweitzer and Tonn, 2002; Stoecklein and Skumatz, 2007). Even though these are mostly related to the functioning of utility companies, they can well translate into economic benefits, i.e., positive welfare changes, as long as similar comfort and service provision levels are achieved with fewer resources.

10.7.8 Social Effects

Energy efficiency in the buildings sector can also contribute to tackling social issues, such as poverty and fuel poverty. High-efficiency retrofitting of the existing building stock or the construction of near-zero-energy new buildings, can alleviate, and in some cases fully eliminate, fuel poverty. This, in turn, saves large amounts of public funds that are being spent on relief for those in fuel or energy poverty.

In general, improved domestic, corporate, and public energy efficiency lowers energy expenditures, therefore leaving higher disposable incomes for bill payers, and thereby improving social welfare.

In addition to immediate social co-benefits – including higher thermal comfort levels, noise protection, and improved indoor air quality – there is an increase in safety – namely fire prevention, as well as a number of long-term social benefits. The conveniences of education and health have far-reaching societal consequences on the development of equity, citizens' rights, and gender and child protection.

10.7.9 Worldwide Review of Studies Quantifying the Impact of Benefits Related to Energy Savings in the Built Environment

When societal interests are considered, many of the identified co-benefits related to improved building energy efficiency should be included in economic cost-benefit assessments that support decision-making processes and to determine whether certain measures or actions are justified on a societal basis or not. Similarly, non-energy benefits, especially those obtained at micro (household or firm) level, are important determinants of private decision making. At the same time, there are a limited number of potential studies or other cost-benefit assessments related to energy efficiency and GHG emission mitigation strategies that incorporate such benefits into the analysis.

Table 10.17 reviews the literature that is available in the public domain that has quantified non-energy benefits in the building sector. Typically these studies quantify physical impacts of energy conservation or GHG mitigation and monetize them. The survey revealed that different types of co-benefits have been examined to different extents. For instance, the effects of reducing outdoor air pollution – e.g., avoided morbidity and mortality – and productivity gains have been intensively studied. The authors were unable to locate research on the quantification of co-benefits such as new business opportunities and costs avoided due to increased awareness.

Most studies focus only on a few regions. The United States is subject of many studies, followed by only a few countries of the European Union. No studies were found that aggregated the quantified co-benefits, especially at regional or national levels. A global aggregation would be especially challenging, because ideally such an effort applies a uniform methodology and approach which has not yet been possible for potential assessments either.

10.8 Sector-Specific Policies to Foster Sustainable Energy Solutions in Buildings

10.8.1 Key Messages

- A wide range of policies has been demonstrated that are successful and cost-effective in reducing energy use in buildings. These include stringent and well enforced building and appliance standards, codes, and labeling, applying also to retrofits.
- Urgent introduction of strong building codes mandating near-zero-energy performance levels, progressively improving appliance standards, as well as strong promotion of state-of-the-art efficiency levels in accelerated retrofits of the existing building stock are crucial. Particular attention should also be paid to addressing non-compliance related to building codes. However, net-zero-energy building mandates may be not feasible for every type of building and in all regions, and in many cases their economics are unfavorable compared to high-efficiency buildings. Policy instruments to encourage deep retrofits should be implemented, including performance standards, performance contracting, energy audits and incentive mechanisms.
- Appropriate energy pricing is fundamental for promoting energy efficiency in buildings. Taxation provides an impetus for a more rational use of energy sources, but especially in poor regions or population segments, subsidies of highly efficient capital stock can be more effective and acceptable.
- Awareness campaigns, education, and the provision of more detailed and direct information, including smart metering, enhance social and behavioral changes. Combining regulation, incentives and information measures has the highest potential to increase energy efficiency in buildings.

10.8.2 Overall Presentation and Comparison of the Policy Instruments

The previous sections, in addition to earlier work, have demonstrated that there is a very broad spectrum of technologies and know-how that can save significant amounts of energy in buildings without compromising the level of energy services provided, often at net societal benefits rather than costs (Levine et al. 2007; Ürge-Vorsatz et al., 2007). Much of this potential though has not been captured due to the especially strong and diverse barriers that prevail in this sector. However, many of these barriers can be removed or lowered by appropriate policies, programs, and measures.

Table 10.17 | Benefits of GHG mitigation in the buildings sector and methodologies for their assessment in the worldwide literature.

Co-benefits	Country/ region	Impact of GHG emissions or energy demand reduction		References
		Physical indicator	Monetary indicator	
Health effects				
Morbidity and other negative physiological effects reduction	USA, New Zealand, Denmark	• USA: Improved indoor air quality reduced asthma occasions by 38.5%; a 25% reduction in asthma incidence in an average 900-student school translates into 20 fewer children/yr. with asthma. • Denmark: The improvement of thermal air quality led to better concentration of 15% of respondents and a 34% decrease in the number of respondents with sick building syndrome.	• USA: Ventilation increased may result in net savings of US_{2005}\$527/employee-yr. that represent the productivity lost on a national scale of US_{2005}\$30 billion/yr. • USA: Better ventilation and indoor air quality could reduce influenza and cold by 9–20% in population (ca. 16–37 million fewer cases) that translates into annual savings of US_{2005}\$7.5–17.4 billion.	National Medical Expenditure Survey, 1999; Kats, 2005 Milton et al., 2000; Schweitzer andTonn, 2002; Stoecklein andSkumatz, 2007; Fisk,1999
Mortality reduction	Hungary; USA, Ireland, Norway, worldwide	• USA: Every 10 g/m^3 increase in ambient particulate matter (the day before deaths occur) brings a 0.5% increase in the overall mortality. • Ireland, Norway: The share of excess winter mortality attributable to poor thermal housing standards is 50% for cardiovascular disease and 57% for respiratory disease. • Worldwide: more than 3 billion people cook with solid fuels on open fires or traditional stoves, resulting in more than 1.5 million deaths annually and a multitude of negative economic and environmental impacts.	• Hungary: The energy saving program resulted in the total health benefit of US_{2005}\$854 million/yr. due to a decrease of chronic respiratory diseases and premature mortality. • reland: the expected health-benefits (mortality and morbidity reduction) of a proposed domestic energy efficiency program amount to US_{2005}\$1.88 billion (at the 5% Irish government's discount rate) over 20 years. • Worldwide: the global annual economic benefits (incl. less expenditure on health care, health-related productivity gains, fuel collection and cooking time savings, and environmental impacts) of halving the population currently lacking access to cleaner fuels (LPG) would amount to US_{2005}\$91 billion at a net intervention cost (incl. fuel, stove, and program costs, from which monetary fuel cost savings are subtracted) of US_{2005}\$13 billion. Improving stoves would generate US_{2005}\$105 billion in economic benefits at a negative net cost of US_{2005}\$34 billion.	Aunan et al., 2000; Samet et al., 2000; Clinch and Healy, 1999; Clinch and Healy, 2001; Hutton et al., 2007
Ecological co-benefits				
Reduced impacts on ecosystems and crops	Europe	• The application of the Kyoto protocol in Europe is expected to reduce from 16.1% (93.4 million ha in 1990) to 1.5% (8.7 million ha in 2010) the share of ecosystems unprotected to acidification. The figures for areas with excess deposition of nutrient nitrogen are, respectively, 30.5% (166 million ha in 1990) and 18.8% (103 million ha in 2010).		Van Vuuren et al., 2008
Construction and demolition waste benefits reduction	USA	• The Construction and demolition diversion rates are 50–75% lower in green buildings (with the maximum of 99% in some projects) as compared to an average practice		SBTF, 2001; Kats, 2005

Continued next page →

Table 10.17 | (*cont.*)

Co-benefits	Country/ region	Impact of GHG emissions or energy demand reduction		References
		Physical indicator	Monetary indicator	
Lower water consumption and sewage production	USA	• The NPV of reduction in waste water and sewage over the measure lifetime isUS$3.4–657/ household.		Schweitzer andTonn, 2002
Economic co-benefits and ancillary financial impacts				
Lower energy prices	USA	• A 1% decrease of the national natural gas demand through energy efficiency and renewable energy measures leads to a long-term wellhead price reduction of 0.8% – 2% or 0.75% – 2.5%;		Wiser et al., 2005; Platts Res. &Consult, 2004
Employment creation	USA, EU	• USA: The US Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) macroeconomic (input-output) analysis of its energy efficiency residential and commercial buildings program found a potential to increase employment by up to 446,000 jobs by 2030. • EU: the SAVE program, based on data for 9 EU countries in the 1990s, estimated that investing in energy efficiency in residential and commercial/public buildings generated between 4.0 and 12.3 jobs per million $US_{2005}$$.		Scott et al., 2008; Wade et al., 2000
Rate subsidies avoided	USA	• The NPV of avoided rate-subsidies over the lifetime of the measures is US$6 – 70/household.		Schweitzer andTonn, 2002
Enhanced value of the buildings capital stock.	Switzerland, the Netherlands	• An economic analysis using the hedonic pricing approach shows a valuation of energy efficient windows of 2–3.5% of the selling price of existing single-family houses and reveals that new single-family houses certified with the 'Minergie' Label yield higher selling prices by almost 9% (with a standard error of about 5%) • A hedonic value analysis of the Dutch housing sector, where an early, voluntary adoption of the EU EPBD energy labeling system is in place, found out a premium in the sale value of energy-efficient properties, with a 2.8% higher transaction price in houses with an A, B, or C certificate.		Borsani and Salvi, 2003; Brounen and Kok, 2010.
Energy security	USA	• The Oak Ridge National Laboratory estimated the energy security benefits of reduced US oil use at $13.58: $8.90 coming from monopsony component plus $4.68 related to macroeconomic disruption / adjustment costs. This approach estimates the incremental benefits to society not reflected in the market price of oil, in $US_{2004}$$per barrel, of reducing US imports.Omitted from this "oil premium" calculation are environmental costs and possible non-economic or unquantifiable effects, such as effects on foreign policy flexibility or military policy		Leiby, 2007
Improved productivity	USA	• In efficient buildings labor productivity rises by about 6–16%; students' test scores shows ~20–26% faster learning in schools well day lighted; retail sales can rise 40% in well day lighted stores	• Estimated potential annual savings and productivity gains of better indoor environments related with building energy efficiency in the $US_{2005}$$7.5–17.4 billion (reduced respiratory diseases); $US_{2005}$$1.2–5 billion (reduced allergies and asthma); $US_{2005}$$12.5–37.3 billion (reduced sick building syndrome symptoms); and $US_{2005}$$25–200 billion (direct improvements in worker performance unrelated to health)	Lovins, 2005; Fisk, 2000; Kats, 2003;

Service provision benefits				
T&D loss reduction	USA	• The NPV over the lifetime of the measures installed ranges US$33–80/household.		Schweitzer andTonn, 2002
Fewer emergency gas service calls	USA	• The NPV of fewer emergency gas service calls over the measure lifetime is US$39–201/ household.		Schweitzer andTonn, 2002
Utilities' insurance savings	USA	• The NPV of utilities insurance cost reduction over the lifetime of the measures is US$0–2/ household		Schweitzer andTonn, 2002
Decreased number of bill-related calls	New Zealand	• Bill-related calls became less frequent after the implementation of weatherization program, which amounted savings of $US_{2005}$$24.6 /household-yr, that is 7% of the total saved energy costs		StoeckleinandSkumatz, 2007
Lower bad debt write-off	USA	• The NPV of lower bad debt write-off over the lifetime of the measures is US$15–3462 / household.		Schweitzer andTonn, 2002
Social co-benefits				
Fuel poverty alleviation	UK	• UK: Energy efficiency schemes applied to 6 million households in January-December 2003 resulted in an average benefit of $US_{2005}$$19.9/household-yr.		DEFRA, 2005
Increased comfort,	Ireland, New Zealand, Switzerland	• Ireland: the mean household temperature once completed the proposed domestic energy efficiency program increases from 14 to 17.7 °C. • Switzerland: old windows reduce the level of external noise in the interior of the building by about 20–25 dB, whereas new ones achieve 33–35 dB. 38–40 dB reductions are also possible if asymmetric triple glazing is applied	• Ireland: The total comfort benefits of a proposed domestic energy efficiency program amount to $US_{2005}$$748 million discounted at 5% (Irish government's discount rate) over 20 years; • New Zealand: Comfort (including noise reduction) benefits gained after the implementation of weatherization program amount to $US_{2005}$$130.3/household-yr, equivalent to 43% of the saved energy costs.	StoeckleinandSkumatz, 2007; Jakob, 2006; Clinch and Healy, 2001
Safety increase (fewer fires)	USA	• The NPV over the lifetime of the measures installed is US$0–555/household.		Schweitzer andTonn, 2002

Note: (i) conversion of monetary units to $US_{2005}$$ was done whenever possible by applying Consumer Price Index (CPI) and exchange rates of the corresponding years or periods and nations.

A great variety of policy instruments have been implemented worldwide to promote energy efficiency in the buildings sector. There is no single policy instrument that can capture the entire energy saving potential. Due to the especially diverse and strong barriers in this sector, it requires an equally diverse portfolio of policy instruments for effective and far-reaching energy conservation. Policy instruments for promoting energy efficiency in the buildings sector can be classified in five major categories, namely:

- *Control and regulatory mechanisms*, which are institutional rules aimed at directly influencing the energy performance of buildings and/or energy equipment used in buildings. Policy instruments classified in this group include appliance standards, building codes, procurement regulations, energy efficiency obligations, quotas, etc.

- *Regulatory informative instruments*, which are also institutional schemes that aim to inform energy users about energy efficiency. These comprise mandatory labeling and certification programs, mandatory audit programs, utility demand-side management programs, etc.

- *Economic and market based instruments*, such as energy performance contracting[28], cooperative technology procurement, energy efficiency certificate schemes, the Kyoto flexible mechanisms, regional carbon trading platforms and carbon offset programs, etc. These are directly or indirectly aimed at steering economic actors toward improved energy efficiency.

- *Fiscal instruments*, which usually correct energy prices through either the implementation of taxes, tax exemptions or reductions, public benefit charges, the removal of fossil fuel subsidies, etc., or by providing financial support, e.g., capital subsidies, grants, subsidized loans, rebates, property-assessed clean energy (PACE)[29] financing, etc., if first cost-related barriers are to be addressed.

- *Support and information programs and voluntary action*. Instruments classified under this group are very diverse and comprise voluntary certification and labeling programs, voluntary agreements, public leadership programs, awareness-raising, education and information campaigns, detailed billing and disclosure programs, the establishment (and sufficient funding) of energy agencies, awards and competitions, personalized advice, training of building professionals, etc.

Table 10.18 | Indicators of Cost-effectiveness of policy instruments based on best practice cases.

	High	Medium	Low
cost of energy conserved US_{2005}\$/kWh	<0	0 – 0.01	>0.01
benefit-cost ratio (B/C)	>1	0.8 – 1	<0.8

In this section, the final effects of key categories of policy instruments used in the building sector to improve energy efficiency are reviewed and evaluated. In total, over 80 studies, review articles, and other relevant publications were identified from over 50 countries, covering each inhabited continent. Experts agree that even a brilliantly designed policy tool may lose its value if inadequately enforced. However, the greatest attention is usually given to policy design, whereas implementation and enforcement processes are often neglected (Khan et al., 2007). Due to this reason, special attention was given to limitations and success factors.

Recent reviews (Khan et al., 2007; Novikova, 2010) examined the outcomes of policies. These are: (a) the degree to which a policy tool achieves the target, often referred to as policy effectiveness; (b) the extent to which a tool has made a difference compared to the situation without it, referred to as net impact of the policy tool; and (c) the relationships between the net impact and spending required, referred to as cost-effectiveness. What follows is summarized from perspectives of effectiveness for energy saving and cost-effectiveness of policy tools. Also, the best attempt has been made to identify limitation and success factors.

Since studies reviewed used different methodologies for evaluation of policy effectiveness, these estimates were converted to a uniform format. For each implemented policy case study, the amount of energy saved as a result of the policy instrument in question was determined, both in absolute and relative terms – i.e., compared to a logical baseline, such as total national energy or electricity consumption in the particular sector and/or end-use. However, this was often not possible due to lack of data. Furthermore, the comparability of these estimates with other cases or policy instruments is in many cases very limited. Thus, the effectiveness of the various policy instruments examined was evaluated in a qualitative way, by assigning grades of "low," "medium," and "high" based on energy saving figures, but taking into account the overall applicability and potential of the instrument. The effectiveness of policies working in limited end-use categories was balanced with those affecting most end-uses; if the instrument works in a narrow energy end-use but can achieve an important reduction in that category, such as appliance standards, it could qualify as "high." (See Table 10.18.)

The cost-effectiveness of the policy instruments examined was also evaluated with qualitative grades, which are based on best practice cases and on the approximate ranges presented in Table 10.18.

28 Energy performance contracting is not a policy tool *per se*, but a business model that delivers a similar impact on transformation of the market toward higher energy efficiency as policy tools. Due to this reason, energy performance contracting is often added to policy tools.

29 The PACE model is a relatively new financing structure that enables local governments to raise money through the issuance of bonds or other sources of capital to fund energy efficiency and renewable energy projects, thus lowering the up-front cash payment for property owners. The financing is repaid over a set number of years through a special tax or assessment only on those property owners who voluntarily choose to attach the cost of their energy improvements to their property tax bill. The PACE approach attaches the obligation to repay the cost of improvements to the property, not the individual borrower, creating a way to pay for the improvements if the property is sold.

The comparative assessment of policy instruments presented in Table 10.19 reveals significant differences between them, especially concerning cost-effectiveness. The governmental costs of policy tools in the sample varied widely: figures ranged between -0.13 US_{2005}\$/kWh (i.e., a significant net benefit) and 0.11 US_{2005}\$/kWh. Despite the fact that economic performance of the policy instruments examined is presented in a variety of forms – i.e., economic cost or benefit per unit energy saved, benefit-cost ratio, total amount of estimated savings, etc. – making comparative evaluation extremely difficult, it can be generally stated that appliance standards, energy efficiency obligations and quotas, utility demand-side management (DSM) programs, and tax exemptions were found to be the most cost-effective policy tools in the sample, all achieving significant energy savings at negative costs in several applications. Regarding effectiveness for energy saving overall, appliance standards, building codes, labeling, utility DSM programs, and tax exemptions achieved the highest savings in the sample. More specifically, the implementation of building codes and tax exemptions (investment tax credits) policies in the United States are the two single policy instruments in the sample that have resulted in the maximum absolute energy savings, amounting to 174 TWh/yr each.

When comparing the five different categories of measures, the collected case studies indicate that regulatory and control measures are probably the most effective in terms of energy savings as well as the most cost-effective category, at least in developed countries. They all achieved ratings of high or medium according to both criteria, i.e., effectiveness and cost-effectiveness. Measures that can be designed both as voluntary and as mandatory, such as labeling or energy efficient public procurement policies, have been revealed as more effective when they are mandatory. The Mesures d'Utilisation Rationnelle de l'Energie (MURE) database (MURE, 2007; 2008), which collects and evaluates ex-post estimates of energy savings delivered by policies in the European Union member states and their neighbors, confirms the findings above.

The effectiveness of economic instruments varies, but some of them, such as energy performance contracting (EPC) and cooperative procurement, are promising. Project-based instruments that require credits for savings, e.g., white certificates, may have limited effectiveness due to the complex nature of buildings and resulting high transaction costs, the many efficiency upgrades, and the small project size, if complex monitoring and evaluation are required, but can otherwise be highly cost effective (Eyre et al., 2009).

Fiscal instruments also vary considerably in effectiveness and have numerous success conditions. For instance, in the short run, instruments that increase the energy price such as taxation are often less effective than fiscal incentives for capital investment in energy efficiency, such as tax exemptions, loans, and subsidies, due to the limited energy price elasticity in buildings – i.e., the percentage change in energy demand associated with each 1% change in price. Financing grants and rebates are especially needed in both developed and developing countries, particularly for low-income households, because the first cost barrier often prevents energy efficiency improvements. In general, tax exemptions were found to be the most effective tool in the category of fiscal instruments, while subsidies, grants, and rebates can also achieve high savings, but are usually costly to society.

Voluntary instruments vary in effectiveness that depends, for example, on the demand for energy-efficient products in the case of voluntary labeling and on whether the companies take voluntary commitments seriously. Though they have often failed to reach their goals, they can be a good starting point for countries that are just introducing building energy efficiency policies or when mandatory measures are not possible. Private sector commitments may be more effective where there is the clear prospect of regulation as an alternative, i.e., where they are in the context of negotiated agreements rather than purely voluntary. Finally, information instruments can be effective, but have to be specifically tailored to the target group.

Identification of the most cost-effective instruments was much more difficult because for some instruments, no quantitative information could be found. In the assessed sample, appliance standards, mandatory audits, utility demand-side management programs, mandatory labeling, energy efficiency obligations, energy performance contracting, cooperative procurement, and tax exemptions seem to be the most cost-effective policy measures. Thus, the category of regulatory and control instruments is apparently also the most cost-effective one, in contrast to a generally prevailing expectation that economic instruments are the most cost-effective (IPCC, 1995). These findings are partly confirmed by the MURE database. Such results are specific to the building sector, and might be explained by considering which barriers specific policy instruments address and the low sensitivity to prices of most non-intensive energy users.

Table 10.20 summarizes the major barriers and corresponding potential policy instruments to overcome them.

10.8.3 Combinations or Packages of Policy Instruments

Every policy measure is tailored to overcome one or a few market barriers, but none can address all the barriers and all targets and target groups. In addition, most instruments achieve higher savings if they operate in combination with other tools, and often these impacts are synergistic, i.e., the impact of the two is larger than the sum of the individual expected impacts (IEA, 2005b). Figure 10.A.8 in the GEA Chapter 10 Online Appendix diagrams the combined effect of the three policy instruments: appliance standards, labeling, and financial incentives.

A number of combinations of policy instruments are possible, as illustrated in Table 10.21. Usually, combining sticks (regulations), and carrots (incentives), with tambourines (measures to attract attention such as information or public leadership programs) has the highest potential to increase energy efficiency (Warren, 2007) by addressing a number of barriers.

Table 10.19 | Comparative assessment of all policy instruments from a governmental standpoint.

