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Working Group III – Mitigation of Climate Change

Chapter 9

Buildings

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Executive Summary

In 2009 buildings accounted for 32% of total global final energy *[high agreement, robust evidence]*, approximately 30% of total energy related CO_2 emissions (including electricity-related ones) *[high agreement, medium evidence]*, approximately two-thirds of halocarbon *[medium agreement, medium evidence]* and 25–33% of black carbon emissions *[medium agreement, medium evidence]*. The substantial new construction taking place in developing countries represents both a significant risk and opportunity from a mitigation perspective. At the same time, over 2 billion people presently do not have access to modern energy carriers *[high agreement, medium evidence];* shifting their energy services electricity and other clean fuels will drive trends in building-related emissions.

There is a large (up to 60% of baseline) potential for energy savings in existing and new buildings throughout the world *[high agreement, medium evidence*]. Analysis shows that technological improvement replenishes the potential for efficiency improvement, so that the potential for cost-effective energy efficiency improvement has not been diminishing *[medium agreement, robust evidence]*. The technology solutions to realize this potential exist and are well documented. Recent developments in technology and know-how enable construction and retrofit of very low- and zero-energy buildings, often at little marginal investment cost, typically paying back well within the building lifetime *[high agreement, robust evidence]*. Passive design (both modern and traditional) offers important cost savings and CO_2 mitigation potentials compared to use of energy active systems *[high agreement, robust evidence]*. In existing buildings 50 – 90% energy savings have been achieved throughout the world through deep retrofits *[high agreement, medium evidence]*. Depending on design and actual usage, ICT can be both a driver of more energy consumption and/or provide an opportunity to optimize efficiency in and decarbonize other sectors *[high agreement, robust evidence]*.

Strong barriers hinder the market uptake of these cost-effective opportunities, and large potentials will remain untapped without strong policies *[medium agreement, robust evidence]*. Market forces alone are not likely to achieve the necessary transformation fast enough without external stimuli *[medium agreement, robust evidence]*. Policy intervention, plus new business and financial models are essential to overcome first-cost hurdles *[medium agreement, robust evidence]*. There is a broad portfolio of effective policy instruments available to remove these barriers, some of them being implemented also in developing countries, saving emissions at large negative costs *[high agreement, robust evidence]*. Overall, the history of energy efficiency programmes in buildings shows that 25-30% efficiency improvements have been available at costs substantially lower than marginal supply *[medium agreement, medium evidence]*. Dynamic developments in building-related policies in some developed countries have demonstrated the effectiveness of such instruments, as total building energy use trends have started decreasing in some countries *[high agreement, robust evidence]*. As many new buildings will be added to the stock in developing countries, including energy intensive appliances, and therefore adequate building codes and energy requirements on appliance eco-design are necessary to address mitigation objectives *[medium agreement, medium evidence]*. For the existing stock, especially in developed nations, energy efficiency measures applied during the process of retrofitting can be cost effective *[high agreement, medium evidence]*. Building codes with strong energy efficiency requirements can be enforced, tightened over time and made appropriate to local climate conditions *[medium agreement, medium evidence]*. Making information public on energy performance influences the market in buildings *[medium agreement, medium evidence]*. There is no evidence that energy pricing instruments deliver change in building energy efficiency *[low agreement, low evidence]* and experience shows that pricing is less effective than programs and regulation *[medium agreement, medium evidence]*. Financial instruments, policies and other opportunities are available to improve energy efficiency in buildings, but the results obtained to date are still insufficient to deliver the full potential *[medium agreement, medium evidence]*. Combined and enhanced, these approaches could provide better results, in terms of both improved energy access and energy efficiency *[medium agreement, medium evidence]*.

Some effective existing policies, and especially financial mechanisms, take into account the long life times and renovation cycles of both new and existing buildings *[high agreement, robust evidence]*. Compromises in performance standards, as compared to state-of-the-art, in both new and retrofit buildings may lead to locking-in carbon intensive options for several decades *[medium agreement, robust evidence]*. For instance, even if today's most ambitious policies in buildings are implemented, approximately 80% of 2005 final building energy use can be "locked in" as compared to a scenario where today's best practice buildings become the standard in newbuild and retrofit *[medium agreement, medium evidence]*. In order to provide enough time for the construction industry and market to develop, important factors to minimise this lock-in effect are promptly enabled ambitious policy frameworks *[high agreement, robust evidence]*. This includes policies to address all points of the building lifecycle including building codes, promotion of best practices, adequate low-C materials and building energy management, as well as enforcement *[high agreement, robust evidence]*.