Policyinstrument	Country/ regions examples	Effective-ness	Energy reductions for selected best practices	Cost-effectiveness	Cost of energy reduction for selected best practices in $US_{2005}$$	Special conditions for success, major strengths and limitations, co-benefits	References
Control and regulatory mechanisms – normative instruments							
Appliance standards	EU, USA, JPN, AUS, BRA, CHN, MAR, DEU, NLD	High	DEU: app. 214 GWh/yr USA: 129 TWh in 2000 = 2.5% of electricity use, 6% = 252 TWh in 2020 NLD (coupled with rebate): 0.06 TWh/yr. in 1995–2004	High / Medium	AUS: -0.13$/kWh EU: -0.08$/kWh USA: -0.05$/kWh MAR: 0.009$/kWh NLD: 0.07–0.11 $/kWh	Factors for success: periodic update of standards, independent control, information, communication and education	IEA 2005b, Schlo-mann et al. 2001, Gillingham et al. 2004, ECS 2002, WEC 2004, Australian GHG office 2005, IEA 2003, Fridley and Lin 2004, Khan et al.2007
Building codes	SGP, PHL, HKG, EGY, USA, UK, NLD, CHN, EU	High	HKG: 1% of total el. saved USA: 174 TWh in 2000 EU: up to 60% energy savings for new dwellings CHN: 15–20% of bdg. energy saved in urban regions NLD: 0.2 TWh/yr. or 0.1% of the sectoral reference energy use in 1996–2004	Medium	NLD: 0.02–0.05$/kWh for society, -0.09 – -0.002 $/kWh for end-user	No incentive to improve beyond target. Only effective if enforced.	WEC 2001, Lee and Yik 2004, Schaefer et al. 2000, Joosen et al. 2004, Geller et al. 2006, ECCP 2001, IEA 2005a, DEFRA 2006c, Khan et al 2007
Procurement regulations	USA, EU, CHN, MEX, KOR, JPN	High	MEX: 4 cities saved > 5,000 MWh in 1 year CHN: 4.6 TWh expected EU: 52–115 TWh potential EU: Energy+ programme for cold appliances 0.3 TWh/yr. in 1999–2004 USA: 18–61.6 TWh by 2010	Medium	MEX: $1million in equipment purchases saves $ 726,000/yr. in electricity costs EU: 0.007$/kWh EU: Energy + programme for cold appliances 0.001$/kWh	Factors for success: Enabling legislation, energy efficiency labelling and testing. Energy efficiency specifications need to be ambitious.	Borg et al. 2003, Harris et al. 2005, Van Wie McGrory et al. 2006, Gillingham et al. 2006, Khan et al 2007
Energy efficiency obligations and quotas	UK, BEL, FRA, ITA, DNK, IRL	High	UK: In 2002–2005: 2.5 TWh/yr. or 0.5% of sectoral reference energy use; 2010 savings: 6.1 TWh of electricity, 7.4 TWh of natural gas BEL: 0.36 TWh/yr. or 0.2% of sectoral reference energy in 2003–2004	High	Flanders: -0.04$/kWh for households, -0.014$/kWh for other sectors UK: -0.02$/kWh UK: 0.00004 $/kWh BEL: 0.0001 $/KWh	Continuous improvements necessary: new energy efficiency measures, savings target change, short term incentives to transform markets etc.	UK government 2006, Sorell 2003, Lees 2008, Collys 2005, Bertoldi and Rezessy 2006, DEFRA 2006c, Khan et al 2007

Regulatoryinformative instruments							
Mandatory labelling and certification programs	USA, CAN, AUS, JPN, MEX, CHN, CRI, EU, ZAF	High	AUS: 6.3 TWh savings 1992–2000, 102 TWh 2000–2015 ZAF: 623 GWh/yr DNK: 8 TWh	High	AUS:-0.02$/kWh	Effectiveness can be boosted by combination with other instrument, and regular updates.	WEC 2001, OPET network 2004, HoltandHarrington 2003, IEA 2003
Mandatory audit programs	USA, FRA, NZL, EGY, AUS, CZE	High but variable	USA: Weatherisation pro-gram: 22% saved in weatherized households after audits (30% according to IEA)	Medium/ High	USAWeatherisation program: BC-ratio: 2.4	Most effective if combined with other measures such as financial incentives, regular updates, stakeholder involvement in supervisory systems.	WEC 2001, IEA 2005b
Utility demand-side management programs	USA, CHE, DNK, NLD, DEU, AUT, THA, JAM	High	USA: 54.7 TWh in 2004 JAM: 13 GWh/year, 4.9% less electricity use DNK: 179 GWh THA: 5.2 % of annual electricity sales 1996–2006	High / Medium	EU: -0.07$/kWh DNK: ca.-0.06$/kWh USA: average costs app. -0.05$/kWh THA: 0.01$/kWh	More cost-effectivein the commercial sector than in residences, success factors: combination with regulatory incentives, adaptation to local needs & market research, clear objectives.	IEA 2005b, Kushler et al. 2004, Evander et al. 2004, Mills 1991, Parfomak and Lave 1996, Gillingham et al. 2006
Economic and market-based instruments							
Energy performance contracting/ ESCO support	DEU, AUT, FRA, SWE, FIN, USA, JPN, HUN, CHN	High	FRA, SWE, USA, FIN: 20–40% of buildings energy saved EU: 104–144 TWh by 2010 USA: 6.3 TWh/yr CHN: 44 TWh	Medium/High	EU: mostly at no cost, rest at <0.008$/kWh USA: Public sector: B/C ratio 1.6, Private 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 2003, WEC 2004, Goldman et al. 2005, Evander et al. 2004
Cooperative technology procurement	DEU, ITA, SVK, UK, SWE, AUT, IRL, USA, JPN	Medium/ High	USA: 15–56 TWh/yr estimated by 2010 USA: 192,750 MWh saved in refrigerator procurement DEU: German telecom company: up to 60% energy savings for specific units	High/ Medium	USA: -0.07$/kWh SWE: 0.12$/kWh (BELOK-program)	Combination with standards and labelling, choose products with technical and market potential.	Oak Ridge National Lab 2001, Le Fur B. 2002, Borg et al. 2003, Nilsson 2006, Gillingham et al. 2006
Energy efficiency certificate schemes	ITA, FRA	Medium	ITA: 3.25TWh in 2006, 9.1 TWh by 2009 expected	Medium	FRA: max. 0.01$/kWh estimated	No long-term experience yet. Transaction costs can be high. Adv. institutional structures needed. Profound interactions with existing policies. Benefits for employment.	OPET network 2004, Bertoldi/Rezessy 2006, Lees 2006, Defra 2006c, IEA 2006, Beccis 2006

Continued next page →

Table 10.19 | (*cont.*)

Policyinstrument	Country/ regions examples	Effective-ness	Energy reductions for selected best practices	Cost-effectiveness	Cost of energy reduction for selected best practices in $US_{2005}$$	Special conditions for success, major strengths and limitations, co-benefits	References
Fiscal instruments and incentives							
Taxation (on household fuels)	NOR, DEU UK, NLD, DNK, CHE, SWE	Low/ Me-dium	DEU: household energy usereduced by 0.9 % in 2003: app. 10 TWh NOR: 0.1–0.5% 1987–1991 NLD: 1.1–1.6 TWh in 2000 SWE: 5% 1991–2005, 48 TWh	Low		Effect depends on price elasticity. Revenues can be earmarked for further energy efficiency improvements. More effective when combined with other tools.	WEC 2001,Kohlhaas 2005, Larsen and Nesbakken 1997, MURE 2007, Brink and Erlandsson 2004
Tax exemptions/ reductions	USA, FRA, NLD, KOR	High	USA: 174 TWh in 2006 FRA: 25 TWh NLD[1]: 0.4 TWh/yr. or 0.3% of sectoral reference energy in 1997–2004	High / Medium	USA: B/C ratio Com-mercial buildings: 5.4 New homes: 1.6 NLD: 0.02$/kWh	If properly structured, stimulate introduction of highly efficient equipment and new buildings.	Quinlan et al. 2001, Geller and Attali 2005, MURE 2007, Khan et al 2007
Public benefit charges	BEL, DNK, FRA, NLD, USA, BRA	Medium	USA: 0.1–0.8% of total el. sales saved each year, 2.8 TWh/yr savings in 12 states NLD: 7.4TWh in 1996 BRA: 1.95 TWh	Medium	USA:0.03–0.05$/kWh	Success factors: Independent administration of funds, involve-ment of all stakeholders, regular evaluation/ monitoring& feed-back, simple and clear program design, multi-year programs	Western Regional Air Partnership 2000, Kushler et al. 2004, Lopes et al. 2000
Capital subsidies, grants, sub-sidised loans	JPN, SVN, NLD, DEU, CHE, USA, CHN, UK, ROU, DNK, BRA	High/ Medium	SVN: up to 24% energy savings for buildings BRA: 5.2 TWh UK: 13 GWh/yr ROU: 414 GWh DEU: 0.7–1.0 TWh/yr. or 0.1% of sectoral reference energy in 1996–2004	Estimates vary from Low to High	DNK: -0.004$/kWh UK: 0.01$/kWh for government, -0.05$/kWh net NLD: 0.02–0.05$/kWh DEU: 0.02–0.04$/kWh	Positive for low-income households, risk of free-riders, may induce pioneering investments.	ECS 2002, Martin Y. 1998, Schaefer et al. 2000, Geller et al. 2006, Joosen et.al. 2004, Shorrock 2001, Berry and Schweitzer 2003, Khan et al 2007
Support, information and voluntary action							
Voluntary certification and labelling	DEU, CHE, USA, THA, BRA, FRA	Medium/ High	BRA: 5.3 TWh in 1998 USA: 53 TWh in 2004, 3558 TWh in total by 2012 THA: 311 MWh	High	USA: -0.03$/kWh BRA: $20 million saved	Effective with fiscal incentives, voluntary agreements and regulations, adaptation to local market is important.	OPET 2004, Geller et al. 2006,WEC 2001, Webber et al. 2003, US EPA 2003

Voluntary and negotiated agreements	Mainly Western Europe, JPN, USA, DEN	Medium/ High	USA: app. 275 TWh in 2000 EU: 100 GWh/yr (300 buildings) UK: app. 41 TWh in 2006 DEN (coupled with subsidies): 0.3 TWh/yr. or 0.5% of sectoral reference energy in 1996–2003	Medium	SWE: 0.02$/kWh DEN: 0.01$/kWh	Can be effective when regulations are difficult to enforce. Effective if combined with fiscal incentives, and threat of regulation. Inclusion of most important manufacturers, and all stakeholders, clear targets, effective monitoring important.	Geller et al. 2006, Cottrell 2004, Gillingham et al. 2006, Bertoldi et al. 2005, Bertoldi and Rezessy 2007, DEFRA 2007a, Khan et al 2007
Public leadership programs	NZL, MEX, USA, PHL, ARG, BRA, ECU, ZAF, DEU, GHA	Medium/High	DEU: 25% public sector energy savings in 15 years USA: 4.8 GWh/yr USA: 0.4% of sectoral reference energy in 1985–2004 BRA: 140 GWh/yr GHA: 27 MWh (14% of baseline) MEX: 200 GWh/yr(13% of baseline)	Medium	USA: DOE/FEMP estimates $4 savings for every $1 invested USA: 0.04 $/kWh EU: $13.5 billion savings by 2020 ZAF: 0.07$/kWh BRA: -0.08$/kWh	Can be used to demonstrate new technologies and practices.Man-datory programs have higher potential than voluntary ones. Clearly state, communicate and monitor, adequate funding and staff, involve building managers and experts.	Borg et al. 2003 &2006, Harris et al. 2005, Van Wie McGrory et al. 2006, OPET 2004, Van Wie McGrory et al. 2002, Khan et al 2007
Awareness raising, education, information campaigns	DNK, USA, UK, FRA, CAN, BRA, JPN, SWE, ARG	Low/ Medium	UK: app. 50 GWh annually ARG: 25% in 2004/05, 4.1 TWh FRA: 1 GWh/yr BRA: 69 GWh/yr, 203–381 TWh/yr with voluntary labeling 1986–2005 SWE: 48 GWh/yr	Medium/ High	BRA: -0.002$/kWh UK: -0.02$/kWh (households), -0.02$/kWh(business) SWE: 0.02$/kWh	More applicable in residential sector than commercial. Deliver understandable message and adapt to local audience.	Bender et al. 2004, Dias et al. 2004, IEA 2005b, Darby 2006b, Ueno et al. 2006, Defra 2006c, Lutzenhiser 1993, Savola, 2007
Detailed billing and disclosure programs	Ontario, ITA, SWE, FIN, JPN, NOR, AUS, USA, CAN, UK	Medium	Max.20% energy savings in households concerned, usually app. 5–10% savings UK: 3% NOR: 8–10 % USA: 2.1%	High	NOR: -0.04$/kWh USA: -0.07$/kWh	Success conditions: combination with other measures and periodic evaluation. Comparability with other households is positive.	Crossleyet al., 2000, Darby 2000, RobertsandBaker 2003, Energywatch 2005, Wilhite and Ling 1995, Allcot 2010.

Country name abbreviations: DZA – Algeria, ARG – Argentina, AUS – Australia, AUT – Austria, BEL – Belgium, BRA – Brazil, USA/Cal – California, CAN – Canada, BC/CAN – British Columbia, CEE – Central and Eastern Europe, CHN – China, CRI – Costa Rica, CZE – Czech Republic, DEU – Germany, DNK – Denmark, ECU – Ecuador, EGY – Egypt, EU – European Union, FIN – Finland, FRA – France, GHA – Ghana, HKG – Hong Kong, HUN – Hungary, IRL – Ireland, ITA – Italy, JAM – Jamaica, JPN – Japan, KOR – Korea (South), MAR – Morocco, MEX – Mexico, NLD – Netherlands, NOR – Norway, NZL – New Zealand, PHL – Philippines, POL – Poland, ROU – Romania, ZAF – South Africa, SGP – Singapore, SVK – Slovakia, SVN – Slovenia, CHE – Switzerland, SWE – Sweden, THA – Thailand, UK – United Kingdom (Great Britain and Northern Ireland), USA – United States.

[1] The tool covers the commerce and the industry and the results are for both sectors.

Table 10.20 | Barriers to energy efficiency and policy instruments as remedies.

Barrier category	Examples of barriers	Instrument category	Policy instruments as Remedies
Economic barriers	Higher up-front costs for more efficient equipment / buildings; lack of access to financing; energy subsidies; lack of internalization of environmental, health, and other external costs	Regulatory-normative/ regulatory-informative Economic instruments Fiscal instruments	Appliance standards, building codes, energy efficiency obligations, requiring the use of a technology or a building with specific standards. Procurement regulations ensuring the purchase of energy efficient equipment. DSM programs. Under EPC, ESCOs finance energy efficiency improvements (addressing the issues of high front-up costs as well the lack of access to financing) and are paid from the energy cost reductions achieved. Cooperative procurement, which is used by big buyers to specify the energy efficient standards for the equipment they use. Energy efficiency certificates. Other risk-sharing/financing instruments like co-operation with banks/public-private partnerships, guarantee schemes. Tax exemptions, subsidies/rebates/grants to reduce up-front costs. Taxation and/or public benefit charges to increase energy prices and to internalize externalities.
Hidden costs/benefits	Costs and risks due to potential incompatibilities, transaction costs, etc.	Regulatory-normative Economic instruments Support action	Appliance standards and building codes, requiring the use of particularly technologies or solutions. Labelling for informing the public about product standards, etc., resulting in reducing transaction costs for seeking information. ESCOs can undertake a significant part of these hidden costs and risks. Public leadership programs to demonstrate new technologies and to gain experience from their implementation. Information and advice programs.
Market imperfections	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)	Regulatory-normative/ regulatory/informative Economic instruments Fiscal instruments Support, information, voluntary action	Appliance standards, building codes, energy efficiency obligations, imposing specific standards to buildings/equipment. A holistic approach engaging engineers, architects, etc., from the early stages of the design process. Mandatory labelling for informing the public about product standards. Procurement regulations and DSM programs. Regular monitoring and evaluation of programs and implemented policies. ESCOs can handle more effectively the administrative barriers for implementing energy conservation in buildings. Energy efficiency certificates and Kyoto Flexibility mechanisms can create incentives for implementing energy conservations measures. Taxation and public benefit charges giving the right price signals. Tax exemptions, subsidies/rebates/grants to accelerate first-movers. Public leadership programs, awareness raising campaigns.Education programmes for builders, architects, engineers, etc.
Cultural/ behavioral barriers	Tendency to ignore small opportunities for energy conservation, organizational failures (e.g., internal split incentives); tradition, behavior, lack of awareness and lifestyle; non-payment and electricity theft.	Support, information, voluntary action Fiscal instruments Regulatory-normative	Awareness raising through information campaigns. Detailed billing programmes, providing information to the final consumers as regards the most energy-requiring uses and equipment. Public leadership programs to demonstrate new technologies and practices. Voluntary agreements between governmental bodies and a business or organization, which undertakes the responsibility to increase its energy efficiency. Voluntary labelling programmes. Taxation and/or public benefit charges to increase energy prices and to give the right signal in the market. Appliance and equipment standards as well as other normative measures are a good way to overcome the tendency to ignore small opportunities (cf. phasing out of incandescent bulbs).
Information barriers	Imperfect information.	Support, information, voluntary action Regulatory-informative	Awareness raising through information campaigns. Detailed billing programmes, providing information to the final consumers as regards the most energy-requiring uses/equipment. Public leadership programs to demonstrate new technologies and practices. Voluntary labelling programmes. Mandatory labelling for informing the public about product standards. Procurement regulations ensuring the purchase of energy efficient equipment. DSM programs. Mandatory audits.

Source: IPCC, 2007; Carbon Trust, 2005; Ürge-Vorsatz et al., 2007.

Table 10.21 | Characteristic examples of possible policy instrument packages and examples of commonly applied combinations.

Measure	Regulatory Instruments	Information Instruments	Financial /Fiscal Incentives	Voluntary Agreements
Regulatory instruments	Building codes and standards for building equipment	Standards and information programs	Building codes and subsidies	Voluntary agreements with a threat of regulation
Information instruments	Appliance standards and labelling	Labelling, campaigns, and retailer training	Labelling and subsidies	Voluntary MEPS and labelling
Financial/Fiscal Incentives	Appliance standards and subsidies	Energy audits and subsidies Labelling and tax exemptions	Taxes and subsidies	Technology procurement and subsidies
Voluntary Agreements	Voluntary agreements with a threat of regulation	Industrial agreements and energy audits	Industrial agreements and tax exemptions	

10.8.3.1 Standards, Labeling, and Financial Incentives

There are several effective policy options available to accelerate the transformation of appliance markets toward higher efficiency, including MEPS (Minimal Energy Performance Standards), voluntary or mandatory consumer information labels, and publicity or rebate programs sponsored by utilities or government agencies. Appliance efficiency standard and labeling programs have by now become a core part of energy efficiency programs in many countries.

Among the oldest and most comprehensive programs are the US federal MEPS program, the comparative labeling program implemented by the European Union, and the Energy Star endorsement label program, which is a program of the United States but has become widely recognized internationally. Minimum performance standards are used in the European Union, as well as in developing countries such as China, Tunisia, and Thailand. Appliance standards have been perhaps the most successful policy for improving energy efficiency, in part because they capture 100% of the market in a few years' time (US DOE, 2008) and they remove key market barriers – such as lack of interest, incentives, etc. – and transaction costs.

For office equipment, voluntary information programs have induced manufacturers to improve efficiency (US EPA, 2007). The year 2007 brought new Energy Star specifications for office and imaging equipment. In addition to reducing power use of the products themselves, the new specifications also set additional requirements for accessories. If an imaging product is sold with an external power adapter, cordless handset, or digital front-end, these accessories must meet Energy Star External Power Supply, telephony, or computer specifications. These requirements ensure that the Energy Star represents only the market's most energy-efficient products. Energy Star-qualified office and imaging products use 30–75% less electricity than standard equipment.

Due largely to the example set by the success of programs in the United States, the European Union, and Japan, there has been a proliferation of similar programs throughout the world in the past two decades. The number of programs exceeds 60 (Wiel and McMahon, 2005), and they cover dozens of different residential, commercial, and industrial products.

Appliance standards are often combined with labeling and rebates in order to give incentives for investments beyond the level required by the minimum energy efficiency standard. McNeil et al. (2008) demonstrate the importance of implementing both energy efficiency labeling and standards, showing that enforcing such policies on a global scale would lead to worldwide savings of 1113 TWh/yr of electricity and 327 TWh/yr of fuels by 2020, and 3385 TWh/yr of electricity and 928 TWh/yr of fuels by 2030. In addition, rebates for the most energy-efficient products encourage consumers to buy these, which reinforces and sustains market transformation.

The Japanese Top Runner approach is another unique and successful method to improve the energy efficiency of appliances (Murakoshi et al., 2005). In the Top Runner approach, government sets target energy efficiency values and years for appliances, including scope, based on the highest energy efficiency products on the market, and encourages manufacturers to make products better than this target energy efficiency value. Energy efficiency values and indicator labels are voluntarily displayed in catalogs and other advertising and publicity material so that consumers can consider energy efficiency when making purchases. In addition, the Top Runner program sets fleet standards for appliances. This system of voluntary agreements between the Japanese government and manufacturers has been highly effective, leading Japan's appliance market to be among the most efficient in the world.

Building codes can also be combined successfully with voluntary or mandatory certification of buildings (IEA, 2010c) such as through rating systems like the British BREEAM,[30] the Japanese CASBEE,[31] and the

30 BREEAM (BRE Environmental Assessment Method) is a widely used environmental assessment method for buildings. It was developed by BRE (Building Research) Trust Companies and covers a wide range of building types (www.breeam.org/).

31 CASBEE (Comprehensive Assessment System for Built Environment Efficiency) is an assessment tool based on the environmental performance of buildings or urban area. CASBEE evaluates a building from the two viewpoints of environmental quality and performance (Q=quality) and environmental load on the external environment (L=load) and defines a new comprehensive assessment indicator, the Building Environmental Efficiency (BEE), by Q/L (www.ibec.or.jp/CASBEE/english/index.htm).

American LEED system.[32] The European Union's EPBD[33] is actually an example of combining codes with certification. A number of developing countries, such as China, intend to introduce building rating schemes to complement building codes (Ürge-Vorsatz and Koeppel, 2007). In the United States, mandatory energy efficiency regulations are sometimes coupled with voluntary labels, such as ENERGY STAR, and tax credits to manufacturers and to consumers. This combination eliminates the least efficient products, while compensating manufacturers for some of the increased production costs both through tax credits and through premiums charged for ENERGY STAR designs.

10.8.3.2 Regulatory and Information Programs

Regulatory policy instruments are usually effective, but lack of enforcement can be a barrier and the rebound effect may result in some benefits being taken as increased service rather than reduced consumption. Awareness might improve compliance and help overcome the rebound effect in more affluent population groups where energy service levels are not constrained.

10.8.3.3 Public Leadership Programs and Energy Performance Contracting (EPC)

By improving its own energy efficiency, the public sector can not only save costs, but also demonstrate to the private sector the potential and feasibility of energy efficiency improvements and trigger market transformation. EPC in the public sector is especially advantageous, as the budget of many public administrations is limited. Executive orders that oblige public authorities to reduce energy use by 30% and the federal energy management program in the United States, as well as the Energy Saving Partnership in Berlin, Germany, have boosted the energy service company (ESCO) industry (Ürge-Vorsatz and Koeppel, 2007). However, significant barriers still hamper EPC in the public sector in developing countries.

10.8.3.4 Financial Incentives and Labeling

In order for financial incentives such as loans, subsidies, and tax credits to be most effective, the labeling of energy efficient products is necessary, which ensures that only the most efficient categories of equipment are financially supported (Menanteau, 2007). On the other hand, labeling, particularly voluntary labeling alone, might not be effective (Menanteau, 2007), because if the premium labeled products are substantially more expensive, that discourages especially low-income households from purchasing them. This implies that governments might consider incentive schemes for companies that undertake labeling.

10.8.4 Policy Instruments Addressing Selected Barriers and Aspects Toward Improved Energy Efficiency in Buildings

10.8.4.1 Policies for Retrofit

While the majority of broad policy approaches – information, labeling, standards, incentives, etc. – are in principle as applicable to building retrofit as new buildings, there are clearly important differences in the policy measures required. In most countries, due to the long lifetime of buildings replacement rates of the building stock are low, and therefore retrofit will be essential to achieving rapid progress in energy efficiency.

Securing low-energy retrofit activity raises some different issues. This is partly because codes and standards are expected to deliver much more in new construction. Retrofitting existing buildings is a discretionary investment – no action is an option, and often an easier option. Building owners and occupiers therefore need to be persuaded not only of the merits of energy investment, but to finance it and bear whatever disruption it entails. Incentives may therefore need to be higher than for new buildings. This sub-section therefore focuses upon the differences in policy mix that may be required for building retrofit.

The incentive policies reviewed above are particularly relevant to retrofitting policies. In some cases, e.g., in the United Kingdom, there is support for energy efficiency measures in low-income households from government-funded programs. More commonly energy efficiency retrofits are supported through a variety of fiscal measures, including income tax credits – e.g., in the United States and France – and low rates of relevant sales taxes – e.g., reduced rate value added tax (VAT) in some European Union countries. In some cases, these formed part of green stimulus packages in 2009.

Programs of financial support for building energy efficiency through energy utility regulation are increasingly common and growing in size. First known as Demand Side Planning or Integrated Resource Planning and used in the United States in the 1980s in vertically integrated monopoly utilities, they have now been adapted to a range of regulatory environments. In principle, any category of energy efficiency may be addressed in this way, but in practice building retrofits predominate. In some states of the United States and some European Union countries, the United Kingdom, Italy and France, program savings approach or exceed 1% of regulated energy use (e.g., York, 2008; Eyre et al., 2009).

Performance contracting by energy service companies is widely used in many countries for the retrofitting of commercial buildings. Subsidized energy advice has been used widely to increase information on energy

32 LEED (The Leadership in Energy and Environmental Design) is a Green Building Rating System developed by the United States Green Building Council and providing a suite of standards for environmentally sustainable construction (www.usgbc.org/).

33 EPBD (EU Directive on the Energy Performance of Buildings) is a range of provisions aimed at improving energy performance of residential and non-residential buildings, both newly built and already existing (www.buildingsplatform.org/cms/).

efficiency opportunities in the existing building stock. These have been linked to incentive schemes, which may be in the form of grants, loans, tax incentives, or energy company incentive payments.

An audit is generally recognized as the precursor to effective retrofit investment. The logic of this is reflected in policies that increasingly require mandatory labeling and audit and certification of buildings, e.g., European Performance of Buildings Directive. The first aim of such labeling is to provide consumer information, but labeling schemes are also essential as a tool in incentive or regulatory policies that are linked to building performance.

Although codes and standards are best known for use in new buildings, they are increasingly used in retrofit. This can be to require performance standards at the time of major refurbishment, and this applies in the European Union to buildings through the Energy Performance of Buildings Directive. Standards are also applied to individual components in retrofit, e.g., heating, glazing, air conditioning, and this is very cost effective (e.g., DEFRA, 2007b). Germany has extended this principle to both fabric elements and whole building performance at the point of major refurbishment (Dilmetz, 2009). However, to date there has been very limited use of standards for whole building performance to require refurbishment, for example at the point of sale or rent. At present, actual regulation of this type has probably been confined to a few parts of the United States – San Francisco, Berkeley, Davis, Burlington, Ann Arbor, and the state of Wisconsin (CLG, 2010). The adoption of mandatory labeling and retrofit codes (e.g., in Europe) in principle provides a basis for wider use of this approach.