Beyond technologies and architecture, lifestyle has a major effect on energy use (and thus emissions) in buildings potentially causing 3-5 times differences *[high agreement, low evidence]*. In developed countries, evidence indicates that behaviours informed by awareness of energy and climate issues can reduce demand by up to 20% in the short term and 50% by 2050 *[medium agreement, medium evidence]*. There is a high risk of emerging countries following the same path as developed economies, which will lead to building energy use doubling by mid-century *[high agreement, high evidence]*. Strategies providing high levels of building services at much lower energy inputs, incorporating learning from traditional lifestyles, architecture and construction techniques exist and can help avoid such trends *[high agreement, robust evidence]*. Behaviour and lifestyles can be either guided or influenced with elaborated strategies *[high agreement, medium evidence]*. Better energy indicators include those related to sufficiency and not only efficiency *[high agreement, robust evidence]*. Reducing demand includes meeting needs for space effectively, including promoting density, high and mixed use space utilization, and optimised occupant behaviours *[high agreement, robust evidence]*.

Beyond direct energy cost savings, many mitigation options in this sector have significant and diverse co-benefits that offer attractive entry points for mitigation action into policy-making even in countries/jurisdictions where financial resources for mitigation are limited *[high agreement, robust evidence]*. These include, but are not limited to, energy security, air pollution and health benefits; productivity, competitiveness and net employment gains; increased social welfare, alleviated energy and fuel poverty, decreased need for energy subsidies and less exposure to energy price volatility risks; increased value for building infrastructure, improved comfort and services *[high agreement, medium evidence]*. These often substantially exceed the climate and energy benefits but are rarely recognised as such and thus rarely internalised by policies *[medium agreement, medium evidence]*. There are tools to quantify and monetize co-benefits e.g. proper lifecycle accounting; however without more integration into the decision-making processes such effects are not realized *[high agreement, medium evidence]*.

In a holistic approach the whole lifespan of the building is considered, and includes master planning, life cycle analysis, and integrated building design to obtain the broadest positive impact possible in the building industry, although misinformation and simplified techniques are risks to this understanding *[high agreement, robust evidence]*. To this end, improved and more comprehensive databases on real building energy use are an important tool *[high agreement, robust evidence]*. Continuous monitoring and dynamic modification of performance levels with dynamic evolution of codes maximise achieving efficiency opportunities and their related co-benefits *[high agreement, robust evidence]*. There has been a significant strengthening of energy provisions of building codes over the last 10 years, and further strengthening is underway, but this is still insufficient for ambitious climate goals *[medium agreement, robust evidence]*. Delivering low-carbon options raises major challenges for education, capacity building and training *[high agreement, robust evidence]*.

The chapter, in harmony with the whole AR5, uses emission decomposition by identities as a key organising framework. According to this framework, *mitigation options* are decomposed into four primary mitigation strategy components: (i) *carbon efficiency*, e.g. building integrated renewable energy systems; (ii) *energy efficiency of technology*, e.g. efficient equipment and building components, ; (iii) *systemic and infrastructure efficiency* e.g. holistic improvements in buildings, such as nearly/net zero energy buildings (NZEB), Integrated Design Process, urban planning, district heating/cooling, commissioning and (iv) *service demand reduction* e.g. behavioural and lifestyle change. Table 9.1 synthesises the key findings of the chapter organised by these key identities.

Table 9.1: Summary of chapter's main findings organized by major mitigation strategies (identities)