It is increasingly recognized that substantial retrofit will be required if older buildings are to reach the energy efficiency standards implied by the ambitious targets of many governments. Traditional incentive mechanisms that support individual components will not be sufficient to deliver the major changes in fabric, airtightness, and heating and cooling system efficiency that are required. Policies that support very substantial improvement are beginning to be explored. For example, in Germany there are 100% low interest loans up to Euro 50,000 (approximately US_{2005}\$59,000) for CO_2 rehabilitation of buildings, supporting very low energy refurbishment (Schonborn, 2008). In Berkeley, California, to encourage energy-efficient renovations of residential and commercial buildings, the municipality provides funds that are to be repaid within 20 years through property taxes (Fuller et al., 2009). Since the 2009 financial crisis, with lending significantly reduced, schemes of this type are of increasing importance for supporting retrofits. However, policies of this type are on hold in the United States because of concerns that they infringe on contractual obligations to mortgage lenders.

Policies for retrofit to low energy standards also need to deal with practical complexities inherent in the diversity of current buildings, many already significantly altered since original construction and often poorly built, maintained, and documented. Retrofit has to deliver the range of outcomes defined by building owners or managers and provide the services expected by future occupants, when known. In general, these clients will have little energy knowledge and very little insight into the challenge of low energy retrofits. Moreover, in the case of minor changes and even major ones to small buildings, e.g., single-family dwellings, retrofit may frequently be done without the oversight of architects or energy services professionals. In this environment, delivering the very low levels of air infiltration and thermal bridging implied by passive building standards involves some practical challenges for the retrofit process. At the very least, the widespread adoption of low energy retrofit programs will also require a substantial program of training in the building sector (Killip, 2008).

10.8.4.2 Policies Addressing Non-compliance Related to Building Codes

Building codes have served as a major policy tool for reducing energy required, especially for building services such as heating, cooling, water heating, and lighting (Listokin et al., 2004). Existing practices in several countries show there are mainly two types of building codes: (1) overall performance-based codes requiring that a building's predicted energy demand or energy cost (usually determined through an energy modeling software), is equal to or lower than a baseline target that has been specified by the code; and (2) prescriptive codes, which set separate energy performance levels for major envelope and equipment components. A combination of an overall performance requirement with some component performance targets (e.g., wall insulation) is also possible.

Computer simulation tools have existed since the 1970s to calculate the energy performance of buildings based upon their design, and the results have been validated – or improved – by comparison with measured energy use. The full potential for energy savings from building codes has not been achieved, in part because compliance and enforcement are not complete. The range of experiences is broad, from jurisdictions where even the structural integrity of buildings may be compromised – sometimes revealed when earthquakes cause widespread damage in a region – to buildings failing to meet fire codes, to buildings meeting some but not all requirements, to those meeting all requirements.

Good statistics are lacking to quantify the problem globally. In many parts of the world, there are no legal requirements for building code enforcement. Even in some of the most prosperous regions, the level of resources available for enforcement, such as the number of local code enforcement officials or information and tools available to them, is often inadequate. In some developed areas, code compliance has been shown to be about 50% (Usibelli, 1997). A recent California study found rates of non-compliance by measure ranging from 28–73% for residential and 44–100% for non-residential. In both cases, the lowest non-compliance was for lighting, and the highest was for ducts (Sami Khawaja et al., 2008).

While performance measurement, by means of commissioning or research on occupied buildings, may be necessary to rigorously compare actual performance with the energy performance projected by computer models using design parameters, simpler inspections are sufficient to detect significant non-compliance. Failure to comply can occur because actual construction practice deviated from design, or inferior materials or equipment were substituted, or installation was flawed or incomplete. Studies have suggested ways to improve building regulations (for a recent European example, see Garcia Casals, 2006).

Aiming at enhancing the effectiveness of building codes, there has been much discussion recently about a new energy code compliance framework based on actual post-construction energy performance outcomes of buildings, called outcome-based building codes (Hewitt et al., 2010). In other words, owners would have the flexibility to pursue whichever retrofit strategies they deem appropriate to their individual buildings, but would be required to actually achieve a pre-negotiated performance target, demonstrated through mandatory annual reporting of energy use. Although no current codes regulate actual energy use, outcome-based codes may be a very critical tool toward deep energy savings in existing buildings. As existing buildings do have an energy performance history, benchmarking plays a vital role in establishing an outcome-based compliance path in energy codes (Denniston et al., 2010). An outcome-based performance path may be based on either requiring certain percent improvement in energy performance, assuming old energy performance needs are known, or absolute performance goals, given sufficient data about building performance needs in order to establish those goals are available.

Generally, successful building energy codes will likely require: (1) clear, consistent code documentation, that is as simple as possible; (2) providing sufficient information, training, and motivation to practitioners; (3) adequate local resources to check compliance, keeping in mind that the sheer size of the construction industry argues for simpler methods and sampling using statistical methods, rather than rigorous checking of every building; (4) feedback to architects, designers, builders, contractors, and consumers to identify good and bad practice; (5) penalties for consistent bad practice; and (6) performance-based rating systems to close the loop from actual performance back to design and construction.

10.8.4.3 Policies Addressing Professional, Social, and Behavioral Opportunities and Challenges

A substantial part of the huge energy conservation potential in buildings requires the effective engagement of human dimensions of providing, adopting, and using energy efficient technologies and buildings. These are set out in Section 10.4.8 above. In many cases, these factors constitute significant barriers for capturing even low cost, energy conservation potential. To overcome these barriers, appropriately designed policies or portfolios of policies can be implemented that are briefly described below.

The adoption of behavior to use less energy by building occupants can be enhanced through information, advice, and educational programs and the provision of more detailed and direct feedback on energy use by end-use and energy expenditures. It has been noted that, in many cases, people underestimate the amount of energy they use for specific energy uses. To this end, detailed billing and disclosure programs have been estimated to potentially save up to 20% of energy (Darby, 2000) and are mostly cost-effective (Ürge-Vorsatz et al., 2007).

However, better feedback to final consumers on energy use may increase costs and reduce revenues for the energy supplier. The policy implication is that regulation is likely to be needed to set a minimum standard for the quality and frequency of energy use information. This could include frequency of meter reading and billing and requirements for comparison with historical data and consumption of similar users. The advent of smart meters provides new opportunities to enhance information across the energy supply chain, including to final users. Again, this needs a clear regulatory framework to be successful, including timescales for deployment and standards for inter-operability, consumer information, and data transfer.

Carefully designed and targeted awareness-raising programs to secure specific outcomes can have a place in policy packages to reduce energy use. The Japanese "Cool Biz" campaign is a good example (see Box 10.3). However, there is limited evidence that general exhortation, e.g., advertising campaigns, has a significant lasting impact. Energy saving information needs to be clear and relevant and provided at the point of key decisions; product labeling is the best example of this. Advice on energy saving opportunities is generally most effective when it is specific to personal circumstances, especially when provided by trusted sources independently of energy companies and as part of policy packages including incentives and other support to act. Consumers are unlikely to seek this out, or pay for it at cost, and therefore it needs to be provided as a public or community service, for example by local government or specialist energy agencies.

Energy pricing may also be a useful tool for influencing energy use behavior in buildings. Furthermore, even if residential energy price elasticities are relatively low in high income countries, appropriate energy pricing systems, e.g., with the adoption of staggered rates, may provide impetus for a more rational use of energy sources in buildings (Reiss and White, 2008; National Action Plan for Energy Efficiency, 2009).

Finally, non-technological options to reduce energy use in new buildings related to architectural decisions at an early design stage, e.g., building shape, form, orientation, size, etc. (see Section 10.4.2), can be supported through appropriately designed building codes, regulations on urban density, building heights, and the mix of land uses, etc. (WBCSD, 2008). These mechanisms already exist in many countries. However, their effective implementation and particularly their revision to incorporate energy efficiency aspects remain a challenge in most developing and in several developed countries.

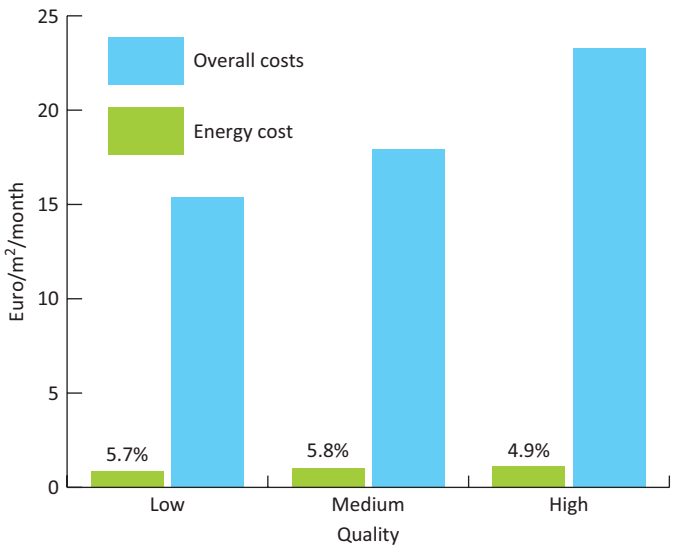

Figure 10.30 | Average values of total costs by quality of fittings. Source: Jones Lang LaSalle, 2006; based on 397 buildings with six million m^2 in 2006.

Most policies to address human dimensions of energy use in buildings are designed to improve energy efficiency, rather than to bring about more fundamental lifestyle changes. However, broader policy frameworks do have implications for culture and lifestyle, although these raise complex and controversial issues. Greater attention to these may be required in the future and should be the subject of further research. These broader lifestyle issues are addressed in Chapter 21.

10.8.4.4 Energy Cost Information and Analysis

Energy is typically a small proportion of total operating costs for buildings. For example, in a high quality office building in Germany, heating and electricity made up less than 5% of the total running cost of the building – about 1.1 out of every €23.3 (1.4 out of $US_{2005}$$29.8) spent (see Figure 10.30).

Energy costs are more significant for direct investors. Energy efficiency is part of the due diligence for the procurement of new properties by those who will own and operate them. For other investors, energy costs are not important. There is emerging evidence that an energy-efficient building can command a premium. One US study (McGraw-Hill Construction, 2006) found that professionals expect greener buildings to achieve an average increase in value of 7.5% over comparable standard buildings, together with a 6.6% improved return on investment. Average rents were expected to be 3% higher.

The insurance industry faces substantial risks from climate change. Based on the consideration of those risks, many insurance companies are providing incentives toward more energy efficient, and climate neutral, buildings. Green insurance is not very common yet, and only exists in developed countries, but is gaining increasing significance.

While energy costs are a relatively small part of total occupancy costs, they can still be a significant factor in motivating energy efficiency action. But profitable opportunities for energy savings are often overlooked because of inadequate cost information. Despite real estate managers' stated interest in energy efficiency, a study in 2006 found that only two-thirds of companies tracked energy data and only 60% tracked energy costs (WBCSD, 2007).

In the United States, only 30% of real estate managers or facilities managers claimed to have included energy efficiency requirements into requests for proposals. Despite these findings, the study surprisingly suggested that energy costs are the most important driver for energy efficiency, both currently and in the future. Energy managers and investment decision makers need to develop a common methodology and language for valuing energy efficiency projects in a similar manner to other investments (Jackson, 2008). With such a risk analysis framework in place, energy efficiency experts and investment decision makers could exchange the information they need to expand investment into energy efficient buildings projects. Accurate and robust analysis demands a high level of understanding of the physical aspects of energy efficiency, which enables physical performance data to be translated into the language of investment. However, while there is a general recognition that energy efficiency practices and products are becoming more widespread in the market place, there are limited data on how these factors impact the value of buildings. The financial effectiveness of capital improvements that target energy demand reduction is usually assessed in terms of simple payback times and does not typically reflect a property investor's valuation methods.

10.8.4.5 New Business Models – ESCOs

Appropriate commercial relationships can increase the focus on energy costs by altering commercial relationships, removing the split incentives problem and introducing more effective incentives for reducing energy use and costs.

An energy performance contract is an arrangement between a property owner and an ESCO that covers both the financing and management of energy-related costs. It involves a variety of mechanisms to help property owners use the knowledge of energy professionals to reduce energy costs. While the effectiveness of ESCOs is well documented, miscalculation of financial and technical risks has caused many failures of these firms.

ESCOs generally act as project developers, installers, and operators over a seven–ten year time period. They assume the technical and performance risk associated with the project. The services offered are bundled into the project's cost and are repaid through operational savings generated, with the ESCO's profit coming from a proportion of cost savings or a fixed fee based on projected energy savings.

As an additional service in most contracts, the ESCO provides any specialized training needed so that the customer's maintenance staff can take over at the end of the contract period. ESCOs have placed great emphasis on measurement and verification and have led the way to verify, rather than estimate, energy savings. One of the most accurate means of measurement is the relatively new practice of metering, which is the direct tracking of energy savings according to sanctioned engineering protocols.

10.8.4.6 New Financial Instruments

Ways to shift the financial equation in favor of energy-efficient investment include reducing the first cost or increasing the savings in the early years.[34] One widely recognized way of increasing potential savings is to increase the cost of energy. These are useful mechanisms across the broader economy. However, WBCSD modeling shows they are likely to have a limited impact on building energy investment decisions if set at a level that is acceptable politically and economically. Even a relatively high carbon price, for example US$60/t$CO_2$, does not add enough to the energy cost to make energy savings sufficiently attractive.

Potential savings can be increased through commercial means. In some countries, utility-charging practices may encourage waste because of discounts for higher use – the unit rate typically declines above specified consumption levels. Reversing this practice would increase the cost of energy at higher consumption levels. This is already the case in Japan, where the first 120kWh of monthly electricity consumption are charged at JPY17.87/kWh (US¢18), increasing to JPY22.86 (US¢23) up to 300kWh and JPY24.13 (US¢24) above that level. A high feed-in tariff for renewable energy supplied to the grid may encourage investment in on-site renewable generation, as is already the case in countries like Germany and France.

WBCSD/EEB modeling has clearly shown that many potentially attractive energy investments do not meet the short-term financial return criteria of businesses, investors, and individuals. While significant savings are possible with relatively modest investment premiums, a first-cost-sensitive buyer will never adopt transformative solutions.

Solutions are to attract new sources of funding, learning from best practice and experience with business models such as ESCOs. Several opportunities are available to open up finance for energy investment:

- Pay as you save: the first cost is financed in full or in part by an energy utility, which recoups the outlay through regular surcharges on the monthly bill; these surcharges attach to the house, not the specific customer.
- ESCOs: utilities or other providers contract to achieve specified energy performance for a commercial building and share the savings with the owner.
- Energy performance contracting: schemes enabling energy services companies or other players to offer innovative contracts guaranteeing the level of services and the energy savings to the customer, as above.
- Locally available loans: local authorities provide loans to finance energy investment, and repayments are made through an addition to the property tax charge.
- Cross-subsidized mortgages for energy-efficient buildings: higher rates for low-efficiency buildings and lower rates for efficient ones.
- Energy efficiency investment funds: capitalizing on the lower risk of mortgage lending on low-energy housing, funds to provide such investment could be attractive to socially responsible investment funds.

10.8.4.7 Toward Low-energy and Zero-energy Buildings

Recently, several countries and organizations adopted ambitious goals with far-reaching implications regarding energy use in buildings. In the United Kingdom, the government is already committed to all new housing being carbon neutral from 2016. In the United States, a number of zero-energy initiatives have been adopted at the state level. For example, in California the zero-energy target has been specified for all new residential buildings by 2020 and for all new commercial buildings by 2030. Analogous targets have been adopted by several other countries, such as Denmark, France, the Netherlands, etc. Table 10.22 reviews these ambitious targets and the related policies that have been adopted by key countries to substantially reduce energy use in new buildings.

Also, the recast of the European Union's EPBD is stimulating Member States to develop frameworks – national plans, etc. – for higher market uptake of low- or zero-energy and carbon buildings. To this end, Member States shall set specific targets for 2020 with respect to the penetration of these buildings in relation to the total number of buildings and the total useful floor area.

The WBCSD in the context of the Energy Efficiency in Buildings project has adopted a vision in which all buildings in the world will consume zero net energy by 2050. In addition, the buildings must also be aesthetically pleasing and meet other sustainability criteria, especially for air quality, water use, and economic viability (WBCSD, 2008). Also, Architecture 2030, an independent nonprofit organization, proposed the 2030 Challenge in 2006, tasking the global architecture and building community to adopt a plan for making new buildings and major renovations carbon neutral by 2030. The plan sets an immediate energy

34 Increasing access to capital requires a very different set of tools, such as preferential rate loans, risk-guarantee mechanisms, or others.

Table 10.22 | Examples of countries and regions which already adopted ambitious targets toward low-energy and zero-energy buildings.

Country / Region	Nature of target	Explanation of the target	Year of target	Source	Legal status of target
UK	Zero carbon homes[1]	All new houses built in the UK must be carbon neutral by 2016. Intermediate targets: carbon performance of new houses to be improved by 25% by 2010 and 44% by 2013, as compared to 2006 Building Regulations.	2016 (with intermediate targets for 2010 and 2013)	Department for Communities and Local Government (2007)	Government plan to be cast into law over time according to the interim targets, until then not legally binding
California	Zero-net-energy buildings[2]	All new residential construction will be zero-net-energy by 2020, while all new commercial construction will be zero-net-energy by 2030.	2020 (for all new residential buildings) 2030 (for all new commercial buildings)	California Public Utilities Commission (CPUC), California Energy Efficiency Strategic Plan (2008)	Strategic goal, not legally binding
Denmark	Continuous reduction of energy use in new buildings	Maximum energy demand in new buildings must be, compared to the requirements[3] of 2006: – 25% lower by 2010 – 50% lower by 2015 – 75% lower by 2020	2010, 2015, 2020	Engelund Thomsen (2008), Danish Government (2009)	Agreement among all major parties of Danish parliament in 2008, confirmed by government strategy in 2009, but not yet cast into law
Austria	Passive house standard[4]	Social housing subsidies[5] shall only be granted for passive buildings from 2015.	2015	Engelund Thomsen et al. (2008), Federal Ministry of Agriculture, Forestry, Environment and Water Management (2007)	Goal of federal government, but not binding for federal states in charge of implementation
France	Energy positive buildings[6]	All new buildings must be energy positive from end of 2020. Intermediate target: maximum primary energy demand of 50 kWh/m^2 for new tertiary buildings from end of 2010 and all new buildings from end of 2012.	2020 (with intermediate target for 2010–2012)	Assemblée Nationale (2008)	Legislative process for binding law ongoing as of May 2009
Germany	Climate-neutral buildings	All new buildings should use zero amount of primary energy by 2020. Existing buildings should undergo efficiency renovation in 2020–2050 to achieve a 80% reduction in their primary energy demand.	2020 for new buildings; 2050 for existing buildings	Ministry of Economics and Technology and Ministry of Environment, Nature Conservation, and Nuclear Safety (2010)	The targets set in the national Energy Concept. The supporting Laws, regulations, and other implementation documents are under discussion and development.
Hungary	Zero carbon residential and public buildings	Granting building permits for residential and public buildings only if they are carbon neutral.	2025	Ministry of Environment and Water (2008)	Strategic goal, not legally binding
The Netherlands	Energy-neutral buildings[7]	All new buildings shall be energy neutral from 2020. The following intermediate targets apply: – 2011: 25% improved energy performance[8] compared to regulations of 2007 – 2015: 50% improved energy performance compared to regulations of 2007	2020 (with intermediate targets for 2011 and 2015)	Engelund Thomsen et al. (2008), Ministry of Economic Affairs (2007), Ministry of Housing, Spatial Planning and the Environment (2007)	Government target, not yet cast into law

[1] Zero carbon means that a home should be zero carbon (net over the year) for all energy use in the home. This would include energy use from cooking, washing and electronic entertainment appliances as well as space heating, cooling, ventilation, lighting and hot water.
[2] CPUC defines zero-net-energy building as a building with a net energy use of zero over a typical year, i.e. the amount of energy provided by on-site renewable energy sources is equal to the amount of energy used by the building.
[3] The minimum requirements for energy efficiency in buildings in Denmark as of April 1, 2006, are defined as follows: the total demand of supplied energy to a building to deal with heat losses, ventilation, cooling and domestic hot water must not exceed 70 + 2200/A kWh/m^2/a for residential and 95 + 2200/A kWh/m^2/a for offices, schools, institutions and other buildings (A is the heated gross floor area).
[4] Passive house standard is defined in Austria as annual heating energy use ≤15 kWh/m^2, where the area refers to net area in Austria in general, but to the useful area in the federal state of Styria and to heated area in the federal state of Tirol.
[5] The share of social housing is high in Austria, this measure is therefore expected to have a great impact on market development for low-energy buildings.
[6] Energy positive buildings are defined as buildings with a lower consumption of primary energy than the amount of energy they produce themselves from renewable sources.
[8] Energy-neutral buildings are defined as not requiring any fossil fuel.
[9] The Netherlands use an Energy Performance Coefficient to measure energy performance. In 2007, its maximum value for new residential buildings was 0.8. This will be lowered to 0.6 from 2011 and to 0.4 from 2015, which roughly corresponds to passive house standard for heating.

reduction target of 50% for all new buildings and major renovations compared to the regional or national average of each building type, with a goal of increasing this target by 10% every five years, reaching 100% by 2030. These goals have been adopted by several organizations, including the American Institute of Architects, the United States Green Building Council, the Environmental Protection Agency, and ASHRAE (Arens, 2008).

However, as mentioned earlier, zero-energy buildings may not be feasible for every type of building and in all regions, and in many cases their economics are unfavorable compared to high-efficiency buildings. They also may not be the most environmentally sustainable solution, as compared to very high-efficiency buildings supplied with partially on-site renewable and zero-carbon grid energy. In fact, universal net zero-energy mandates may even have negative environmental consequences. First, they may encourage urban sprawl, since net zero-energy buildings are easier – or even technologically only feasible – to implement in low-density, low-rise developments, but these increase transportation energy use. Second, if limited budgets of investors and building owners are forced to be spent on relatively more expensive PV panels, larger opportunities are foregone that would have been unlocked if the same investments had been made into efficiency measures that might have eliminated the need to produce more energy.

Nevertheless, in cases where zero-energy and very low-energy buildings are economically and environmentally justified, their promotion requires the implementation of a portfolio of policies that will motivate the several stakeholders and the billions of building owners and occupants.

The adoption of stricter energy performance requirements is of particular importance. As an example, in the United Kingdom the tightening of local planning regulations and building codes will be the basic policy instruments to achieve the carbon neutral target for all new buildings by 2016. Also, the adoption of stricter appliance and equipment standards that are periodically updated will decrease the total electricity loads that should be compensated by on-site generation.

The implementation of economic incentives in the form of subsidies, tax exemptions, etc., either for entire buildings, or for specific equipment components, will improve the economic performance of low-energy and zero-energy buildings and will accelerate the integration of renewable or other efficient technologies in their design. As an example, in France, new buildings respecting certain environmental criteria can be exempted from property taxes for 15–30 years (European Commission, 2009). There is some evidence that economic incentive programs are critical for preparing the market to adopt zero-energy goals in the present (premature) phase (Arens, 2008).

The adoption of preferably mandatory energy performance certification schemes and labeling programs will ensure compliance with energy code requirements and achievement of the targets set, thus enhancing market value. In fact, development of the Passivhaus scheme in Germany and the MINERGIE standards in Switzerland was instrumental in the strong development of low-energy buildings over the past decade.

Lack of awareness and technical capabilities for constructing low-energy and zero-energy buildings among practicing architects, engineers, interior designers, and professionals in the building industry may be a major impediment to their development and the fulfillment of the ambitious goals set. Consequently, the development of capacity building programs to expand know-how is of particular importance. More specifically, there is a significant need in most countries to create comprehensive, integrated programs at universities and other educational establishments to train current and future building professionals in the design and construction of low-energy buildings. Finally, the development of pilot projects is helpful to demonstrate the effectiveness and the everyday functionality of the new buildings. In this context, the role of the public sector as an early adopter is crucial.

10.8.5 Energy conservation versus the rebound effect

Energy efficiency measures often have other, unintended effects on society. These ripple effects include rebound effects, co-benefits, and trade-offs with other resource use and pollution, and spillovers (Hertwich, 2005a). The rebound effect is defined first in Chapter 2, and discussed in detail in Chapter 22. Here it is reviewed with regard to building energy efficiency programs.

There have been a large number of empirical and modeling studies addressing the rebound effect (Greening et al., 2000; Schipper and Grubb, 2000; Hertwich, 2005a; Sorrell, 2007). Empirical studies of the micro-rebound effect consistently find that simple engineering-economic estimates of energy savings from an energy efficiency measure overestimate the savings by 0–30% (Table 10.23), with some outliers in the case of energy poverty (Roy, 2000). When people cannot afford to heat or cool their homes, but efficiency measures make these energy services affordable, these efficiency measures can in fact increase energy use. In all cases, the "rebound" implies that consumers enjoy a higher level of energy service as a result of increased efficiency.

With regard to macro effects, the main concern is that increased efficiency leads to the substitution of energy services for other inputs to production such as labor, capital, and land, alleviating resource constraints and thus enabling economic growth. Empirical studies show that the substitution effect does not lead to an increase in energy use for the same basket of goods (Schipper and Grubb, 2000). As energy is usually a small portion of the overall costs of a product or service, changes in the energy content of the product or service are unlikely to have a substantial effect on demand. It can be observed, however, that energy productivity has increased more slowly than labor productivity. Overall, the input of physical work has increased in lock-step with economic output (Ayres and Warr, 2005), suggesting that increased efficiency of converting primary energy to physical work may have contributed

Table 10.23 | Rebound effect for energy efficiency measures for different energy services.

Energy service	Rebound	Region/study
Residential space heating	10–30% 10–30% (1.4–60%) 20–30%	Review USA (Greening et al., 2000) Review OECD (Sorrell, 2007) Austria (Haas and Biermayr, 2000)
Residential space cooling	0–50% 1–36% 57–70%	Review USA (Greening et al., 2000). OECD (Sorrell, 2007) S.Korea (Jin, 2007)
Appliances	0 0	Austria (Haas, Biermayr et al., 1998) USA (Greening et al., 2000).
Lighting	5–12% 200%	USA (Greening et al., 2000) India (Roy, 2000)
Automotive transport	0 10–30% 5–26% 10–30% (5–87%) 57–67%	Switzerland (de Haan et al., 2006) USA (Greening et al., 2000) USA (Small and Van Dender, 2005) Review global (Sorrell, 2007) Germany (Frondel et al., 2008)

substantially to economic growth. Increased input of energy services in agriculture was essential both for raising yields and for freeing labor for work in industry (Erb et al., 2008). Empirical evidence for the importance of energy efficiency for economic growth, however, remains contested (Schipper and Grubb, 2000). The debate about how much energy efficiency increases economic growth and thus demand for energy services has yet to be resolved.

Taxes on energy or energy-related pollution or a cap and trade approach have been identified as an effective way to counteract both micro-rebound and macro-rebound effects because these effects are envisaged to operate through a price mechanism. The rebound effect, while limiting the effectiveness of efficiency measures in reducing overall demand, provides additional economic welfare arguments for energy efficiency as necessary for overcoming energy poverty and as being potentially beneficial for economic growth.

10.8.6 Focus on Developing Countries

10.8.6.1 Existing Policy Instruments in Developing Countries

A recent review of building energy codes (Janda, 2009) found that at least 61 countries had energy codes for buildings in 2008 of which the majority (40) were mandatory. The majority of these are developed countries, but several developing countries are included in this list: Mexico, Singapore, Vietnam, the United Arab Emirates, Jamaica, Jordan, Kazakhstan, Kuwait, Cote d'Ivoire, Thailand, India, China, Chile, South Africa, Indonesia, Malaysia, the Philippines, Lebanon, Tunisia, and Pakistan. Several more plan to introduce building energy codes, including Morocco, Brazil, and Colombia (Janda, 2009), as well as Kenya and Uganda, often supported by international organizations. The most commonly applied measures are voluntary and mandatory labeling, appliance standards, building codes, public leadership programs, DSM programs, subsidies, grants and rebates, awareness-raising campaigns, and mandatory audits. However, only very few evaluations of instruments in these countries are available.

10.8.6.2 Enabling Factors: High Energy Price Levels and Energy Shortages

Increasing energy prices are often considered the most important precondition for improved energy efficiency in developing countries (Levine et al., 2007). Low, subsidized energy prices in many developing countries imply very long payback periods for energy efficiency investments, which renders such projects unprofitable. The differences in energy prices explain why certain governments in the Mediterranean region, such as Tunisia and Morocco, are interested in energy efficiency while others, especially oil-producing countries such as Algeria, are not or are less interested. Revenues from lower energy price subsidies can be rechanneled into rebates for energy efficient programs, loans, and special assistance for low-income households to increase their energy efficiency and thereby reduce energy costs. Since policymakers often consider energy efficiency a lower priority than more vital economic goals, such as poverty alleviation or increased employment, it is essential that non-energy benefits are well mapped, quantified, and well understood by policymakers.

10.8.6.3 Need For Technical Assistance and Training

Sustainable construction know-how needs to be introduced into the base curriculum of architects and other construction-related professions all over the world. This is even more important in developing countries because of the often much more dynamic new construction rates. As the training of a countries' own nationals will take some time, technical assistance through international organizations can bridge this gap for a period. Even in Tunisia – which is often considered a best practice developing country due to its successful energy efficiency policy in the buildings sector (Ürge-Vorsatz and Koeppel, 2007) – representatives of the energy efficiency agency request technical assistance for the development of thermal building standards due to a lack of national expertise in this area (Ürge-Vorsatz and Koeppel, 2007).

10.8.6.4 Need For Demonstration Projects and Information

In addition to the lack of information and awareness, there are also human barriers – for instance, a lack of trust. Trust and awareness can be raised through pilot projects or demonstration projects in the public

sector. Demonstration programs at all levels, from the capital city to villages, such as the Green Buildings for Africa program in South Africa, prove the advantages of energy efficiency to every citizen irrespective of education level.

10.8.6.5 Need For Financial Assistance or Funding Mechanisms

The higher first cost of energy efficient technologies may still hamper penetration in developing countries, especially if the technologies must be imported. For example, high-performance glass is an expensive proposition in many countries, including India. Though it is proven to save energy, the higher first cost of about six-seven times that of the conventional single glazing systems deters many users from investing in it. However, as the market grows, the industry is expected to achieve economies of scale and thus the cost of such technologies should be reduced. Tax breaks can provide an initial push toward energy efficient technologies. Other financial mechanisms such as low interest loans from banks for energy efficient and renewable energy technologies are important, too. For example, in India, interest subsidy is available to buy solar water heating systems.

Especially poorer consumers need investment support or affordable loans, governmental funding, or ESCO financing (Deringer et al., 2004). For example, in July 2008, the World Bank approved a US$15 million grant to Argentina in order to support energy efficient projects and develop incentives for reducing demand on fossil fuels (WB, 2008). Developing countries can raise money on their own through public benefit charges or taxes. For instance, Brazil has obliged utilities to spend 1% of annual revenues on end-use energy efficiency improvements and on R&D. In 2007, India introduced prepayment electricity metering in public buildings and for private consumers to ensure bill payment (IEA Online Database). In Thailand, the government has raised funds through a petrol tax since 1992 (Brulez and Rauch, 1998). The tax revenues are collected in a fund and are now used to support energy efficiency projects. It is important that such funds are managed by independent agencies or institutions to avoid political influence.

10.8.6.6 The Role of Regulatory Measures

Many developing countries, such as Malaysia, Brazil, Morocco, and partly Thailand, first introduced voluntary standards or voluntary labeling for appliances or buildings which are, however, often less effective than mandatory ones. Mandatory audits for public buildings and commercial sector buildings above a certain annual demand are a frequently used instrument, applied, for example, in Tunisia and Thailand. However, compliance is often difficult to achieve. In order to ensure enforcement, special efforts are necessary, such as combining regulatory measures with incentives like subsidies or awards.

10.8.6.7 Importance of Monitoring and Evaluation

While many strategies to encourage or mandate energy efficient buildings or energy efficiency get introduced by government, many fail due to the lack of proper implementation and monitoring mechanisms. There is a major gap between political statements and actual action or changes in building design and construction. For instance, in India, while the government has initiatives to encourage integration of the Energy Conservation Building Code with the National Building Code for the uniform and larger adoption of the energy code, there is currently no concrete plan for the implementation of the code, or for monitoring and verification. Incentives, both financial and symbolic, are crucial for the wider adoption of these programs.

In many countries, baseline data on energy demand are missing. This is problematic, since measuring the success of implemented policy instruments requires knowledge of the baseline consumption. Regular monitoring and evaluation of programs are necessary in order to adapt the program, if possible, to changing circumstances and maximize its outcome. Evaluation studies quantifying energy savings are needed to determine cost-effectiveness and make necessary program adjustments (Jannuzzi, 2005).

10.8.6.8 Role of Institutionalization

Developing countries with successful energy efficiency policies have usually started with the adoption of an Energy Efficiency law or an Energy Efficiency Strategy, as is the case in Thailand, South Africa, and Tunisia. For example, the Tunisian National Agency for Energy Management is one of the main drivers behind the country's currently successful energy efficiency programs. Numerous Arab states are currently introducing such agencies, often with external assistance. The agency can be established as a nonprofit foundation, which provides flexibility in hiring and contracting (Szklo and Geller, 2006). The aim of this institutionalization is to get energy efficiency recognized as a priority among government officials, as well as among utilities and other stakeholders. Furthermore, in universities, the establishment of energy management curricula can contribute to knowledge dissemination and the training of professionals. These professionals can then become competent staff members of the mentioned institutions.

10.8.6.9 Importance of Adaptation to Local Circumstances

Finally, although best practices and experiences can be shared and regional cooperation is useful, the success of programs depends, among other factors, on adaptation to the local economic, political, social, and cultural context. Many programs have already failed because they copied programs from other countries without taking into account differences in culture, political systems, or other areas (Ürge-Vorsatz and Koeppel, 2007). Therefore, a thorough assessment of the local social,

economic, political, and cultural fabric as it affects the operation of the policy instrument is important before decisions are taken. In large countries, the design of energy efficiency programs is most effective if adjusted to different regional contexts and institutional realities, such as the frailty of the regulatory certainty or the tendency of high contract failures. Moreover, the specificities of emerging economies – the social, legal, or economic context – can result in an increasing difficulty for customers in accessing capital. As it is, the higher rates of contractual failures in India or China, for instance, have resulted in investors finding it even more difficult to invest in energy efficiency projects (Taylor et al., 2008).

10.8.7 Implications of Broader Policies on Energy Efficiency in Buildings

10.8.7.1 Liberalization and Restructuring of Electricity Markets

Substantial literature exists on the impacts, both actual and estimated, of the liberalization and resulting restructuring of electricity markets on energy use in final demand sectors and particularly in residential and commercial buildings.

A number of authors (Burtraw et al., 2000; Sondreal et al., 2001; Sevi, 2004; Pollitt, 2008) suggest that electricity restructuring results in lower average prices for electricity, particularly in cases in which the regulated utilities were relatively inefficient. They point out that lower prices are likely to generate higher demand from consumers. However, as household sector long run price elasticity is relatively low, energy market liberalization may have only a small effect on demand even if price reductions are quite substantial. Following liberalization, prices will not necessarily fall in all areas, as price changes may start from different initial levels. If the local regulated utility is a low cost supplier of electricity compared to its neighbors, then prices in the local area could actually rise under competition (Palmer, 1999; Sevi, 2004). Furthermore, the experience with retail competition in Massachusetts and Pennsylvania shows that large industrial and some medium-size customers are the likely beneficiaries of lower prices, while the average price to residential and small commercial customers is likely to rise over time (Sverrisson et al., 2003).

The restructuring of electricity markets is also expected to produce more widespread use of time-differentiated pricing of electricity. This form of pricing will lead to a shifting of demand from peak to off-peak periods and will encourage building occupants to improve their energy-using behavior.

Several studies also indicate that the trend in new utility-funded DSM programs has been downward in the United States due to the deregulation of electricity markets (Eikeland, 1998; Palmer, 1999; Dubash, 2003; Sverrisson et al., 2003; Sevi, 2004; Blumstein et al., 2005) unless there is a regulatory environment that decouples sales of electricity from profits (WBCSD, 2008). For instance, in the United States, many state restructuring laws and federal restructuring bills also include a mechanism for funding DSM initiatives, e.g., through an electricity surcharge, which does not discriminate among electricity suppliers and could result in some energy savings. The Consortium for Energy Efficiency reports a doubling of total DSM expenditures by 88% of the utilities in the United States from 2006 through 2009 (Nevius et al., 2010). In many European countries, energy market reform has been accompanied by the introduction of a formal regulatory system for the first time. In some cases the opportunity has been taken to introduce energy saving obligations on energy companies, using "white certificates" or related mechanisms. In these countries, the introduction of energy efficiency obligations in conjunction with market restructuring has resulted in significantly increased activity on energy efficiency by energy companies (Pavan, 2008; Lees, 2008; Eyre et al., 2009).

The impact of energy market restructuring on energy efficiency is therefore dependent on the prior conditions and details of policy. The restructuring of electricity markets may also lead to increased penetration of distributed generation, both in industrialized and developing countries. More specifically, in a region with relatively high electricity prices stemming, for example, from expensive past investments, a customer can avoid these expenses by operating a distributed generator (e.g., PV units, small wind mills, etc.).

In developing countries, different patterns of current energy use and the relative unavailability of electricity distribution infrastructure will likely lead to very different effects of electricity restructuring than are likely in the developed world. The removal of subsidies that many developing nations provide to energy use, as well as the diversification in the level of service and pricing to reflect local actual costs, could lead to higher electricity prices in many cases, enhancing the attractiveness of investments in rural electrification (Burtraw et al., 2000; Nagayama, 2008). However, without an explicit effort, energy markets restructuring will result in decreased electricity accessibility to the poorer segments of the population (Dubash, 2003).

10.8.7.2 Energy Taxation and High Energy Prices

Inevitably, higher end-use energy prices, while not addressing all the market failures in the buildings sector, increase the energy conservation potential. However, the effect of price increases on energy demand depends on how sensitive demand is to energy price fluctuations. As already pointed out, household sector long-term price elasticity is relatively low, at least in developed economies, indicating that variability in energy prices may have only a small effect on demand even if price increases are quite substantial. For example, in the Netherlands, short run price elasticity for electricity in households was estimated to be between 0 and -0.25, whereas the long run elasticity was estimated to be -0.3 to -0.45 (Berkhout et al., 2000). This is mainly attributable to the

fact that in richer countries, energy prices are often a relatively insignificant cost component and therefore receive inadequate attention from building occupiers and owners (WBCSD, 2008).

There is some evidence that energy use behavior may be seriously affected when a significant part of available income is spent on energy. Energy tends to be used carefully in developing countries, and this is also true in richer countries during the last five years due to very high increases in international fuel prices. In the United States, high energy prices over the last five years have stimulated energy saving initiatives. In 2007, two-thirds of United States homebuilders were planning to build green in 15% of their projects, citing customer concern about energy costs as the main reason (Kelleher, 2006).

The increase of end-use energy prices through the imposition of energy taxes at some point in the energy supply chain may provide a second means to energy efficiency through the investment of the tax revenues – or at least part of them – in energy conservation related activities, such as mandatory DSM measures, subsidy schemes, green funds, or other mechanisms.

10.9 Gaps in Knowledge

While buildings are ubiquitous and some aspects are well researched and documented, such as the engineering aspects, there is surprisingly little understanding about their energy use and thus how problems related to their energy demand can be mitigated – both at the micro and macro levels. This section identifies a selection of important gaps in this knowledge, as considered important by the authors of this chapter.

Perhaps the most glaring problem with the knowledge is the shortage of related data and information. Little data exist on how energy in buildings is concretely used and how it is broken down by end-uses, building types, technologies, or other variables. Knowledge gaps exist about detailed energy use by energy service. Another major knowledge gap pertains to region-specific costs of new buildings in relation to their energy performance and region-specific costs of retrofits of existing buildings in relation to the savings in energy use achieved. Sufficient knowledge is also lacking about best practices, that is, the most sustainable means for providing energy services in each developmental, cultural, and individual situation. The interaction between life cycle energy use, environmental impacts, and cost aspects are also not well studied. Most of the published literature on life cycle assessments of different building types is very recent and the field is not yet very mature. Most engineering, environmental, and economic assessments related to sustainability options for buildings rely on their direct energy use, costs, and emissions. However, considering the entire life cycle would probably affect the validity of many decisions and policies, as there are often trade-offs.

The situation regarding energy policies in developing countries clearly requires further research. Only very few ex-post policy impact evaluation studies are currently available and even fewer include quantitative data on effectiveness, cost-effectiveness. The cumulative effect of policy packages, incremental and double counting effects of policy tools, as well as synergy effects, are poorly understood. While the area of co-benefits or ancillary benefits of energy efficiency in the buildings sector also needs to be further explored, even less is known about ancillary costs, which are seldom mentioned in literature. This relates to the better researched field of the obstacles or barriers to the deployment of energy efficiency in the sector.

10.10 Novelties in GEA's Global Building Energy Assessment

There have been several assessments completed recently on building-related opportunities for climate change mitigation or sustainable energy by various organizations. There are several new elements in this chapter as compared to these earlier assessments. These include:

- An energy service-centered approach: the discussion and consideration of opportunities recognizes that energy services are needed rather than energy per se, allowing for a broader spectrum of more innovative alternatives and solutions.
- Life cycle energy and emissions versus only operational ones: considering life cycle energy use and emissions when possible rather than just the operational energy and emissions in buildings, and recognizing the trade-offs. Novel policy recommendations originate from applying such a perspective.
- Applying a holistic, performance-based approach that recognizes that buildings are complex, integrated systems rather than sums of individual components.
- A novel global building energy use model using a performance-centered logic; presenting building thermal en pathways until 2050.
- The importance of the lock-in effect in the building sector has been shown for the first time, as well as detailed quantification of it.
- Large database on quantified or monetized co-benefits, illustrating the large orders of magnitude of such benefits.
- A detailed assessment of non-technological opportunities and challenges, emphasizing human dimensions.

References

ACE, 2000: *Energy Efficiency and Jobs. UK Issues and Case Studies*. Report prepared by the Association for the Conservation of Energy (ACE) for the Energy Saving Trust, London, UK.

ACEEE, 2010: *Panel 10 – Workforce Training. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings*. American Council for an Energy-Efficient Economy (ACEEE), Asilomar, CA.

ADEME, 2009: *Économies d'énergie, Faisons vite ça chauffe*. Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), Paris, France. www.faisonsvite.fr/ (accessed March 15, 2011).

Aebischer, B., M. Jakob, G. Catenazzi, and G. Henderson, 2007*:* Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study 2007*.Colle sur Loup, France.

AEC, 2002: *Energy Design Brief: Building Integrated Photovoltaics*. *Architectural Energy Corporation (AEC)*, Boulder, CO. www.archenergy.com (accessed December 16, 2010).

Ahrestani, S., 2010: *A multi-criteria site selection model for green roofs in the Sydney CBD: A GIS approach*. Institute of Environmental Studies and Faculty of the Built Environment, University of New South Wales, Australia.

Akbari, H., A. H. Rosenfeld, and H. Taha, 1990: *Cooling urban heat islands. Proceedings of the Fourth Urban Forestry Conference.* P. D. Rodbell (ed.) St. Louis, MO.

Akbari, H., S. Menon, and A. Rosenfeld, 2008: Global cooling: Increasing worldwide urban albedos to offset CO_2. *Climatic Change*, **95**(3–4): 275–286.

Allcott, H., 2010: *Social Norms and Energy Conservation*. Working Paper, June 9, 2010, Massachusetts Institute of Technology (MIT) and New York University (NYU).

Alliance to Save Energy, 2008: *India: Manual for the Development of Municipal Energy Efficiency Projects*. The Alliance to Save Energy, Washington, DC.

Amstalden, R. W., M. Kost, C. Nathani, and D. M. Imboden, 2007: Economic potential of energy-efficient retrofitting in the Swiss residential building sector: the effects of policy instruments and energy price expectations. *Energy Policy*, **35**(3): 1819–1829.

Arens, E., 2008: *Getting to zero: How CBE Industry Partners are meeting net-zero energy goals*. Centerline: Newsletter of the Center for the Built Environment at the University of California, Berkeley, CA, USA.

Argiriou, A. A., S. P. Lykoudis, C. A. Balaras, and D. N. Asimakopoulos, 2004: Experimental study of a earth-to-air heat exchanger coupled to a photovoltaic system. *Journal of Solar Energy Engineering,* **126**(1): 620–625.

Armstrong, P. R., S. B. Leeb, and L. K. Norford, 2006: Control with building mass-Part II: Simulation. *ASHRAE Transactions,* **112**(1): 462–473.

Atif, M. R. and A. D. Galasiu, 2003: Energy performance of daylight-linked automatic lighting control systems in large atrium spaces: report on two field-monitored case studies. *Energy and Buildings,* **35**(5): 441–461.

Aunan, K., H. Aaheim, and H. Seip, 2000: Reduced damage to health and environment from energy saving in Hungary. In *Proceedings of the IPCC Workshop on Assessing the Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies*. Washington, DC, USA.

Audenaert, A., S. H. de Cleyn and B. Vankerckhove, 2008: Economic analysis of passive houses and low-energy houses compared with standard houses. *Energy Policy*, **36**(1): 47–5.

Australian Greenhouse Office, 2005: *When you keep measuring it, you know even more about it! Projected impacts 2005–2020*. National Appliance and Equipment Program, Department of the Environment and Heritage, Australian Greenhouse Office, Commonwealth of Australia.

Ayres, R. U. and B. Warr, 2005: Accounting for growth: the role of physical work. *Structural Change and Economic Dynamics,* **16**(2): 181–209.

Baker, N. and K. Steemers, 1999: *Energy and Environment in Architecture: A Technical Design Guide*. E and FN Spon, London, UK.

Balaras, C. A., 2001: Energy retrofit of a neoclassic office building: social aspects and lessons learned. *ASHRAE Transactions,* **107**(1): 191–197.

Banks, N., 2008: *Implementation of Energy Performance Certificates in the Domestic Sector*. UK Energy Research Centre (UKERC), Oxford, UK.

Bryan Christie, 2006: In *Tools for better living: Smoke-free*, Barkeman, E., Fortune. CNN Money.com. http://money.cnn.com/popups/2006/fortune/better_living/5.html (accessed December 31, 2010).

Barry, J.A., 2007: *Watergy: Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment. Cost-Effective Savings of Water and Energy*. The Alliance to Save Energy, Washington, D.C.

Batlles, F. J., S. Rosiek, I. Muñoz, and A. R. Fernández-Alba, 2010: Environmental assessment of the CIESOL solar building after two years operation. *Environmental Science and Technology*, **44**(9): 3587–3593.

Beccis, F., 2006: *Energy efficiency targets using tradable certificates: microeconomic aspects and lessons from Italy. Proceedings of the biennial international workshop – advances in energy studies. "Perspectives on Energy Future,"* September 14, Portovenere, Italy.

Behrens, A. and C. Egenhofer, 2007: *An initial assessment of policy options to reduce – and secure against – the costs of energy insecurity*. Cost Assessment for Sustainable Energy Market. Centre for European Policy Studies, Unit for Climate Change and Energy, Brussels, Belgium.

Bell, M. and R. Lowe, 2000: Building regulation and sustainable housing. Part 2: technical issues. *Structural Survey,* **18**(2): 77–88.

Bender, S., M. Moezzi, M. Gossard, and L. Lutzenhiser, 2004: Using mass media to influence energy consumption behavior: California's 2001 flex your power campaign as a case study. In *Proceedings of the American Council for an Energy Efficient Economy (ACEEE)*, Summer Study, 2004.California Energy Commission, Sacramento, CA.

Berkhout, P. H. G., J. C. Muskens, and J. W. Welthuijsen, 2000: Defining the rebound effect. *Energy Policy,* **28**(6–7): 425–432.

BERR, 2001: *UK Fuel Poverty Strategy*. Report prepared by the Department for Business Enterprise and Regulatory Reform (BERR), London, UK.

Berrueta, V., R. Edwards, and O. R. Masera, 2008: Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy,* **33**(5): 859–870.

Berry, L. and M. Schweitzer, 2003: *Metaevaluation of National Weatherization Assistance: Program Based on State Studies 1993–2002*. Oak Ridge National Laboratory report prepared for the US Department of Energy (US DOE), Oak Ridge, TN, USA.

Bertoldi, P. and C. Ciugudeanu, 2005: *Five-Year Assessment of the European Green Light Programme*. Presentation at the 6th International Conference on Energy Efficient Lighting, 9–11 May, 2005, Shanghai, China.

Bertoldi, P. and S. Rezessy, 2006: *Tradable certificates for energy savings (White Certificates)*. Report prepared by the Joint Research Center of the European Commission (ISPRA), Rome, Italy.

Bertoldi, P. and S. Rezessy, 2007: Voluntary agreements for energy efficiency: review and results of European experiences. *Energy and Environment,* **18**(1):37–73.

Bhattacharya, S. C. and M. A. Leon, 2004: *Prospects for biomass gasifiers for cooking applications in Asia*. Energy Field of Study, Asian Institute of Technology, Bangkok, Thailand.

Bickel, P. and R. Friedrich, 2005: *ExternE. Externalities of energy.Methodology 2005 update*.Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Universität Stuttgart, Germany. Directorate-General for Research, Sustainable Energy Systems, European Commission (EC), Luxembourg.

BioLite, 2009: *Thermoelectrics in biomass stove systems*. Presented at the "Cookstove Workshop," November 18, Asian Institute of Technology, Bangkok, Thailand.

BioLite, 2011: *Introducing the BioLite HomeStove.* http://www.biolitestove.com/HomeStove.html (accessed 19 September 2011).

Blengini, G. A., and T. Di Carlo, 2010: Energy-saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy). *International Journal of Life Cycle Assessment,* 15(7): 652–665.

Blondeau, P., M. Sperandio, and F. Allard, 1997: Night ventilation for building cooling in summer. *Solar Energy,* **61**(5): 327–335.

Blumstein C., C. Goldman, and G. Barbose, 2005: Who should administer energy-efficiency programs? *Energy Policy,* **33**(8): 1053–1067.

Boardman, B., S. Darby, G. Killip, M. Hinnells, C. N. Jardine, J. Palmer, and G. Sinden, 2005: *40% House*. Environmental Change Institute, University of Oxford, UK.

Boardman, B., 2010: *Fixing Fuel Poverty. Challenges and Solutions*. Earthscan, London, UK.

Bodart, M. and A. De Herde, 2002: Global energy savings in office buildings by the use of daylighting. *Energy and Buildings,* **34**(5): 421–429.

Bohne, R. A., H. Brattebo, and H. Bergsdal, 2008: Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level. *Journal of Industrial Ecology,* **12**(1): 52–68.

Boonstra, C., I. Thijssen, and R. Vollebregt, 1997: *Glazed Balconies in Building Renovation*. James and James, London, UK.

Borg, N., Y. Blume, S. Thomas, W. Irrek, H. Faninger-Lund, P. Lund, and A. Pindar, 2003: *Harnessing the Power of the Public Purse*. Final report from the European PROST study on energy efficiency in the public sector, Stockholm, Sweden.

Borg, N., Y. Blume, S. Thomas, W. Irrek, H. Faninger-Lund, P. Lund, and A. Pindar, 2006: Release the power of the public purse. *Energy Policy,* **34**(2): 238–250.

Borjesson, P. and L. Gustavsson, 2000: Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. *Energy Policy,* **28**(9): 575–588.

Bornehag, C. G., J. Sundell, C. J. Weschler, T. Sigsgaard, B. Lundgren, M. Hasselgren, and L. Hägerhed-Engman, 2004: The association between asthma and allergic symptoms in children and phthalates in house dust: a nested case control study. *Environmental Health Perspectives,* **112**(14): 1393–1397.

Bornstein, R. and Q. Lin, 1999: *Urban Convergence Zone Influences on Convective Storms and Air Quality. Proceedings of the WMO International Conference, Congress of Biometeorology and International Conference on Urban Climate*, World Meteorology Organisation (WMO), Sydney, Australia.

Borsani, C. and M. Salvi, 2003: *Analysebericht zum Minergie-Standard*. Memorandum of Züricher Kantonalbank (ZKB) to CEPE-Team. Zurich, Switzerland.

Bottrill, C., 2007: *Internet Tools for Behaviour Change. Proceedings of the European Council for an Energy Efficient Economy (ECEEE)*, June 4–9, Cote d'Azur, France.

Bourassa, N., P. Haves, and J. Huang, 2002: A Computer Simulation Appraisal of Non-residential Low Energy Cooling Systems in California. In *Proceedings of the 2002 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, Vol. 3, Washington, DC, USA.

Bourbia, F. and H. B. Awbi, 2004: Building cluster and shading in urban canyon for hot dry climate, part 1: air and surface temperature measurements. *Renewable Energy,* **29**(2): 249–262.

Brandemuehl, M. and J. Braun, 1999: *The Impact of Demand-Controlled and Economizer Ventilation Strategies on Energy Use in Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA, USA.

BRE, 2003: *Energy Consumption Guide 19. Energy use in Offices*. Report prepared by the Government's Energy Efficiency Best Practice Programme (BRE), Watford, UK.

Bressand, F., N. Zhou, and J. Lin, 2007: Energy use in commercial buildings in China current situation and future scenarios. In *Proceedings of the European Council for an Energy Efficient Economy(ECEEE) 2007 Summer Study – Saving Energy Just Do it*! La Colle sur Loup, France, pp.1065–1071.

Brink, A. and M. Erlandsson, 2004: *Energiskatternas effekt på energianvändningen 1991–2001*. Rapport till Energimyndigheten. [In Swedish: Energy taxes effect on energy consumption 1991–2001. Report to the Swedish Energy Agency], Stockholm, Sweden.

Brophy, V., J.P. Clinch, F. J. Convery, J. D. Healy, C. King, and J. O. Lewis, 1999: *Homes for the 21st Century – the Costs and Benefits of Comfortable Housing for Ireland*. Report prepared for Energy Action Ltd. by the Energy Research Group and Environmental Institute, University College Dublin, Dublin, Ireland.

Brounen, D. and N. Kok, 2010: *On the Economics of EU Energy Labels in the Housing Market*. RICS Research, Erasmus University and Maastricht University, the Netherlands.

Brown, M., 2001: Market failures and barriers as a basis for clear energy policies. *Energy Policy,* **29**(14): 1197–1207.

Brown, M., J. Chandler, M.V. Lapsa, and B. K. Sovacol, 2008: *Lock-in: Barriers to Deploying Climate Change Mitigation Technologies*, Oak Ridge National Laboratory ORNL/TM-2007–124 (revised November, 2008), Oak Ridge, TN.

Brown, M., J. Chandler, M. V. Lapsa, and M. Ally, 2009: *Making Buildings Part of the Climate Solution: Policy Options to Promote Energy Efficiency*. Oak Ridge National Laboratory, TN.

Brulez, D. and R. Rauch, 1998: *Energy Conservation Legislation in Thailand: Concepts, Procedures and Challenges*. In *Compendium on Energy Conservation Legislation in Countries of the Asia and Pacific Region*. United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), Bangkok, Thailand.

Brunklaus, B., C. Thormark, and H. Baumann, 2010: Illustrating limitations of energy studies of buildings with LCA and actor analysis. *Building Research and Information,* **38**(3): 265–279.

Bureau of Energy Efficiency, 2009:*Official website of the Bureau of Energy Efficiency (BEE).* Ministry of Power, Government of India, New Delhi.

Burgess, J., 2003: Sustainable consumption: is it really achievable? *Consumer Policy Review,* **13**(3): 78–84.

Burtraw, D., K. Palmer, and M. Heintzelman, 2000: *Electricity restructuring: Consequences and Opportunities for the Environment, Resources for the Future*, Discussion paper 00–39, Washington, D.C.

Busch, J.F., 1992: A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. *Energy and Buildings,* **18**(3–4):235–249.

Buzar, S., 2007: *Energy Poverty in Eastern Europe: Hidden Geographies of Deprivation*. Ashgate Publishing Group, Aldershot, UK.

Çakmanus, I., 2007: Renovation of existing office buildings in regard to energy economy: an example from Ankara, Turkey. *Building and Environment,* **42**(3): 1348–1357.

Carbon Trust, 2005: *The UK Climate Change Programme: Potential Evolution for Business and the Public Sector*. Technical report prepared by Carbon Trust, London, UK.

Cartalsi C., A. Synodinou, M. Proedrou, A. Tsangrassoulis and M. Santamouris, 2001: Modifications in energy demand in urban areas as a result of climate change: an assessment for the southeast Mediterranean region. *Energy Conversion and Management,* **42**(14) pp.1647–1656.

CEA, 1995: *Supporting Research and Development to Promote Economic Growth: The Federal Government's Role*. Council of Economic Advisers (CEA), Washington, D.C.

Cebon, P. B., 1992: Twixt cup and lip: organizational behavior, technical prediction, and conservation practice. *Energy Policy,* **20**(9): 802–814.

Cedar, J., 2009: *Thermoelectrics in Biomass Stove Systems*. Presented at "Cookstove Workshop." Asian Institute of Technology, November 18, Bangkok, Thailand.

CERES, 2009: *From Risk to Opportunity: Insurer responses to Climate Change*, Report prepared by CERES, 2009.

Chakravarty, S., A. Chikkatur, H. de Coninck, S. Pacala, R. Socolow, and M. Tavoni, 2009: Sharing global CO_2 emission reductions among one billion high emitters. In *Proceedings of the National Academy of Sciences of the United States of America,* 106(29): pp.11884–11888.

Chapman, R., P. Howden-Chapman, H. Viggers, D. O'Dea, and M. Kennedy, 2009: Retrofitting houses with insulation: a cost–benefit analysis of a randomised community trial. *Journal of Epidemiology and Community Health,* **63**(4): 271–277.

Claridge, D. E., M. Liu, S. Deng, W. D. Turner, J. S. Haberl, S. U. Lee, M. Abbas, and H. Bruner, 2001: Cutting heating and cooling use almost in half without capital expenditure in a previously retrofit building. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE), Summer 2001*, **4**: 74–85.

CLG, 2010: *Residential Energy Conservation Ordinance Factsheet*. Prepared by Climate Leaders Group (CLG).

Clinch, J. P. and J. D. Healy, 1999: *Housing Standards and Excess Winter Mortality in Ireland*. Environmental Studies Research Series Working Paper 99/02, Department of Environmental Studies, University College Dublin, Ireland.

Clinch, J. P. and J. D. Healy, 2001: Cost-benefit analysis of domestic energy efficiency. *Energy Policy,* **29**(2): 113–124.

Cooremans, C., 2007: Strategic Fit of Energy Efficiency (Strategic and cultural dimensions of energy-efficiency investments).In *Proceedings of the European Council for an Energy-Efficient Economy (ECEEE) Summer Study*, June 4–9, 2007, la Colle Sur Loop, France.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt, 1997: The value of the world's ecosystem services and natural capital. *Nature,* **387**: 253–260.

Cottrell, J., 2004: *Ecotaxes in Germany and the United Kingdom – A Business View*. Green Budget Germany Conference Report, Berlin, Germany.

Crawford, R. H. and G. J. Treloar, 2004: Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. *Solar Energy,* **76**(1–3): 159–163.

Crossley, D., M. Maloney, and G. Watt, 2000: *Developing Mechanisms for Promoting Demand-side Management and Energy Efficiency in Changing Electricity Businesses*. Research report 3, task 6 of the International Energy Agency (IEA) Demand-side Management Programme, Energy Futures Australia Pty Ltd., New South Wales, Australia.

Cullen, J. M. and J. M. Allwood, 2009: The role of washing machines in life cycle assessment studies. *Journal of Industrial Ecology,* **13**(1): 27–37.

da Graça, G. C., Q. Chen, L. R.Glicksman and L.K. Norfold, 2002: Simulation of wind-driven ventilative cooling systems for an apartment building in Beijing and Shanghai. *Energy and Buildings*, **34**:1–11.

Darby, S., 2000: *Making it obvious: designing feedback into energy consumption*. In Effective Advice. Boardman and S. Darby (eds.), Appendix 4, Environmental Change Institute, University of Oxford, UK.

Darby, S., 2003: Making Sense of Energy Advice. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study*. Stockholm, Sweden.

Darby, S., 2006a: *The Effectiveness of Feedback on Energy Consumption*. A review for the Department for Environment Food and Rural Affairs (DEFRA) of the literature on metering, billing and direct displays. Environmental Change Institute, University of Oxford, UK.

Darby, S., 2006b: Social learning, household energy practice and public policy: lessons from an energy-conscious village. *Energy Policy,* **34**: 2929–2940.

Darby, S., 2008: Energy feedback in buildings: improving the infrastructure for demand reduction. *Building Research and Information,* **36**(5): 499–508.

Dascalaki, E. and M. Santamouris, 2002: On the potential of retrofitting scenarios for offices. *Building and Environment,* **37**(6): 557–567.

Davie, G. S., M. G. Baker, S. Hales and J. B. Carlin, 2007: *Trends and determinants of excess winter mortality in New Zealand: 1980 to 2000*. BMC *Public Health,* **7**:263.

Davis, D. L., A. Krupnick, and G. McGlynn, 2000: Ancillary benefits and cost of greenhouse gas mitigation: an overview. In *Proceedings of Workshop on Assessing the Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies*, March 27–29, 2000, Washington, DC, USA.

de Dear, R. J. and G. S. Brager, 1998: Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions,* **104**(1A):145–167.

de Dear, R. J. and G. S. Brager, 2002: Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings,* **34**(6):549–561.

de Garbino, J. P., 2004: *Children's health and the environment. A global perspective. A resource manual for the health sector*. World Health Organization (WHO), Geneva, Switzerland.

de Haan, P., M. G. Mueller, and A. Peters, 2006: Does the hybrid Toyota Prius lead to rebound effects? Analysis of size and number of cars previously owned by Swiss Prius buyers. *Ecological Economics,* **58**(3): 592–605.

de T'Serclaes, P., 2007: *Financing Energy Efficient Home. Existing Policy Responses to Financial Barriers*. Organization for Economic Co-operation and Development/ International Energy Agency (OECD/IEA), Paris, France.

DECC, 2009: *Annual Report on Fuel Poverty Statistics 2009*. Department of Energy and Climate Change (DECC), London, UK.

DeCanio, S. J. and W. E. Watkins, 1998: Investment In Energy Efficiency: Do the Characteristics of Firms Matter? *The Review of Economics and Statistics,* **80**(1): 95–107.

DEFRA, 2004: *Valuation of Health Benefits Associated with Reductions in Air Pollution*. Department for Environment, Food and Rural Affairs (DEFRA), London, UK.

DEFRA, 2005: *Fuel Poverty Monitoring: Energy Company Schemes 2003*. Annex to UK fuel Poverty Strategy, 3rd Annual Progress Report 2005,Department for Environment, Food and Rural Affairs (DEFRA), London, UK.

DEFRA, 2006b: *Review and Development of Carbon Abatement Curves for Available Technologies as Part of the Energy Efficiency Innovation Review*. Department for Environment, Food and Rural Affairs (DEFRA), ENVIROS Consulting, Ltd., London, UK.

DEFRA, 2006c: *Synthesis of Climate Change Policy Evaluations*. Department for Environment, Food and Rural Affairs (DEFRA), London, UK.

DEFRA, 2007a: Climate Change Agreements: Results of the Third Target Period Assessment. Department for Environment, Food and Rural Affairs (DEFRA), London, UK.

DEFRA, 2007b: *Energy Efficiency Action Plan*. Report prepared by the Department for Environment, Food and Rural Affairs (DEFRA), London, UK.

DEFRA/BERR, 2008: *The UK Fuel Poverty Strategy 6th Annual Progress Report.* Department for Environment, Food and Rural Affairs (DEFRA) / Department of Business Enterprise & Regulatory Reform (BERR), London, UK.

DEG, 2004: *Development of an Improved Two-Stage Evaporative Cooling System*. Davis Energy Group, California Energy Commission Report P500–04–016, St. Davis, CA.

Demirbilek, F. N., U. G. Yalçiner, M. N. Inanici, A. Ecevit, and O. S. Demirbilek, 2000: Energy conscious dwelling design for Ankara. *Building and Environment,* **35**: 33–40.

Den Baars, S., 2008: Energy efficient white LEDs for sustainable solid-state lighting, In *Physics of Sustainable Energy, Using Energy Efficiently and Producing it Renewably*, D. Hafemeister, B. G. Levi, M. D. Levine and P. Schwartz (eds), American Institute of Physics, Melville, NY.

Denniston, S., L. Dunn, J. Antonoff, and R. DiNola, 2010: Toward a future model energy code for existing and historic buildings. In *Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA.

Deringer, J., M. Iyer, and Yu Joe Huang, 2004: Transferred Just on Paper? Why Doesn't the Reality of Transferring/Adapting Energy Efficiency Codes and Standards Come Close to the Potential? In *Proceedings of the 2004 American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*. August 2004, Pacific Grove, CA.

DEWHA, 2008: *Energy Use in the Australian Residential Sector 1986–2020. Part 1*. Report prepared by Energy Efficient Strategies, Department of Environment, Water, Heritage and the Arts (DEWHA), Canberra, Australia.

Dharmadhikari, S., D. Pons, and F. Principaud, 2000: Contribution of stratified thermal storage to cost-effective trigeneration project. *ASHRAE Transactions,* **106**(2): 912–919.

Dias, R., C. Mattos, and J. Balesieri, 2004: Energy education: breaking up the rational energy use barriers. *Energy Policy,* **32**(11): 1339–1347.

Dietz, T., G. T. Gardner, J. Gilligan, P.C. Stern, and M.P. Vandenbergh, 2009: Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. In *Proceedings of the National Academy of Sciences of the United States of America (PNAS),* **106**(44): 18452–18456.

Dilmetz, K., 2009: *Energy Efficiency for Buildings*. Presentation for German American Chamber of Commerce of the Southern United States, Inc. (GACC South), Houston, TX.

Dobson, J. and J. Griffin, 1992: Conservation effect of immediate electricity cost feedback on residential consumption behavior. In *Proceedings of American Council for an Energy-Efficient Economy (ACEEE) 1992 Summer Study on Energy Efficiency in Buildings*10, Pacific Grove, CA, pp.33–35.

Dodoo, A., L. Gustavsson, and R. Sathre, 2010: Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard. *Resources, Conservation and Recycling,* **54**(12): 1152–1160.

DSDNI, 2008: *Ending fuel Poverty: A Strategy for Northern Ireland*. Department for Social Development in Northern Ireland (DSDNI), Belfast, Northern Ireland.

Dubash, N. K., 2003: Revisiting electricity reform: the case for a sustainable development approach. *Utilities Policy,* **11**: 143–154.

Durkin, T., 2006: Boiler system efficiencies. *ASHRAE,* **48**(51–57): 42–43.

Dutta, S., I. H. Rehman, P. Malhotra, and V. P. Ramana, 1997: *Biogas, the Indian NGO Experience*. A FPRO-CHF Network Program, New Delhi, India.

EC, 1995: *ExternE – Externalities of Energy*. Vol. 2: Methodology, EUR 16521. European Commission (EC), Office for Official Publications of the European Communities, Luxembourg.

EC, 2009: *Low Energy Buildings in Europe: Current State of Play, Definitions and Best Practice*. Info note, European Commission (EC), Brussels, Belgium.

ECCJ (Energy Conservation Center, Japan), 2008: *Energy saving appliance catalog*. http://www.eccj.or.jp/index.html.

ECCP, 2001: *Long Report*. European Climate Change Program (ECCP), Brussels, Belgium.

ECCP, 2003: *Can We Meet Our Kyoto Targets?*2nd European Climate Change Programme Progress Report, European Climate Change Program (ECCP), Brussels, Belgium.

Ecofys, 2001: *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Top-down Analysis of Greenhouse Gas Emission Reduction Possibilities in the EU*. Contribution to a study for DG Environment, European Commission by Ecofys Energy and Environment, AEA Technology Environment and National Technical University of Athens, Greece.

ECS, 2002: *Fiscal Policies for Improving Energy Efficiency. Taxation, Grants and Subsidies*. Energy Charter Secretariat (ECS), Brussels, Belgium.

EEA, 2006: *Air Quality and Ancillary Benefits of Climate Change Policies*. European Environment Agency (EEA), Technical Report 4/2006, Copenhagen, Denmark.

Efficiency Vermont, 2009: *For My Home*. Vermont Energy Investment Corporation: Burlington, VT. www.efficiencyvermont.com/for_my_home.aspx (accessed March 15, 2011).

Eichholtz, P., N. Kok, and J. Quigley, 2009: *Why Do Companies Rent Green? Real Property and Corporate Social Responsibility*. Energy Policy and Economics, University of California Energy Institute, Berkeley, CA, USA.

Eicker, U., M. Huber, P. Seeberger, and C. Vorschulze, 2006: Limits and potentials of office building climatisation with ambient air. *Energy and Buildings,* **38**: 574–581.

Eiffert, P., 2003: *Guidelines for the Economic Evaluation of Building-Integrated Photovoltaic Power Systems*. International Energy Agency PVPS

Task 7: Photovoltaic Power Systems in the Built Environment, Technical Report NREL/TP-550–31977, National Renewable Energy Laboratory, Golden, CO.

Eikeland, P. O., 1998: Electricity market liberalization and environmental performance: Norway and the UK. *Energy Policy,* **26**(12): 91–927.

Enerdata, 2009:Global Energy Intelligence. Database:www.enerdata.net (accessed1 September, 2009)

Evander, A., G. Sieböck, and L. Neij, 2004: *Diffusion and Development of New Energy Technologies: Lessons Learned in View of Renewable Energy and Energy Efficiency End-use Projects in Developing Countries*. Report 2004: 2, International Institute for Industrial Environmental Economics, Lund University, Sweden.

Energy Data and Modeling Center, 2008: *Handbook of Energy and Economic Statistics in Japan*. The Energy Conservation Centre, Japan.

Energywatch, 2005: *Get Smart: Bring Meters into the 21st Century*. Energywatch, July 2005. www.energywatch.org.uk/uploads/Smart_meters.pdf (accessed May 30, 2011).

EST, 2009: *Easy Ways to Stop Wasting Energy*. Energy Saving Trust (EST): London, UK. www.energysavingtrust.org.uk/Easy-ways-to-stop-wasting-energy/Stop-wasting-energy-and-cut-your-bills/Tips-to-help-you-stop-wasting-energy/Getting-started (accessed March 15, 2011).

Erb, K. H., S. Gingrich, F. Krausmann, and H. Haberl, 2008: Industrialization, fossil fuels, and the transformation of land use. *Journal of Industrial Ecology,* **12**(5–6): 686–703.

Eurowinter Group,1997: Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. *The Lancet,* **349**: 1341–1346.

Eyre, N., M. Pavan, and L. Bodineau, 2009: Energy company obligations to save energy in Italy, France and the UK: what have we learnt? In *Proceedings of the 2009 European Council for an Energy Efficient Economy (ECEEE) Summer Study*. La Colle sur Loupe, France.

FEEM, 2008: *Social Costs of Electricity Generation and Policy Design.* In *Proceedings of the final conference of the CASES Project*, Fondazione Enni Enrico Matei (FEEM), September 29–30, 2008, Milan, Italy.

Feist, W., 1996: Life-cycle Energy Analysis: Comparison of Low-energy House, Passive House, Self-sufficient House. In *Proceedings of the International Symposium of CIB W67*.Vienna, Austria, pp.183–190.

Feist, W., J. Schnieders, V. Dorer, and A. Haas, 2005: Re-inventing air heating: convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings,* **37**: 1186–1203.

Feist, W., 2007: *Tasks – challenges – perspectives. Conference Proceedings, 11th International Passive House Conference*, Bregenz, Passive House Institute, Darmstadt, Germany, pp. 383–392.

Fisher, D., F. Schmid, and A. J. Spata, 1999: Estimating the energy-saving benefit of reduced-flow and/or multi-speed commercial kitchen ventilation systems. *ASHRAE Transactions,* **105**(1): 1138–1151.

Fisk, B., 1999: *Indoor Air Quality Handbook*, McGraw Hill, New York, NY.

Fisk, W. J., 2000: Health and productivity gains from better indoor environments and their relationship with building energy efficiency. *Annual Review of Energy and the Environment,* **25**(1): 537–566.

Florides, G. A., S. A. Tassou, S. A. Kalogirou, and L. C. Wrobel, 2002: Measures used to lower building energy consumption and their cost effectiveness. *Applied Energy,* **73**: 299–328.

Ford, B., N. Patel, P. Zaveri, and M. Hewitt, 1998: Cooling without air conditioning: The Torrent Research Centre, Ahmedabad, India. *Renewable Energy*, **15**: 177–182.

Francisco, P. W., L. Palmiter, and B. Davis, 1998: Modeling the thermal distribution efficiency of ducts: comparisons to measured results. *Energy and Buildings,* **28**: 287–297.

Frank, T., 2005: Climate change impacts on building heating and cooling energy demand in Switzerland. *Energy and Buildings,* **37**: 1175–1185.

Fridley, D. and J. Lin, 2004: *Potential Carbon Impact of Promoting Energy Star in China and Other Countries*. Lawrence Berkeley National Laboratory (LBNL), Berkeley, USA.

Friel, S. 2007. Housing, fuel poverty and health: A Pan-European analysis (book review). *Health Sociology Review*, **16**(2): 195–196.

Frondel, M., J. Peters, and C. Vance, 2008: Identifying the rebound: evidence from a German household panel. *Energy Journal,* **29**(4): 145–163.

Fujino, J., G. Hibino, T. Ehara, Y. Matsuoka, M. Yuzuru, K. Toshihiko, and M. Kainuma, 2008: Back-casting analysis for 70% emission reduction in Japan by 2050. *Climate Policy,* **8**: S108-S124.

Fülöp, O., 2009: Ösztönzött pazarlás – Lakossági energiaárak állami támogatása 2003–2009. Összefoglaló elemzés. Energia Klub, Budapest, Hungary.

Fuller, Merrian C., S. Compagni Portis, and D. M. Kammen, 2009: Toward a low-carbon economy: municipal financing for energy efficiency and solar power. *Environment Science and Policy for Sustainable Development*. January-February 2009. www.environmentmagazine.org/Archives/Back%20Issues/January-February%202009/FullerPortisKammen-full.html (accessed May 31, 2011).

Gadgil, A., S. Al-Beaini, M. Benhabib, S. Engelage, and A. Langton, 2007: *Domestic Solar Water Heater for Developing Countries*. Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA.

Gallaher, M.P., A. C. O'Connor, J. L. Dettbarn, Jr., and L. T. Gilday, 2004: *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. US Department of Commerce Technology Administration National Institute of Standards and Technology, Gaithersburg, MD, USA.

Gamble, D., B. Dean, D. Meisegeier, and J. Hall, 2004: Building a path towards zero energy homes with energy efficient upgrades. In *Proceedings of the 2004 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*. Vol. 1, Washington, DC, USA. pp.95–106.

Garbesi, K. and L.B. Desroches, 2010: *Max Tech and Beyond: Maximizing Appliance and Equipment Efficiency by Design*. Lawrence Berkeley National Laboratory, Berkeley, CA.

Garcia Casals, X., 2006: Analysis of building energy regulation and certification in Europe: Their role, limitations and differences. *Energy and Buildings,* **38**(5): 381–392.

García-Frapolli E., A. Schilmann, V. Berrueta, H. Riojas-Rodríguez, R. Edwards, M. Johnson, A. Guevara-Sanginés, C. Armendariz, and O. Masera, 2010: Beyond fuelwood savings: valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. *Ecological Economics,* **69**(12): 2598–2605.

Geller, H. and S. Attali, 2005: *The Experience with Energy Efficiency Policies and Programmes in IEA Countries: Learning from the Critics*. International Energy Agency (IEA) Information Paper, Paris, France.

Geller, H., P. Harrington, A. H. Rosenfeld, S. Tanishima, and F. Unander, 2006: Policies for increasing energy efficiencies. 30 years of experience in OECD-countries. *Energy Policy,* **34**(5): 556–573.

Genchi, Y., Y. Okano, and T. Ihara, 2007: *Environmental impact assessment of Urban Heat Island phenomena based on Endpoint-type LCIA Methodology: Part 4 Evaluation of environmental impacts on sleep disorder caused by urban heat island in Tokyo* (in Japanese). Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, Environmental Engineering I, 771–772.

Gillingham, K., Newell, R., and K. Palmer, 2004: The effectiveness and cost of energy efficiency programmes. *Resources. Resources for the Future* (RFF) Technical paper, Washington, DC, USA.

Gillingham, K., R. Newell, and K. Palmer, 2006: Energy efficiency policies: a retrospective examination. *Annual Review of Environmental Resources,* **31**: 161–92.

Goldman, C., N. Hopper, and J. Osborn, 2005: Review of the US ESCO industry market trends: an empirical analysis of project data. *Energy Policy,* **33**(3): 387–405.

Graham, P., 2005: *Design for Adaptability: An introduction to the principles and basic strategies*. The Environment Design Guide GEN 66, Royal Australian Institute of Architects, Canberra, Australia.

Gram-Hanssen, K. 2004. Domestic electricity consumption: consumers and appliances. In *The Ecological Economics of Consumption*. L. A. Reisch and I. Røpke (eds), Edward Elgar Publishing, London, UK, pp.132–149.

Green, M. A., 2006: Consolidation of thin-film photovoltaic technology: the coming decade of opportunity. *Progress in Photovoltaics: Research and Applications,* **14**: 383–392.

Greening, L., D. Green, and C. Difiglio, 2000: Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy,* **28**(6–7): 389–401.

Gustavsson, L. and R. Sathre, 2006: Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment,* **41**(7): 940–951.

Gutschner, M. and Task-7 Members, 2001: *Potential for Building Integrated Photovoltaics*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

Guy, S. and E. Shove, 2000: *A Sociology of Energy, Buildings, and the Environment*. Routledge, London, UK.

Haas, R., P. Biermayr, J. Zoechling, and H. Auer, 1998: Impacts on electricity consumption of household appliances in Austria: a comparison of time series and cross-section analyses. *Energy Policy,* **26**(13): 1031–1040.

Haas, R. and P. Biermayr, 2000: The rebound effect for space heating – Empirical evidence from Austria. *Energy Policy,* **28**(6–7): 403–410.

Halozan, H. and R. Rieberer, 1997: Air heating systems for low-energy buildings. *IEA Heat Pump Centre Newsletter,* **15**(4): 21–22.

Haller, A., E. Schweizer, P. O. Braun, and K. Voss, 1997: *Transparent Insulation in Building Renovation*. James and James, London, UK.

Hamada, Y., M. Nakamura, K. Ochifuji, S. Yokoyama, and K. Nagano, 2003: Development of a database of low energy homes around the world and analysis of their trends. *Renewable Energy,* **28**: 321–328.

Haney, A. B., T. Jamasb, and M. G. Pollitt, 2008: *Smart Metering and Electricity Demand: Technology, Economics and International Experience*. ESRC Electricity Policy Research Group and Faculty of Economics, University of Cambridge, UK.

Harrigan, M. and E. Curley, 2010: *Global Environmental Education, Lacking Energy. Proceedings of American Council for an Energy-Efficient Economy (ACEEE) 2010 Summer Study on Building*, Pacific Grove, CA, USA.

Harris, J., B. Aebischer, J. Glickman, G. Magnin, A. Maier, and J. Vigand, 2005: Public sector leadership: transforming the market for efficient products and services. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study* 2005.ADEME Editions, Paris, France.

Hart & Cooley, Inc., 2009. Composition and Properties of Air. *TechTalk,* **1(2), September-October.**

Hartway, R., S. Price, and C. K. Woo, 1999: Smart meter, customer choice and profitable time-of-use rate option. *Energy,* **24**(10): 895–903.

Harvey, L.D.D., 2006: *A Handbook on Low-Energy Buildings and District-Energy Systems.* Earthscan, London, UK.

Harvey, L. D. D. and M. Siddall, 2008: Advanced glazing systems and the economics of comfort. *Green Building Magazine*, Spring **08**: 30–35.

Harvey, L. D. D., 2009: Reducing energy use in the buildings sector: measures, costs, and examples. *Special Issue: Energy Efficiency: How Far Does it Get Us in Controlling Climate Change?,* **2**(**2**): 139–163.

Harvey, L. D. D., 2010: *Energy and the New Reality, Volume 1: Energy Efficiency and the Demand for Energy Services*. Earthscan, London, UK.

Hassett, K. and G. Metcalf. (1993). Energy conservation investments: do consumers discount the future correctly? *Energy Policy,* **21**(6), 710–716.

Hastings, R. and M. Wall, 2007a: *Sustainable Solar Housing, Volume 1: Strategies and Solutions*. Earthscan, London, UK.

Hastings, R. and M. Wall, 2007b: *Sustainable Solar Housing, Volume 2: Exemplary Buildings and Technologies*. Earthscan, London, UK.

Haus der Zukunft, 2006: *The very first reconstruction in Austria of a one-unit house to passive house standard (Model project in Pettenbach/Upper Austria)*. www.hausderzukunft.at/results.html/id3955 (accessed 30 August, 2011).

Haus der Zukunft, 2007: *PASSIVe house renovation, Makartstrasse, Linz*. www.hausderzukunft.at/results.html/id3951 (accessed 30 August, 2011).

Hausman, J. A., 1979: Individual discount rates and the purchase and utilization of energy-using durables. *Bell Journal of Economics,* **10**(1): 33.

Healy, J. D., 2004:*Housing, Fuel Poverty, and Health: a Pan-European Analysis*. Ashgate Publishing, Aldershot, UK.

Healy, J. D. and J. P. Clinch, 2002: Fuel poverty, thermal comfort and occupancy: results of a national household-survey in Ireland. *Applied Energy,* **73**(3–4): 329–343.

Hegarty, D., 2006: Satisfying a burning need. *Philips Research Password,* **28**(October): (28–31)

Hegedus, S., 2006: Thin film solar modules: The low cost, high throughput and versatile alternative to Si wafers. *Progress in Photovoltaics. Research and Applications,* **14**: 393–411.

Heijne, C., 2003: *Energy Education Hitting Home*. Centre for Sustainable Energy, Bristol, UK.

Hein, L., K.V. Koppen, R.S. de Groot, and E.C. van Ierland, 2005: Spatial scales, stakeholders and the valuation of ecosystem services. *Ecological economics,* **57**(2): 209–228.

Henderson, G., 2005: *Home air conditioning in Europe – how much energy would we use if we became more like American households? Proceedings of the European Council for an Energy Efficient Economy (ECEEE)*, June 2005, Mandelieu, France.

Hermelink, A., 2006: A retrofit for sustainability: meeting occupants' needs within environmental limits. In *Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA, USA.

Hernandez, P. and P. Kenny, 2010: From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings,* **42**(6): 815–821.

Hertwich, E. G., 2005a: Consumption and the rebound effect: An industrial ecology perspective. *Journal of Industrial Ecology,* **9**(**1**–2): 85–98.

Hertwich, E. G., 2005b: Lifecycle approaches to sustainable consumption: a critical review. *Environmental Science and Technology,* **39**(13): 4673–4684.

Hertwich, E. G, 2011: The life cycle environmental impacts of consumption. *Economic Systems Research,* **23**(1): 27–48.

Hestnes, A. G. and N. U. Kofoed, 1997: *OFFICE: Passive Retrofitting of Office Buildings to Improve their Energy Performance and Indoor Environment*. JOULE Programme: JOR3-CT96–0034, European Commission Directorate General for Science Research and Development, Brussels, Belgium.

Hestnes, A. G. and N. U. Kofoed, 2002: Effective retrofitting scenarios for energy efficiency and comfort: results of the design and evaluation activities within the OFFICE project. *Building and Environment,* **37**(6): 569–574.

Hewitt, D., M. Frankel, and D. Cohan, 2010: The future of energy codes. In *Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) 2010 Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA, USA.

Hoffman, A. J. and R. Henn, 2008: Overcoming the social and psychological barriers to green building. *Organization & Environment,* **21**(4): 390–419.

Holt, S. and L. Harrington, 2003*:* Lessons learnt from Australia's standards and labelling programme. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE)2003 Summer Study*. Saint Raphaël, France.

Holton, J. K. and P. E. Rittelmann, 2002: Base loads (lighting, appliances, DHW) and the high performance house. *ASHRAE Transactions,* **108**(Part 1): 232–242.

Howe, M., D. Holland, and A. Livchak, 2003: Displacement ventilation: Smart way to deal with increased heat gains in the telecommunication equipment room. *ASHRAE Transactions,* **109**(Part 1): 323–327.

Howieson, S. G., 2005: Multiple deprivation and excess winter deaths in Scotland. *The Journal of the Royal Society for the Promotion of Health,* **125**(1): 18–22.

Hughes, P. J. and J. A. Shonder, 1998: *The Evaluation of a 4000-Home Geothermal Heat Pump Retrofit at Fort Polk, Louisiana*, ORNL/CON-460, Oak Ridge National Laboratory, TN, USA.

Hui, S. C. M., 2002: *Using performance-based approach in building energy standards and codes. In Proceedings of the Chonqing-Hong Kong Joint Symposium 2002.*8–10 July 2002, Chongqing, China, pp.A52–61.

Humm, O., 2000: Ecology and economy when retrofitting apartment buildings. *IEA Heat Pump Centre Newsletter,* **15**(4): 17–18.

Hunt, A., Watkiss, P., 2011: Climate Change Impacts and Adaptation in Cities: A Review of the Literature. *Climatic Change*, **104** (1): 13–49

Hutton, R. B., G. A. Mauser, P. Filiatrault, and O. T. Ahtola, 1986: Effects of cost-related feedback on consumer knowledge and consumption behaviour: a field experimental approach. *Journal of Consumer Research,* **13**(3): 327–336.

Hutton, G., E. Rehfuess, and F. Tediosi, 2007: Evaluation of the costs and benefits of interventions to reduce indoor air pollution. *Energy for Sustainable Development,* **11**(4): 34–43.

Hutson, S. S., N. L. Barber, J. F. Kenny, K. S. Linsey, D. S. Lumia and M. A. Maupin, 2004: *Estimated Use of water in the United States in 2000*. USGS Circular 1268, United States Geological Survey (USGS), Reston, VA, USA.

IBM, 2007:*Ontario Energy Board Smart Price Pilot Final Report*, IBM Global Business Services and eMeter Strategic Consulting, Ontario Energy Board, Toronto, ON, Canada.

IEA, 1999: *District Cooling, Balancing the Production and Demand in CHP*. Netherlands Agency for Energy and Environment, International Energy Agency (IEA), Sittard, the Netherlands.

IEA, 2003: *Cool Appliances, Policy Strategies for Energy Efficient Homes*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2004: *Energy Balances of non-OECD Countries 2001–2002*.International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2005a*: Evaluating Energy Efficiency Policy Measures & DSM Programmes, Volume 1 Evaluation Guidebook*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2005b: *Saving Electricity in a Hurry – Dealing with Temporary Shortfalls in Electricity Supplies*. International Energy Agency International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2006: *World Energy Outlook 2006*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2007a: *Mind the Gap- Quantifying Principal-Agent Problems in Energy Efficiency*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2007b: *Energy Use in the New Millennium. Trends in IEA countries.* In *Support of the G8 Plan of Action*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2008a: *Energy Technology Perspectives, 2008: Scenarios & Strategies to 2050: in Support of the G8 Plan of Action*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2008b: *World Energy Outlook 2008*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

IEA, 2008c: *Trends in Photovoltaic Applications, Survey Report of Selected IEA Countries Between 1992 and 2007*. Report IEA-PVPS T1–17,International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD)

IEA. 2010a: *Energy Technology Perspective. Scenarios & Strategies to 2050*. International Energy Agency (IEA). Paris, France.

IEA, 2010b: *World Energy Outlook 2010*. International Energy Agency (IEA), Paris, France.

IEA, 2010c: *Energy Performance Certification of Buildings*. International Energy Agency (IEA), Paris, France.

IEA, 2010d: *Energy Poverty. How to make energy access universal?* Special early excerpt of the World Energy Outlook 2010 for the UN General Assembly on the Millennium Development Goals. International Energy Agency (IEA), United Nations Development Programme (UNDP) and United Nations Industrial Development Organization (UNIDO), Paris, France.

IEA Online Statistics, 2007: Statistics and Balances. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France, www.iea.org/stats/index.asp (accessed 28 April 2011).

IIASA, 2007: *GGI Scenario Database*. International Institute for Applied System Analysis (IIASA), Laxenburg, Austria. www.iiasa.ac.at/Research/GGI/DB/ (accessed April 2011).

Indiastat, 2010: *Figures at All-India, State level. Revealing India statistically.* Indiastat.com. www.indiastat.com/power/26/consumptionandsale/70/stats.aspx (accessed April 2011).

Interface Engineering, 2005: *Engineering a Sustainable World: Design Process and Engineering Innovations for the Center for Health and Healing at the Oregon Health and Science University, River Campus*. Interview by Maria Sharmina, 2009. www.interface-engineering.com.

IPCC, 1996: *Climate Change 1995. IPCC Second Assessment*. Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2007: *Climate Change 2007 – Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Itard, L. and G. Klunder, 2007: Comparing environmental impacts of renovated housing stock with new construction. *Building Research and Information,* **35**(3): 252–267.

Jaboyedoff, P., C. A. Roulet, V. Dorer, A. Weber, and A. Pfeiffer, 2004: Energy in air-handling units – results of the AIRLESS European project. *Energy and Buildings,* **36**(4): 391–399.

Jackson, J., 2008: *Energy Budgets at Risk (EBaR): A Risk Management Approach to Energy Purchase and Efficiency Choices*. Wiley Finance, Hoboken, NJ, USA.

Jackson, T., 2009: Prosperity without growth-Economics for a finite planet, Earthscan, Oxford.

Jaffe, A. B. and R. N. Stavins, 1994: The energy-efficiency gap. *Energy Policy,* **22**(10): 804–810.

Jain, M., V. Gaba, and L. Srivastava, 2007: *Managing Power Demand – A Case Study of Residential Sector in Delhi*. The Energy & Resources Institute (TERI), Teri Press, New Delhi, India.

Jakob, M., 2006: Marginal costs and co-benefits of energy efficiency investments – the case of the Swiss residential sector. *Energy Policy,* **34**(2): 172–187.

Janda, K. B., 1998: *Building Change: Effects of Professional Culture and Organizational Context on Energy Efficiency Adoption in Buildings*. Energy and Resources Group, University of California at Berkeley, Berkeley, CA, USA.

Janda, K. B., 1999: *Re-Inscribing Design Work: Architects, Engineers, and Efficiency Advocates. Proceedings of the European Council for an Energy-Efficient Economy (ECEEE) Summer Study*. June 1–6, 2009, Mandelieu, France.

Janda, K. B., C. Payne, R. Kunkle, and L. Lutzenhiser, 2002: What organizations did (and didn't) do: three factors that shaped conservation responses to California's 2001 'crisis'. In Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) 2002 Summer Study, Asilomar, CA, USA.

Janda, K. B., 2008: *Implications of Ownership in the U.S. and U.K.: An Exploration of Energy Star Buildings & the Energy Efficiency Accreditation Scheme. Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, August 17–22, 2008, Asilomar, CA, USA.

Janda, K.B., 2009: Worldwide status of energy standards for buildings: a 2009 update. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study*, June 1–6, 2009, Cote d'Azur, France.

Jannuzzi, G. M., 2005: Energy Efficiency and R&D Activities in Brazil: Experiences from the Wirecharge Mechanism (1998–2004). In *Developing Financial Intermediation Mechanisms for Energy Projects in Brazil, China and India*. Prepared by Econergy International Corporation, Angra dos Reis, Brazil.

Jennings, J. D., F. M. Rubinstein, D. DiBartolomeo, and S. L. Blanc, 2000: *Comparison of Control Options in Private Offices in an Advanced Lighting Controls Testbed*. LBNL-43096 REV, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Jin, S. H, 2007: The effectiveness of energy efficiency improvement in a developing country: Rebound effect of residential electricity use in South Korea. *Energy Policy,* **35**(11): 5622–5629.

Jochem E., T. Barker, S. Scrieciu, W. Schade, N. Helfrich, O. Edenhofer, N. Bauer, S. Marchand, J. Neuhaus, S. Mima, P. Criqui, J. Morel, B. Chateau, A. Kitous, G. J. Nabuurs, M. J. Schelhaas, T. Groen, L. Riffeser, F. Reitze, E. Jochem, G. Catenazzi, M. Jakob, B. Aebischer, W. Eichhammer, A. Held, M. Ragwitz, U. Reiter, and H. Turton, 2009: *Adaptation and Mitigation Strategies: Supporting European Climate Policy*. Report D-M1.2 of the reference scenario for Europe. Fraunhofer ISI, Karlsruhe, Germany.

John, M., M. Smith, and S. Korosec, 2005: *Integrated Energy Policy Report*. California Energy Commission, Sacramento, CA.

Johnson, M., R. Edwards, C. Alatorre, and O. Masera, 2008: In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmospheric Environment,* **42**(2008): 1206–1222.

Jones Lang LaSalle/CREIS, 2006: *OSCAR – Office Service Charge Analysis Report. Based on 397 buildings with 6 million m2 in 2006*.Jones Lang LaSalle. Chicago, IL, USA.

Joosen, S., M. Harmelink, and K. Blok, 2004: *Evaluation Climate Policy in the Built Environment 1995–2002*. Ecofys report prepared for the Dutch Ministry of Housing, Spatial Planning and the Environment, Utrecht, the Netherlands.

Jyukankyo Research Institute and Japan Centre for Climate Change Action, 2007: *Fact sheet of energy saving home electrical appliances II. Energy saving of home electrical appliances (1) Air conditioner (in Japanese).* Jyukankyo Research Institute and the Japan Center for Climate Change Action, Tokyo, Japan.

Kats, G. 2003: *The Costs and Financial Benefits of Green Buildings*. A report prepared for California's Sustainable Building Task Force, Sacramento, CA, USA.

Kats, G., L. Alevantis, A. Berman, E. Mills, and J. Perlman, 2003: *The Costs and Financial Benefits of Green Buildings*. A report to California's Sustainable Building Task Force, Sacramento, CA, USA.

Kats, G., 2005: *National Review of Green Schools: Costs, Benefits, and Implications for Massachusetts*. A report for the Massachusetts Technology Collaborative, Boston, MA.

Katsev, R. D. and T. R. Johnson, 1987: *Promoting Energy Conservation: An Analysis of Behavioral Research*. Westview Special Studies in Natural Resources and Energy Management, Westview Press, Boulder, CO, USA.

Kelleher, E., 2006: *US Homebuilders Go Green*. Clean Energy Solutions, US Department of State, Bureau of International Information Programs, Washington, DC, USA.

Kempton, W., 1992: Psychological research for new energy problems. *American Psychologist,* **47**(10): 1213.

Keshner, M. S. and R. Arya, 2004: *Study of Potential Cost Reductions Resulting from Super-Largescale Manufacturing of PV Modules*. Final Subcontract Report, NREL/SR-520–56846. Washington, DC, USA.

Khan, J., M. Harmelink, R. Harmsen, W. Irrek, and N. Labanca, 2007: From Theory Based Policy Evaluation to SMART Policy Design. Summary Report of the AID-EE Project. *Project executed within the framework of the Energy Intelligence for Europe program*, EIE-2003–114, Brussels, Belgium.

Kikegawa, Y., Y. Genchi, H. Kondo, and K. Hanaki, 2006: Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning. *Applied Energy,* **83**(6): 649–668.

Killip, G., 2008: *Building a Greener Britain: Transforming the UK's Existing Housing Stock*. Environmental Change Institute, Oxford, UK.

King, A. D. (ed.), 1980: *Buildings and Society*. Routledge and Kegan Paul, London, UK.

Kinney, S. and M. A. Piette, 2002: *Development of a California Building Energy Benchmarking Database*. LBNL 50676, Lawrence Berkeley Laboratory Report, Berkeley, CA, USA.

Koch-Nielsen, H., 2002: *Stay Cool: A Design Guide for the Built Environment in Hot Climates*. James and James, London, UK.

Koebel, C. T., 2008: Innovation in Homebuilding and the Future of Housing. *Journal of the American Planning Association,* **74**(1): 45–58.

Kohlhaas, M., 2005: *Gesamtwirtschaftliche Effekte der ökologischen Steuerreform*. (Macroeconomic effects of the ecological tax reform), DIW Berlin, Abteliung Energie, Verkehr, Umwelt, Berlin, Germany.

Kok, N., P. Eichholtz, R. Bauer, and P. Peneda, 2010: *Environmental Performance: A Global Perspective on Commercial Real Estate*. European Centre for Corporate Engagement, Maastricht University School of Business and Economics, Maastricht, the Netherlands.

Kolokotroni, M., 2001: Night ventilation cooling of office buildings: parametric analyses of conceptual energy impacts. *ASHRAE Transactions,* **107**(1): 479–489.

Kooreman, P. and T. Steerneman, 1998: A note energy efficiency investments of an expected cost minimizer. *Resource and Energy Economics,* **20**: 373–381.

Kosmo, M., 1989: Commercial energy subsidies in developing countries: opportunity for reform. *Energy Policy,* **17**(3): 244–253.

Krapmeier, H. and E. Drössler (eds.), 2001: CEPHEUS: *Living Comfort Without Heating*. Springer-Verlag, Vienna, Austria.

Krey, M., 2005: Transaction costs of unilateral CDM projects in India – results from an empirical survey. *Energy Policy,* **33**(18): 2385–2397.

Kushler, M, D. Work, and P. Witte, 2004: *Five Years In: An Examination of the First Half Decade of Public Benefits Energy Efficiency Policy*. American Council for an Energy Efficient Economy (ACEEE). Report U041, Washington, D.C., USA.

Larsen, B. M. and R. Nesbakken, 1997: Norwegian emissions of CO2 1987–1994. *Environmental and Resource Economics,* **9**(**3**): 275–90.

Larsson, N., 2001: Canadian green building strategies. In *Proceedings of the 18th International Conference on Passive and Low Energy Architecture*.7–9 November, Florainopolis, Brazil, pp.17–25.

Laustsen, J., 2008: *Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings*. IEA information paper. International Energy Agency (IEA)of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

Laustsen, J., forthcoming: *Reducing Energy in Buildings with a Factor 4. An IEA Factor Four Strategy for Buildings*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.

Le Fur, B., 2002: *Panorama des dispositifs d'économie d'énergie en place dans les pays de L'Union Européenne*. Club d'Amélioration de l'Habitat, Paris, France.

Leckner, M. and R. Zmeureanu, 2011: Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. *Applied Energy,* **88**(1): 232–241.

Lee, K. H. and R. K. Strand, 2008: The cooling and heating potential of an earth tube system in buildings. *Energy and Buildings,* **40**(4): 486–494.

Lee, W. L. and F. W. Yik, 2004: Regulatory and voluntary approaches for enhancing building energy efficiency. *Progress in Energy and Combustion Science,* **30**(2004): 477–499.

Lees, E., 2006: *Evaluation of the Energy Efficiency Commitment 2002–05*. Oxon, London.

Lees, E. W., 2008: *Evaluation of the Energy Efficiency Commitment 2005–08*. Report to the Department of Energy and Climate Change. Eoin Lees Energy, Oxford, UK.

Lehtomäki, A., S. Huttunen, and J. A. Rintala, 2007: Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources, Conservation and Recycling,* **51**(3): 591–609.

Lenzen, M. and G. Treloar, 2002: Embodied energy in buildings: wood versus concrete – reply to Borjesson and Gustavsson. *Energy Policy,* **30**(3): 249–255.

Lenzen, M., M. Wier, C. Cohen, H. Hayami, S. Pachauri, and R. Schaeffer, 2006: A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy,* **31**(2–3): 181–207.

Levine, M., D. Ürge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling, and H. Yoshino, 2007: Residential and commercial buildings. In *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lewis, M., 2004: Integrated design for sustainable buildings. Building for the future. A Supplement to *ASHRAE Journals,* **46**(9): 2–3.

Li, D. H. W. and J. C. Lam, 2003: An investigation of daylighting performance and energy saving in a daylight corridor. *Energy and Buildings,* **35**: 365–373.

Li, J.-F., O. W. H. Wai, Y. S. Li, J.M. Zhan, Y. A. Ho, J. Li, and E. Lam, 2010: Effect of green roof on ambient CO2 concentration. *Building and Environment,* **45**: 2644–2651.

Liddell, C. and C. Morris, 2010: Fuel poverty and human health: A review of recent evidence. *Energy Policy,* **38**(6): 2987–2997.

Lin, B. and Z Jiang, 2011: Estimates of energy subsidies in China and impact of energy subsidy reform. *Energy Economics,* **33**(2): 273–283.

Lin, Z. and S. Deng, 2004: A study on the characteristics of nighttime bedroom cooling load in tropics and subtropics. *Building and Environment,* **39**(9):1101–1114.

Listokin, D. and D. Hattis, 2004: *Building Codes and Housing*. Rutgers University, NJ, USA and Building Technology Inc., MA, USA.

Liu, M. and D. E. Claridge, 1999: Converting dual-duct constant-volume systems to variable-volume systems without retrofitting the terminal boxes. *ASHRAE Transactions,* **105**(Part 1): 66–70.

Liu, M., D. E. Claridge and W. D. Turner, 2003: Continuous commissioning of building energy systems. *Journal of Solar Energy Engineering,* **125**(3): 275–281.

Lloyd, B., 2006: Fuel poverty in New Zealand. *Social Policy Journal of New Zealand,* **27**: 142–155.

Lopes, C., L. Pagliano and S. Thomas, 2000: Conciliating the economic interest of energy companies with demand-side management – A review of funding mechanisms in a changing market. In *Proceedings of the UIE International Conference – Electricity for a Sustainable Urban Development*, Lisbon, Portugal.

Lorenzioni, I., S. Nicholson-Cole, and L. Whitmarsh, 2007: Barriers perceived to engaging the UK public with climate change and their policy implications. *Global Environmental Change,* **17**(3–4): 445–459.

Loudermilk, K. J., 1999: Underfloor air distribution solutions for open office applications. *ASHRAE Transactions,* **105**(Part 1): 605–613.

Lovins, A. B., 2005: *Energy End-Use Efficiency. A Part of its 2005–06 Study, Transitions to Sustainable Energy Systems*. Inter Academy Council, Amsterdam, the Netherlands.

Lu, L. and H. X. Yang, 2010: Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. *Applied Energy,* **87**(12): 3625–3631.

Lutzenhiser, L., 1993: Social and behavioral aspects of energy use. *Annual Review of Energy and the Environment,* **18**: 247–289.

Lutzenhiser, L., 1994: Innovation and organizational networks. *Energy Policy,* **22**(10): 867–876.

Lutzenhiser, L., K. B. Janda, R. Kunkle, and C. Payne, 2002: *Understanding the Response of Commercial and Institutional Organizations to the California Energy Crisis California Energy Commission*. Sacramento, CA.

MacAvoy, H., 1997: *All-Ireland Policy Paper on Fuel Poverty and Health*. Institute of Public Health in Ireland, Dublin, Ireland.

Manisha, J., V. Gaba and L. Srivastava, 2007: *Managing Power Demand – A case study of the residential sector in Delhi*. The Energy and Resources Institute (TERI), New Delhi, India.

Mansur, E. T., R. Mendelsohn, and W. Morrison, 2005: *A Discrete-Continuous Choice Model of Climate Change Impacts on Energy*. Columbia University, New York, NY, USA.

Marchand, C., M. H. Laurent, R. Rezakhanlou, and Y. Bamberger, 2008: Le bâtiment sans énergie fossile? Les bâtiments pourront-ils se passer des énergies fossiles en France à l'horizon 2050. *Futuribles,* **343**(July): 79–100.

Martens, R., B. Bass, and S. S. Alcazar, 2008: Roof–envelope ratio impact on green roof energy performance. *Urban Ecosystems,* **11**(4): 399–408.

Martinsen D, V. Krey, and P. Markewitz, 2007: Implications of high energy prices for energy system and emissions – the response from an energy model for Germany. *Energy Policy,* **35**(9): 4504–4515.

Masera, O. R., B. D. Saatkamp, and D. M. Kammen, 2000: From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model for rural households. *World Development,* **28**(12): 2083–2103.

Masera, O., R. Edwards, C. Armendáriz, V. Berrueta, M. Johnson, L. Rojas, and H. Riojas-Rodríguez, 2007: Impact of "Patsari" improved cookstoves on indoor air quality in Michoacan, Mexico. *Energy For Sustainable Development,* **11**(2): 45–56.

McDonell, G., 2003: Displacement ventilation. *The Canadian Architect,* **48**(4): 32–33.

McDonell, G., 2004: *Personal communication. Omicron Consulting*, Vancouver, Canada, December, 2004.

McGraw-Hill Construction, 2006: *Green Building SmartMarket Report*. McGraw-Hill Construction, New York, NY, USA.

McMakin, A. H., E. L. Malone, and R. E. Lundgren, 2002: *Motivating Residents to Conserve Energy without Financial Incentives*, **34**(6): 848–863.

McNeil, M. and V. Letschert, 2008: *Future Air Conditioning Energy Consumption in Developing Countries and what can be done about it: The potential of Efficiency in the Residential Sector*. Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

McNeil, M.A., V.E. Letschert, and S. de la Rue du Can, 2008: *Global Potential of Energy Efficiency Standards and Labeling Programs*. LBNL-760E, Lawrence Berkeley National Laboratories, Berkeley, CA, USA.

McNeil, M. A. and V. E. Letschert, 2010: Modeling diffusion of electrical appliances in the residential sector. *Energy and Buildings,* **42**(6):783–790.

Meier, A. and A. Eide, 2007: How many people actually see the price signal? Quantifying market failures in the end-use of energy. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study*, 2007, Stockholm, Sweden.

Melichar, J., M. Havranek, V. Maca, M. Scasny, and M. Kudelko, 2004: *Implementation of ExternE Methodology in Eastern Europe*. Final Report on Work Package 7, Contract No. ENG1-CT-2002–00609, Extension of Accounting Framework and Policy Applications, The European Commission (EC), Brussels, Belgium.

Menanteau, P., 2007: *Policy Measures to Support Solar Water Heating: Information, Incentives and Regulations*. Technical Report prepared for the World Energy Council (WEC), London, UK and Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), Paris, France.

Meyers, S., J. E. McMahon, and B. Atkinson, 2008: *Realized and Projected Impacts of U.S. Energy Efficiency Standards for Residential and Commercial Appliances* – LBNL-63017. Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Michaelowa, A. and F. Lotzo, 2005: Transaction costs, institutional rigidities and the size of the clean development mechanism. *Energy Policy,* **33**(4): 511–523.

Mills, E., 1991: Evaluation of European lighting programmes: utilities finance energy efficiency. *Energy Policy,* 19 (3): 266–278.

Mills, E., 2009: Building Commissioning: *A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions*. LBNL report prepared for California Energy Commission Public Interest Energy Research (PIER), Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Milne, G. and B. Boardman, 2000: Making cold homes warmer: the effect of energy efficiency improvements in low-income homes. A report to the Energy Action Grants Agency Charitable Trust. *Energy Policy,* **28**(6–7): 411–424.

Milton D., P.M. Glencross, and M.D. Walters, 2000: Risk of sick leave associated with outdoor ventilation level, humidification, and building related complaints. *Indoor Air,* **10**(4): 212–21.

Mirasgedis, S., Y. Sarafidis, E. Georgopoulou, V. Kotroni, K. Lagouvardos, and D.P. Lalas, 2007: Modeling framework for estimating impacts of climate change on electricity demand at regional level: case of Greece. *Energy Conversion and Management,* **48**(5): 1737–1750.

MOE, 2006: Ministry of Environment, Government of Japan, press release on 11/10/2006 (in Japanese). www.env.go.jp/press/press.php?serial=7690 (accessed December 31, 2010).

Monahan, J. and J. C. Powell, 2011: An embodied carbon and energy analysis of modern methods of construction in housing: a case study using a lifecycle assessment framework. *Energy and Buildings,* **43**(1): 179–188.

Morch, A. Z., J. Parsons, and J. C. P. Kester, 2007: *Smart Electricity Metering as an Energy Efficiency Instrument: Comparative Analyses of Regulation and Market Conditions in Europe*. In European Council for an Energy Efficient Economy (ECEEE) Summer Study, Stockholm, Sweden.

Morrison, C., and N. Shortt, 2008: Fuel poverty in Scotland: refining spatial resolution in the Scottish Fuel Poverty Indicator using a GIS-based multiple risk index. *Health & Place,* **14**(4): 702–717.

Mundaca, L., 2007: Transaction costs of tradable white certificate schemes: the energy efficiency commitment as case study. *Energy Policy,* **35**(8): 4340–4354.

Murakoshi, C., H. Nakagami, M. Tsuruda, and N. Edamura, 2005: *New Challenges of Japanese Energy Efficiency Program by Top Runner Approach*. Proceedings of the European Council for an Energy Efficient Economy (ECEEE) 2005 Summer Study, Stockholm, Sweden.

MURE, 2007: *Mesure d'Utilisation Rationnelle de l'Energie (MURE) Database*. www.isis-it.com/mure/ (accessed December 31, 2010).

MURE, 2008: *Mesure d'Utilisation Rationnelle de l'Energie (MURE) Database*. www.isis-it.com/mure/ (accessed December 31, 2010).

Nagayama, H., 2008: Electric Power Sector Reform Liberalization Models and Electric Power Prices in Developing Countries: An Empirical Analysis Using International Panel Data. *Energy Economics,* **31**(3): 463–472.

Nahuelhual, L., P. Donoso, A. Ñara, D. Nuñez, C. Oyárzun, and E. Neira, 2007: Valuing ecosystem services of Chilean temperate forests. *Environment, Development and Sustainability,* **9**(4):481–499.

Narumi, T., 2007: *Impact of the Temperature Change upon the Human Health in Osaka Prefecture* (in Japanese). Summaries of Technical Papers of Annual Meeting. Architectural Institute of Japan. *Environmental Engineering* **I**: 763–764.

Nassen, J., J. Holmberg, A. Wadeskog, and M. Nyman, 2007: Direct and indirect energy use and carbon emissions in the production phase of buildings: an input-output analysis. *Energy,* **32**(9): 1593–1602.

National Action Plan for Energy Efficiency, 2009: *Customer Incentives for Energy Efficiency Through Electric and Natural Gas Rate Design*. Prepared by William Prindle, ICF International, Inc.

National Medical Expenditure Survey, 1999: The economic burden of asthma in US children. *Journal of Allergy, Clinical Immunology,* **104**(5): 957–963.

National Research Council, 2009: *America's Energy Future: Technology and Transformation*. National Research Council (NRC) of the National Academies Press, Washington, DC, USA.

NETL, 2008: *National Energy Technology Laboratory Advance Metering Infrastructure*, Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy (US DOE), Washington, DC, USA.

Nevius, M, R. Eldridge, and J. Krouk 2010: *The State of the Efficiency Program Industry Budgets, Expenditures, and Impacts 2009*. Consortium of Energy Efficiency (CEE), Boston, MA, USA.

Nilsson, l., 2006: *Evaluation of BELOK-procurement group for commercial buildings(Sweden)*,EIE-2003–114, Active Implementation for the European Directive on Energy Efficiency (AID-EE), Intelligent Energy-Europe, Brussels, Belgium.

Niu, J. L., L. Z. Zhang, and H. G. Zuo, 2002: Energy savings potential of chilled-ceiling combined with desiccant cooling in hot and humid climates. *Energy and Buildings,* **34**(5): 487–495.

Nordman, B. and K. Christensen, 2010: The next step in reducing IT energy use. Green IT column. *IEEE Computer,* **43**(1): 91–93.

Novikova, A., 2010: *Methodologies for Assessment of Building's Energy Efficiency and Conservation: A Policy-Maker View*. DIW Berlin, Working Paper. German Institute for Economic Research (DIW-Berlin). Berlin, Germany.

Oak Ridge National Laboratory, 2001: *Improving the methods used to evaluate voluntary energy efficiency*. Programs Report, US Department of Energy (US DOE) and US Environmental Protection Agency (US EPA), Washington, DC, USA.

Oke, T.R., 1982: The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society,* **108**(455): 1–25.

OPET Network, 2004: *OPET Building European Research Project*: final reports.

Osawa, H. and M. Hayashi, 2009: Present status of the indoor chemical pollution in Japanese houses based on the nationwide field survey from 2000 to 2005. *Building and Environment,* **44**(7): 1330–1336.

Pachauri, S. and D. Spreng, 2002: Direct and indirect energy requirements of households in India. *Energy Policy,* **30**(6): 511–523.

Pachauri, S. and L. W. Jiang, 2008: The household energy transition in India and China. *Energy Policy,* **36**(11): 4022–4035.

Palmer, K., 1999: *Electricity Restructuring: Shortcut or Detour on the Road to Achieving Greenhouse Gas Reductions?* Resources for the Future Climate Issue Brief 18, Resources for the Future, Washington, DC, USA.

Parfomak, P.W. and L.B. Lave, 1996: How many kilowatts are in a negawatt?: verifying ex post estimates of utility conservation impacts at the regional level. *The Energy Journal,* **17**(4): 59–88.

Parker, D. S., J.R. Sherwin, J.K. Sonne, S.F. Barkaszi, D.B. Floyd, and C. R. Withers, 1998: *Measured energy savings of a comprehensive retrofit in an existing Florida residence*. In *Proceedings of the 1998 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, vol. 1, Washington, DC, USA pp. 235–251.

Parker, D. S., J. K. Sonne, and J. R. Sherwin, 2002: Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida. In *Proceedings of the 2002 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, Vol.1., Washington, D.C., pp.219–234.

Parker, D., D. Hoak, A. Meier, and R. Brown, 2006: *How Much Energy Are We Using? Potential of Residential Energy Demand Feedback Devices.* In *Proceedings of 2006 Summer Study on Energy Efficiency in buildings*. Florida Solar Energy Center. Lawrence Berkley National Laboratory, Berkeley, CA, USA.

Passivehaus Institut, 2009: Passive House Institute US. www.passivehouse.us/passiveHouse/PHIUSHome.html (accessed August 2, 2010).

Pavan, M., 2008*:* Not Just Energy Savings: Emerging Regulatory Challenges from the Implementation of Tradable White Certificates. In *Proceedings of the 2008 American Council for an Energy Efficiency Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, August, 2008, Washington, DC.

CBD, 2001: *The value of ecosystems. Convention on Biological Diversity*, CBD Technical Series No. 4, Convention on Biological Diversity (CBD), Montreal, Canada.

Peters, G. P., C. L. Weber, D. Guan, and K. Hubacek, 2007: China's growing CO_2 emissions-a race between increasing consumption and efficiency gains. *Environmental Science & Technology,* **41**(17): 5939–5944.

Petersdorff, C., T. Boermans, J. Harnisch, O. Stobbe, S. Ullrich, and S. Wartmann, 2005a: *Cost-Effective Climate Protection in the EU Building Stock*. Report established by ECOFYS, Utrect, the Netherlands, for the European Insulation Manufacturers Association (EURIMA), Brussels, Belgium.

Petersdorff, C., T. Boermans, S. Joosen, I. Kolacz, B. Jakubowska, M. Scharte, O. Stobbe, and J. Harnisch, 2005b: *Cost-Effective Climate Protection in the Building Stock of the New EU Member States: Beyond the EU Energy Performance of Buildings Directive*. Report established by ECOFYS, Utrect, the Netherlands, for the European Insulation Manufacturers Association (EURIMA), Brussels, Belgium,

Piette, M. A., S. K. Kinney, and P. Haves, 2001: Analysis of an information monitoring and diagnostic system to improve building operations. *Energy and Buildings,* **33**: 783–791.

Platts Research and Consulting, 2004: *Hedging Energy Price Risk with Renewables and Energy Efficiency*, New York, NY, USA.

Pollitt, 2008: Electricity reform in Argentina: lessons for developing countries. *Energy Economics,* **30**(4): 1536–1567.

Porta-Gándara, M. A., E. Rubio, and J. L. Fernández, 2002: Economic feasibility of passive ambient comfort in Baja California dwellings. *Building and Environment,* **37**(10): 993–1001.

Power, M., 2006: Fuel poverty in the USA: the overview and the outlook. *Energy Action,* **98**.

Quinlan, P., H. Geller, and S. Nadel, 2001: *Tax incentives for innovative energy-efficient technologies (Updated)*. Report Number E013, American Council for an Energy Efficient Economy (ACEEE), Washington, DC, USA.

Rajvanshi, A. K., S. M. Patil, and B. Mendonca, 2007: Low concentration ethanol stove for rural areas of India. *Energy for Sustainable Development,* **11**(1):63–68.

Ramesh, T., R. Prakash, and K. K. Shukla, 2010: Life cycle energy analysis of buildings: an overview. *Energy and Buildings,* **42**(10): 1592–1600.

Rapoport, A., 1969: *House Form and Culture*. Prentice-Hall, Englewood Cliffs, N.J.

Reinhart, C. F., 2002: *Effects of Interior Design on the Daylight Availability in Open Plan Offices*. In *Proceedings of the 2002 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, vol. 3., Washington, DC, USA, pp. 309–322.

Reiss, P. and M. White, 2008: What changes energy consumption? Prices and public pressures. *The RAND Journal of Economics,* **39**(3): 636–663.

Ricci, A., 2009: *Policy use of the needs results*. New Energy Externalities Developments for Sustainability (NEEDS), Rome, Italy.

Rivière, A, L. Grignon-Masse, S. Legendre, D. Marchio, G. Nermond, S. Rahim, P. Riviere, P. Andre, L. Detroux, J. Lebrun, J. L'hoest, V. Teodorose, J.L. Alexandre, E. SA, G. Benke, T. Bogner, A. Conroy, R. Hitchin, c. Pout, W. Thorpe and S. Karatasou, 2008: Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation), Tasks 1 to 5. Draft reports as of July 2008, *Directorate-General for Energy, European Commission*, Brussels, Belgium.

Roberts, S., 2008: Energy, equity and the future of the fuel poor. *Energy Policy,* **36**(12): 4471–4474.

Roberts, S. and W. Baker, 2003: *Towards Effective Energy Information: Improving Consumer Feedback on Energy Consumption*. A report to Ofgem. Center for Sustainable Energy, Bristol, UK.

Romieu, I., H. Riojas-Rodriguez, A. T. Marrón-Mares, A. Schilmann, R. Perez-Padilla, and O. Masera, 2009: Improved biomass stove intervention in rural Mexico: Impact on the respiratory health of women. *American Journal of Respiratory and Critical Care Medicine,* **180**(7): 649–656.

Rosenfeld, A. H., H. Akbari, J. J. Romm, and M. Pomerantz, 1998: Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings,* **28**(1): 51–62.

Roth, K. W., F. Goldstein, and J. Kleinman, 2002: *Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings*. Volume 1: Energy Consumption Baseline. Arthur D. Little Inc., Cambridge, MA, USA.

Roth, K.W., D. Westphalen, and J. Brodrick, 2003: Saving energy with building commissioning. *ASHRAE Journal,* **45**(11):65–66.

Roudil, N., 2007: *Artisans et énergies renouvelables: une chaîne d'acteurs au cœur d'une situation d'innovation*. Les Annales de la Recherche Urbaine. Ministère de l'Ecologie, du Développement et de l'Aménagement Durables (MEDAD), **103:**101–111, Paris, France.

Roux, C., 2010: *The Life Cycle Performance of Energy Using Household Products*. Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway.

Roy, J., 2000: The rebound effect: some empirical evidence from India. *Energy Policy,* **28**(6–7): 433–438.

Roy, A. N., A. R. Mahmood, O. Baslev-Olesen, S. Lojuntin, C. K. Tang, and K. S. Kannan, 2005: *Low Energy Office Building in Putrajaya, Malaysia. Case studies and innovations. In Proceedings of Conference on Sustainable Building South Asia*.11–13, Kuala Lumpur, Malaysia, pp.223–230.

Rubel, F. and M. Kottek, 2010: Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift,* **19**:135–141.

Rubinstein, F. and S. Johnson, 1998: *Advanced Lighting Program Development*. Final Report, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Rubinstein, F., H. J. Jennings, and D. Avery, 1998: *Preliminary Results from an Advanced Lighting Controls Testbed*. LBNL-41633, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Rudd, A., P. Kerrigan, Jr., and K. Ueno, 2004: What will it take to reduce total residential source energy use by up to 60%? In *Proceedings of the 2004 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*.Vol.1, Washington, DC, USA, pp.293–305.

Rypdal, K., N. Rive, S. Aström, N. Karvosenoja, K. Aunan, J. L. Bak, K. Kupiainen, and J. Kukkonen, 2007: Nordic air quality co-benefits from European post-2012 climate policies. *Energy Policy,* **35**(12)6309–6322.

Sadler, R., 2002: *The Benefits of Energy Advice*. Energy Efficiency Partnership for Homes (EEPH), London, UK.

Sailor, D.J. 2008: A green roof model for building energy simulation programs. *Energy and Buildings*, **40**: 1466–1478.

Saiz, S., Kennedy, C., Bass, B., Pressnail, K., 2006: Comparative Life Cycle Assessment of Standard and Green Roofs. *Environmental Science and Technology*, **40**: 4312–4316.

Samet, J., S. Zeger, F. Dominici, F. Curriero, I. Coursac, D.W. Dockery, J. Schwartz, and A. Zanobetti, 2000: The national morbidity, mortality, and air pollution study – part II: morbidity and mortality from air pollution in the United States. *Research Report Health Effects Institute,* **94**(Part 2):5–70.

Sami Khawaja, M. et al., 2008: Statewide Codes and Standards Market Adoption and Noncompliance Rates. Final Report CPUC Program, No. 1134–04, SCE0224.01, San Francisco, CA, USA.

Sanstad, A. H., C. Blumstein, and S. Stoft, 1995: How high are option values in energy-efficiency investments? *Energy Policy,* **23**(9): 739–744.

Santamouris, M., 2001: *Energy and Climate in the Urban Built Environment*, James and James, London, UK.

Santamouris, M., Pavlou, C, Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., Patargias, P., 2007: Investigation and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. *Energy*, **32**: 1781–1788.

Sartori, I. and A. G. Hestnes, 2007: Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy & Buildings,* **39**(3): 249–257.

Sathaye, J. and A. Gupta, 2010: *Eliminating Electricity Deficit through Energy Efficiency in India: An Evaluation of Aggregate Economic and Carbon Benefits*, LBNL-3381E, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Savola, H., 2007: International Institute for Industrial Environmental Economics (IIIEE), Lund, Sweden. Email communication, contribution by filling out the questionnaire for several evaluation studies in Swedish, sent on May 7, 2007.

SBTF, 2001: *Building Better Buildings: A Blueprint for Sustainable State Facilities*. California State and Consumer Services Agency and Sustainable Building Task Force (SBTF), Sacramento, CA, USA.

Schaefer, C., C. Weber, H. Voss-Uhlenbrock, A. Schuler, F. Oosterhuis, E. Nieuwlaar, R. Angioletti, E. Kjellsson, S. Leth-Petersen, M. Togeby, and J. Munksgaard, 2000*: Effective Policy Instruments for Energy Efficiency in Residential Space Heating – an International Empirical analysis*. University of Stuttgart, Institute for Energy, Stuttgart, Germany.

Schiellerup, P. and J. Gwilliam, 2009: Social production of desirable space: an exploration of the practice and role of property agents in the UK commercial property market. *Environment and Planning C: Government and Policy,* **27**(5): 801–814.

Schipper, L. and M. Grubb, 2000: On the rebound? Feedback between energy intensities and energy uses in IEA countries. *Energy Policy,* **28**(6–7): 367–388.

Schlomann, B., W. Eichhammer, and E. Gruber, 2001: Labelling of electrical appliances – an evaluation of the Energy Labelling Ordinance in Germany and resulting recommendations for energy efficiency policy. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study*.11–16 June 2001, Mandelieu, France.

Schmidt, T., D. Mangold and H. Muller-Steinhagen, 2004: Central solar heating plants with seasonal storage in Germany. *Solar Energy*, **76**(1–3):165–174.

Schnieders, J. and A. Hermelink, 2006: CEPHEUS results: Measurements and occupants satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy,* **34**(2): 151–171.

Schonborn, M., 2008: *Energy efficiency for residential buildings*. Presentation at London School of Economics, December, 2008. London, UK.

Schweitzer, M. and B. Tonn, 2002: Nonenergy benefits from the weatherization assistance program: A summary of findings from the recent literature. Prepared for US Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Scott, S., 1996: *Social welfare fuel allowances…to heat the sky?* Working Paper No. 74. The Economic and Social Research Institute (ESRI), Dublin, Ireland.

Scott, S., S. Lyons, C. Keane, D. McCarthy, and R.S.J. Tol, 2008: *Fuel Poverty in Ireland: Extent, Affected Groups and Policy Issues*. Working Paper No. 262. Prepared by the Economic and Social Research Institute (ESRI), Dublin, Ireland.

Sekhar, S. C. and K. J. Phua, 2003: Integrated retrofitting strategy for enhanced energy efficiency in a tropical building. *ASHRAE Transactions,* **109**(1): 202–214.

Seppanen, O. A., W. J. Fisk, and M. J. Mendell, 1999: Association of ventilation rates and CO2 concentrations with health and other human responses in commercial and institutional buildings. *Indoor Air,* **9**(4): 226–52.

Sevi, B., 2004: *Consequences of electricity restructuring on the environment: a survey.*Technical Paper. Centre de Recherche en Economie et Droit de l'Energie (CREDEN), Montpellier Cedex, France.

Shepherd, D. and A. Zacharakis, 2001: The venture capitalist-entrepreneur relationship: control, trust and confidence in co-operative behaviour. *Venture Capital: An International Journal of Entrepreneurial Finance*, **3**(2): 129–149.

Shorrock, L., 2001: Assessing the effect of grants for home energy efficiency improvements. In *Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study*.11–16 June 2001, Mandelieu, France.

Singer, T., 2002: *IEA DSM Task X- Performance Contracting- Country Report: United States*. International Energy Agency (IEA), Paris, France.

Skumatz, L.A. and C. A. Dickerson, 1997: Recognizing All Program Benefits: Estimating the Non-Energy Benefits of PG and E's Venture Partner Pilot Program (VPP).In *Energy Evaluation Conference*, Chicago, IL, USA.

Small, K. and K. Van Dender, 2005: *A Study to Evaluate the Effect of Reduced Greenhouse Gas Emissions on Vehicle Miles Traveled*. Sacramento: State of California Air Resources Board.

Smeds, J. and M. Wall, 2007: Enhanced energy conservation in houses through high performance design. *Energy and Buildings,* **39**: 273–278.

Smith, K.R., R. Edwards, K. Shields, R. Bailis, K. Dutta, C. Chengappa, O. Masera, and V. Berrueta, 2007: Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the household energy and health project. *Energy for Sustainable Development,* **11**(2): 5–18.

Smith-Sivertsen, T., E. Díaz, D. Pope, R.T. Lie, A. Díaz, J. McCracken, P. Bakke, B. Arana, K. R. Smith, and N. Bruce, 2010:Effect of reducing indoor air pollution on women's respiratory symptoms and lung function: the RESPIRE Randomized Trial, Guatemala. *Am. J. Epidemiol,* **170**(2): 211–220.

Socolow, R. H., 1978: *Saving energy in the home: Princeton's experiments at Twin Rivers*. Ballinger Press, Cambridge, MA, USA.

SOM, 2010: *Lever House – Curtain Wall Replacement*. Skidmore, Owings & Merrill LLP, New York, NY, USA. www.som.com/content.cfm/lever_house_curtain_wall_replacement (accessed 22 September, 2010).

Sondreal, E., M. Jones, and G. Groenewold, 2001: Tides and trends in the world's electric power industry. *The Electricity Journal,* **14**(1): 61–79.

Sorrell S., E. O'Malley, J. Schleich, and S. Scott, 2004: *The Economics of Energy Efficiency*. Edward Elgar Pub, Cheltenham, UK.

Sorrell, S., 2007: *The Rebound Effect: An Assessment of the Evidence for Economy-Wide Energy Savings from Improved Energy Efficiency*. UK Energy Research Centre (UK ERC), London, UK.

Spala, A., Bagiorgas, H.S., Assimakopoulos, M.N., Kalavrouziotis, J. Matthopoulos, D., Mihalakakou, G., 2008: On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece, *Renewable Energy*, **33**: 173–177.

Springer, D., G. Loisos, and L. Rainer, 2000: Non-compressor cooling alternatives for reducing residential peak load. In *Proceedings of the 2000 American Council for an Energy Efficient Economy (ACEEE)Summer Study on Energy Efficiency in Buildings*.Vol.1., Washington, DC, pp.319–330.

Stern, P.C., 1999: Information, incentives and pro-environmental consumer behaviour. *Journal of Consumer Policy,* **22** (4): 461–478.

Stetiu, C., and H. E. Feustel, 1999: Energy and peak power savings potential of radiant cooling systems in US commercial buildings. *Energy and Buildings* **30**(2): 127–138.

Still, D., 2009: *New Biomass Stoves and Carbon Credits*. Aprovecho Research Center, Cottage Grove, OR, USA.

Summerfield, A.J., R.J. Lowe, and T. Oreszczyn, 2010: Two models for benchmarking UK domestic delivered energy. *Building Research &Information***38** (1): 12–24.

Stoecklein, A. and L. Skumatz, 2007: Zero and low energy homes in New Zealand: the value of non-energy benefits and their use in attracting homeowners. In *Proceedings for the European Council for an Energy Efficient Economy (ECEEE) Summer Study*.4–9 June, La Colle sur Loup, France.

Sverrisson, F., J. Li, M. Kittell, and E. Williams, 2003: *Electricity restructuring and the environment: lessons learned in the United States*, Center for Clean Air Policy, Washington, DC, USA.

Swanson, R. M., 2006: A vision for crystalline silicon photovoltaics. *Progress in Photovoltaics*: *Research and Applications,* **14**(5): 443–453.

Szklo, A. and H. Geller, 2006: Policy Options for Sustainable Energy Development. In *Brazil: A Country Profile on Sustainable Energy Development*. International Atomic Energy Agency (IAEA), Vienna, Austria.

Takebayashi, H., and M. Moriyama, 2007: Policy Options for Sustainable Energy Development. *Building and Environment,* **42**(8): 2971–2979.

Taylor, R., C. Govindarajalu, J. Levin, A. S. Meyer, and W. A. Ward, 2008: *Financing Energy Efficiency: Lessons from Brazil, China, India, and Beyond*. World Bank, Washington, DC, USA.

Tenorio, R., 2007: Enabling the hybrid use of air conditioning: a prototype on sustainable housing in tropical regions. *Building and Environment,* **42**(2): 605–613.

Thompson, P., 1997: Evaluating energy efficiency investments: accounting for risk in the discounting process. *Energy Policy,* **25**(12): 989–996.

Thiers, S., and B. Peuportier, 2008: Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France. *Solar Energy,* **82**(9): 820–831.

Tirado Herrero, S. and D. Ürge-Vorsatz, 2010: *Fuel poverty in Hungary. A first assessment*. Center for Climate Change and Sustainable Energy Policy (3CSEP), Central European University, Budapest, Hungary.

Tirado Herrero, S., in preparation: *Fuel poverty in Hungary: Assessing the co-benefits of residential energy efficiency*. PhD dissertation. Center for Climate Change and Sustainable Energy Policy (3CSEP), Central European University, Budapest, Hungary

Tochihara, Y., 1999: Bathing in Japan: A review. *Journal of Human-Environment System,* **3**(1): 27–34.

Torcellini, P. A., R. Judkoff, and S. J. Hayter, 2002: Zion National Park Visitor Center: Significant energy savings achieved through a whole-building design process. In *Proceedings of the 2002 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, Vol. 3., Washington, D.C., pp.361–372.

Torcellini, P. A. and D. B. Crawley, 2006: Understanding zero-energy buildings. *ASHRAE Journal,* **48**(9): 62–69.

Torras, M., 2000: The total economic value of Amazonian deforestation, 1978–1993. *Ecological Economics,* **33**(2): 283–297.

Treloar, G., R. Fay, P. E. D. Love, and U. Iyer-Raniga, 2000: Analysing the life-cycle energy of an Australian residential building and its householders. *Building Research and Information,* **28**(3): 184–195.

Ueno, T., F. Sano, O. Saeki, and K. Tsuji, 2006: Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Applied Energy,* **83**(2): 166–183.

UKERC, 2009: Making *the Transition to a Secure and Low-Carbon Energy System*: Synthesis Report prepared by the UK Energy Research Centre (UKERC), London, UK.

UNIDO, 2003*: Bundling small-scale energy efficiency projects*: Issue Paper, United Nations Industrial Development Organization (UNIDO), Vienna, Austria.

UNEP, 2009: *Common Carbon Metric for Measuring Energy Use and Reporting Greenhouse Gas Emissions from Building Operations*, United Nations Environment Programme (UNEP), Sustainable Buildings and Climate Initiative (SCBI), Paris, France.

UNFCCC, 2002: AIJ project reports to the United Nations Framework Convention on Climate Change (UNFCCC), http://unfccc.int/program/coop/aij/aijproj.html. (accessed 10 February, 2010).

Unruh, G. C., 2000: Understanding carbon lock-in. *Energy Policy,* **28**(12): 817–830.

Ürge-Vorsatz, D. and S. Koeppel, 2007: *An assessment of Energy Service Companies worldwide*. Report submitted to the World Energy Council (WEC), London, UK.

Ürge-Vorsatz, D., S. Koeppel, and S. Mirasgedis, 2007: An appraisal of policy instruments for reducing buildings' CO2 emissions. *Building Research and Information,* **35**(4): 458–477.

Ürge-Vorsatz, D., A. Telegdy, S. Fegyverneki, D. Arena, S. Tirado Herrero, and A.C. Butcher, 2010: *Employment Impacts of a Large-Scale Deep Building Energy Retrofit Programme in Hungary*. Prepared by the Center for Climate Change and Sustainable Energy Policy (3CSEP) of Central European University on behalf of the European Climate Foundation. Budapest, Hungary.

Ürge-Vorsatz, D., K. Petrichenko, A. Butcher, and M. Sharmina, in preparation: *World Building Energy Use and Scenario Modeling*. Prepared for United Nations Environmental Programme, the Sustainable Buildings and Climate Initiative, Paris, France and the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Ürge-Vorsatz, D., E. Wojcik-Gront, S. Tirado Herrero, P. Foley et.al. In preparation: *Employment Impacts of a Large Scale Deep Building Energy Retrofit Programme in Poland*. Prepared by the Center for Climate Change and Sustainable Energy Policy (3CSEP) of Central European University, Budapest, in collaboration with FEWE (Polish Foundation for Energy Efficiency) for the European Climate Foundation, the Hague, the Netherlands.

US Census, 2000: *Population*. www.allcountries.org/uscensus/2_population.html (accessed December 31, 2010).

US Census Bureau, 2008: *Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2000 to July 1, 2008*. www.census.gov/popest/states/tables/NST-EST2008–01.xls.

US DOE, 2008: *2008 Buildings Energy Data Book*. Report prepared for the Buildings Technologies Program, Office of Energy Efficiency and Renewable Energy, United States Department of Energy by D and R International, Ltd., Washington, D.C.

US DOE, 2010: *Summary of Gaps and Barriers for Implementing Residential Buildings Energy Efficiency Strategies*. Report prepared by the National Renewable Energy Laboratory for the United States Department of Energy (US DOE) Building Technologies, Washington D.C.

US EIA, 2005: *Residential Energy Consumption Survey*. U.S. Energy Information Administration (US EIA), Washington, DC, USA. http://www.eia.doe.gov/emeu/recs/contents.html (accessed 2009/2010).

US EIA, 2008: *Annual Energy Review. Energy consumption by Sector 1949–2008*. United States Energy Information Administration (US EIA), Washington, DC, USA.

US EIA, 2010: *Annual Energy Outlook*. United States Energy Information Administration (US EIA), Report #: DOE/EIA-0383(2010), Washington, DC, USA.

US EIA, 2011: *State Energy Consumption Database*, June 2011 for 1980–2009. U.S. Energy Information Administration (US EIA), Washington, DC, USA.

US EIA, 2012: *Annual Energy Outlook 2012 Early Release*, Jan. 2012, Summary Reference Case. U.S. Energy Information Administration (US EIA), Washington, DC, USA.

US EPA, 1991: *Indoor Air Facts No. 4 (revised) Sick Building Syndrome*. Air and Radiation Research and Development (6609J). United States Environmental Protection Agency (US EPA), Washington, DC, USA.

US EPA, 2003: Energy Star: *The Power to Protect the Environment Through Energy Efficiency*. United States Environmental Protection Agency (US EPA), EPA 430-R-03–008. Washington, DC, USA.

US EPA, 2007: Energy Star: *New Specifications for Many Office Products in 2007.* United States Environmental Protection Agency (US EPA), Washington, DC, USA. www.energystar.gov/index.cfm?c=ofc_Equip.pr_office_Equipment. (Accessed 12 May, 2010).

US EPA, 2011: Fans, Ceilings for Consumers. URL: www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup8pgw_code=CF. (Accessed 5 January, 2011)

Usibelli, T., 1997: *The Washington State Energy Code: The Role of Evaluation in Washington State's Non-Residential Energy Code. Washington State University Cooperative Extension Energy Program*, WSU/EEP 97–007, Pullman, WA, USA.

van Houwelingen, J. and F.W. van Raaij, 1989: The effect of goal setting and daily electronic feedback on in-home energy use. *Journal of Consumer Research,* **16**(1): 98–105.

van Vuuren, D.P., J. Cofala, H. E. Eerens, R. Oostenrijk, C. Heyes, Z. Klimont, M. G. J. den Elzen, and M. Amann, 2008: Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energy Policy,* **34**(2006): 444–460.

van Wie McGrory, L., J. Harris, M. Breceda Lapeyre, S. Campbell, S. Constantine, M. della Cava, J. G. Martínez, S. Meyer, and A. M. Romo, 2002: Market Leadership by Example: Government Sector Energy Efficiency in Developing Countries. In *Proceedings of the 2002 American Council for an Energy Efficient Economy (ACEEE) Summer Study*. Report LBNL-5098, Asilomar, CA, USA.

Vasile, C. F., 1997: *Residential Waste Water Heat Recovery System: GFX*. Center for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) newsletter, December 4, 1997.

Venkatataraman, C., and S. Maithel, 2007: *Advanced Biomass Energy Technology for cooking*. DACE Workshop, October 12–13, 2007, Mumbai, India.

Viridén, K., T. Ammann, P. Hartmann, and H. Huber, 2003: *P+D – Projekt Passivhaus im Umbau* (in German), Viriden + Partner, Zürich, Switzerland

Vojdani, A., 2008: Smart Integration. *Power and Energy Magazine, IEEE***6** (**6**): 71–79.

Voss, K., 2000: Solar energy in building renovation – results and experience of international demonstration buildings. *Energy and Buildings,* **32**(3): 291–302.

Voss, K., S. Herkel, J. Pfafferott, G. Löhnert, and A. Wagner, 2007: Energy efficient office buildings with passive cooling – results and experiences from a research and demonstration programme. *Solar Energy,* **81**(3): 424–434.

Wade, J., W. Wiltshire, and I.Y. Scrase, 2000: *National and Local Employment Impacts of Energy Efficiency Investment Programmes*. Vol.1: Summary Report. SAVE contract XVII/4.1031/D/97–032, Association for the Conservation of Energy, London, UK.

Wagner, A., S. Herkel, G. Löhnert, and K. Voss, 2004: *Energy efficiency in commercial buildings: Experiences and results from the German funding program SolarBau*. Presented at EuroSolar 2004, Freiburg, Germany.

Walker, C. E., L. R. Glicksman and L.K. Norford, 2007: Tale of two low-energy designs: Comparison of mechanically and naturally ventilated office buildings in temperate climates. *ASHRAE* Transactions, **113** (Part 1): 36–50.

Wang, U., 2008: *Building a Cool World, With New Roofs*. Greentechmedia. www.greentechmedia.com/articles/read/building-a-cool-world-with-new-roofs-5438/ (accessed June 27, 2010).

Warren, A., 2007: Taxation. *Presentation at the Energy Efficiency in Buildings (EEB) Forum. Driving Investments for Energy Efficiency in Buildings*. July 5, Brussels, Belgium.

WB, 2008: *Global Environment Facility and World Bank Donate US$15 Million to Support Energy Efficiency In Argentina*, Press Release No: 2008/212/LCR, World Bank, Washington, DC, USA.

WBCSD, 2007: *Energy Efficiency in Buildings: Business Realities and Opportunities*. Report prepared by the World Business Council for Sustainable Development (WBCSD), Geneva, Switzerland.

WBCSD, 2008: *Energy Efficiency in Buildings: Business Realities and Opportunities*. Report prepared by the World Business Council for Sustainable Development (WBCSD), Geneva, Switzerland.

WBCSD, 2009: *Energy Efficiency in Buildings – Transforming the Market*. Report prepared by the World Business Council for Sustainable Development (WBCSD), Geneva, Switzerland.

WEA, 2000: *World Energy Assessment Energy and the Challenge of Sustainability*. United Nations Development Programme (UNDP), *United Nations Department of Economic and Social Affairs (UNDESA)*, New York, NY, USA, and World Energy Council (WEC), London, UK.

WEA, 2004: *World Energy Assessment, Energy and the Challenge of Sustainability, Overview2004 Update*. United Nations Development Programme (UNDP), United Nations Department of Economic and Social Affairs (UNDESA), New York, NY, USA, and World Energy Council (WEC), London, UK.

Webber, C., R. Brown, M. McWhinney, and J. Koomey, 2003: *2002 Status Report: Savings Estimates for the ENERGY STAR Voluntary Labeling Program*. Lawrence Berkeley National Laboratory, LBNL-51319, Berkeley, CA, USA.

Weber, C. L., 2009: *Energy Cost of Living Calculation*, personal communication, January 6, 2009.

WEC, 2001: *Energy Efficiency Policies and Indicators*. World Energy Council (WEC), London, UK.

WEC, 2004*: Energy Efficiency: A Worldwide review. Indicators, Policies, Evaluation*. World Energy Council (WEC), London, UK.

Wei, Y. M., L. C. Liu, Y. Fan, and G. Wu, 2007: The impact of lifestyle on energy use and CO2 emission: An empirical analysis of China's residents. *Energy Policy,* **35**(1): 247–257.

Western Regional Air Partnership, 2000: Air Pollution Prevention Meeting Summary. In *Air Pollution Prevention Forum Meeting*, May 31-June 1, San Francisco, CA, USA.

WHO, 2000: *Development of World Health Organisation (WHO) Guidelines for Indoor Air Quality*. Report on a Working Group Meeting, October 23–24, 2006, Bonn, Germany.

WHO, 2007: *Housing, energy and thermal comfort. A review of 10 countries within the WHO European Region*. World Health Organization (WHO).Regional Office for Europe, Copenhagen, Denmark

WHO, 2008: World Health Organization (WHO) Statistics 2008 – quote on COPD's www.who.int/respiratory/copd/World_Health_Statistics_2008/en/ (accessed February 25, 2010).

WHO, 2009: The Energy Access Situation in Developing Countries. *A Review focusing on the Least Developing Countries and Sub-Saharan Africa*. United Nations Development Programme (UNDP), New York, NY, USA, and World Health Organisation (WHO), Geneva, Switzerland.

Wilhite, H., H. Nakagami, T. Masuda, Y. Yamaga, and H. Haned, 1996: A cross-cultural analysis of household energy use behaviour in Japan and Norway. *Energy Policy*, **24**(9): 795–803.

Wilhite, H., and R. Ling, 1995: Measured energy savings from a more informative energy bill. *Energy and Buildings*, **22**(2): 145–155.

Williams, E., 2004: Energy intensity of computer manufacturing: Hybrid assessment combining process and economic input-output methods. *Environmental Science and Technology*, **38**(22): 6166–6174.

Wilson, A. and J. Boehland, 2005: Small is beautiful: US house size, resource use, and the environment. *Journal of Industrial Ecology*, **9**(1–2):277–287.

Winner, L., 1977: *Autonomous Technology*. MIT Press, Boston, MA.

Winther, B. N. and A. G. Hestnes, 1999: Solar versus green: the analysis of a Norwegian row house. *Solar Energy*, **66**(6): 387–393.

Wiser, R., M. Bolinger, and M. St. Clair, 2005: *Easing the Natural Gas Crisis: Reducing Natural Gas Prices through Increased Deployment of Renewable Energy and Energy Efficiency*. Testimony prepared for a hearing on Power Generation Resource Inventive & Diversity Standards, Senate Committee on Energy and Natural Resources, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Withers, C. R. and J. B. Cummings, 1998: Ventilation, humidity, and energy impacts of uncontrolled airflow in a light commercial building. *ASHRAE Transactions*, **104**(2): 733–742.

Wong, N.H., Tay, S.F., Wong, R., Ong, C.L. Sia, A., 2003: Life cycle cost analyses of rooftop gardens in Singapore, *Building and Environment*, **38**: 499–509.

Wood, G. and M. Newborough, 2003: Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy and Buildings*, **35**(8): 821–841.

Yanbing, K. and W. Qingpeng, 2005: Analyses of the impacts of building energy efficiency policies and technical improvements on China's future energy demand. *International Journal of Global Energy Issues*, **24**(3–4): 280–299.

Yang, J., Q. Yu, and P. Gong, 2008: Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment*, **42**(31): 7266–7273.

Yeang, K., 1994: *Bioclimatic Skyscrapers*. Ellipsis, London, UK.

Yonehara, T., 1998: Ventilation windows and automatic blinds help to control heat and lighting. *CADDET Energy Efficiency Newsletter*, December 1998: 9–11.

York, D., 2008: What's working well: lessons from a national review of exemplary energy efficiency programs. In *Proceedings of the American Council for an Energy Efficient Economy (ACEEE)*, Asilomar, CA, USA.

Yoshino, H., F. Hasegawa, H. Arai, K. Iwasaki, S. Akabayashi, and M. Kikuta, 1985: Investigation of the relationship between the indoor thermal environment of houses in the winter and cerebral vascular accident (CVA). *Japanese Journal of Public Health*, **32**(4).

Zhang, S., X. Yang, Y. Jiang, and Q. Wei, 2010: Comparative analysis of energy use in China building sector: current status, existing problems and solutions. *Frontiers of Energy and Power Engineering in China*, **4**(**1**).

Zhen, B., L. Shanhou, and Z. Weifeng, 2005: Energy efficient techniques and simulation of energy consumption for the Shanghai ecological building. In *Proceedings 2005 World Sustainable Building Conference*. September 27–29, Tokyo, Japan, pp.1073–1078.

Zhivov, A. M., and A. A. Rymkevich, 1998: Comparison of heating and cooling energy consumption by HVAC system with mixing and displacement air distribution for a restaurant dining area in different climates. *ASHRAE Transactions*, **104**(part 2): 473–484.

Zhou, N., M. A. McNeil, D. Fridley, L. Jiang, L. Price, S. de la Rue du Can, J. Sathaye, and M. Levine, 2007: *Energy Use in China: Sectoral Trends and Future Outlook*. Lawrence Berkeley National Laboratory Report LBNL-61904, Berkeley, CA, USA.

Zweibel, K., 2005: *The Terawatt Challenge for Thin-Film PV*. NREL Technical Report, NREL/TP-520–38350, National Renewable Energy Laboratory (NREL), Golden, CO, USA.