	Carbon efficiency	**Energy efficiency of technology**	**System/ (infrastructure) efficiency**	**Service demand reduction**
Mitigation options	Building integrated RES (BiRES, BiPV)	High-performance building envelope (HPE). Efficient appliances (EA). Efficient lighting (EL). Efficient HVAC systems (eHVAC). Building automation and control systems (BACS)	Passive house standard (PHS). Nearly/net zero energy buildings (NZEB). Integrated Design Process (IDP). Urban planning (UP). District heating/cooling (DH/C). Commissioning (C).	Behavioural change (BC). Lifestyle change (LSC).
Potential	Average CO2 reduction potential of identity: 20-45% of baseline	Average CO2 reduction potential of identity: of 20-45% of baseline	Average CO2 reduction potential of identity: 30-70% of baseline **Energy savings:** - PHS & NZEB/new: min. reduction in heating demand in res. by factor of 6, in com. by factor of 2 (both heating & cooling)compared to local conventional buildings(9.3.3.1& 9.3.3.3) - Deep retrofits/res.: most of the retrofits in WE and EEU show energy savings of 40-80% after retrofit - Integrated design process can bring savings of up to 70% final energy by 2050 (Table 9.4)	Average CO2 reduction potential of identity: 20-40% of baseline LSC in buildings: can lead to cca 40% reduction inelectricity use (Table 9.4).
Associated direct costs	BiRES: technology & installation cost	-	- PHS &NZEB/new/res.: 5-24% additional costs vs. standard, com.: 4-10% or less (Table 9.5). - Deep retrofits/res.: additional costs of 100-400 €/m2 (9.3.4.2). - DH/C: infrastructure costs, retrofit & new	BC: administrative costs of programmes & awareness campaigns
Cost-effectiveness	-	- Retrofit of separate measures: average CCE: 0.01-0.10 $/kWh (Fig. 9.13) - Efficient Appliances: CCE: -0.07 Euro/kWh/yr (9.3.4.2)	PHS&NZEB/new/Europe&US: CCE: 0.7-0.2 $/kWh (Figure 9.11, 9.12) Deep retrofit with energy savings of 60-75%: CCE of 0.05-0.25 $/kWh (Fig. 9.13)	
Co-benefits, co-risks, co-costs	NZEB: reduction of air pollution	HPE: CB: increased value for building infrastructure, property premium. CR: lock-in effect	PHS: CB: energy security, lower fuel poverty, social welfare, lower need for energy subsidies, lower exposure to energy price volatility risks, health benefits, productivity, competitiveness and net employment gains, thermal comfort, improved energy services	CR: misinformation: simplified techniques
Key barriers	Suboptimal measures, subsidies to conventional fuels	High transaction costs, limited access to financing, principal agent problems, fragmented market and institutional structures, poor feedback	Energy and infrastructure lock-in, fragmented market and institutional structures, poor enforcement of regulations	Imperfect information, risk aversion, cognitive and behavioural patterns, lack of awareness, poor personnel qualification
Key policies	Carbon tax, feed-in tariffs extended for small capacity; carb. cap&trade	energy tax, public procurement, appliance standards	Building codes, preferential loans, subsidised financing schemes, ESCOs, EPCs, suppliers' obligations, white certificates, or e.g. Incorporating Integrated Design Process into Urban Planning	Awareness raising, education, energy audits, energy labelling, building certificates & ratings

9.1 Introduction

Since the AR4, recent advances in IT, design, construction and operation know-how have opened new opportunities for a transformative change in building-sector related emissions at socially acceptable costs, or often benefits that can contribute to meeting ambitious climate targets.

FAQ 9.1. What are the recent advances in building sector technologies and know-how since the AR4 that are important from a mitigation perspective?

The main advances since AR4 do not lie in major technological developments, but rather in their extended systemic application as well as in incremental improvements in the performance and reductions in the cost of several technologies. For instance, there are over 20,000 buildings meeting Passive house standard in central Europe, and nearly zero energy new construction has become the law in the 27 member states of the European Union. Even higher energy performance building levels are being successfully applied to new and existing buildings, including non-residential buildings. The costs have been gradually declining; for residential buildings at the level of Passive house standard accounting for 5-8% of conventional building costs, and some net zero or nearly zero energy commercial buildings having been built at equal costs (see 9.3 and 9.6).

Building design and activities in buildings are responsible for a significant share of GHG emissions, but these are also the key to mitigation strategies. In 2009, the building sector accounted for approximately 125 EJ or 32% of global final energy consumption and 30% of energy-related CO_2 emissions; 23% of global primary energy use; 30% of global electricity consumption, and approximately 30% of global energy-related CO_2 emissions including electricity-related ones, plus F-gas emissions. The chapter argues that beyond a large emission role, mitigation opportunities in this sector are large, often very cost-effective, and are often associated with significant co-benefits that can exceed the direct benefits by orders of magnitude. The sector has significant mitigation potentials at low or even negative costs. Nevertheless, without strong actions emissions are likely to grow considerably due to several drivers. Specific policies have been effective, several new ones are emerging. The significance of co-benefits has made them increasingly entry points to policymaking. The purpose of this chapter is to update the knowledge on the sector from a mitigation perspective since AR4. The chapter uses a novel conceptual framework, in line with the general analytical framework of AR5 – focusing on identities as an organizing principle. This section describes the identity decomposition Chapter 9 chooses to apply for assessing the literature, resting on the general identity framework described in Chapter 6. Building-related emissions and mitigation strategies have been decomposed by different identity logics. Commonly used decompositions include factors such as CO_2 intensity, energy intensity, structural changes and economic activity (Isaac and Van Vuuren, 2009a; Zhang et al., 2009), as well as the IPAT (Income-Population-Affluence-Technology) approach (MacKellar et al., 1995; O' Mahony et al., 2012). In this assessment, the review focuses on the main decomposition logic described in Chapter 6, adopted and further decomposed into four key identities to drive emissions*:*

$$CO_2 emissions = CI * TEI * SEI * A$$

where (i) CO_2 are the (direct and electricity-related indirect) emissions from the building sector; (ii) CI is the carbon intensity; (iii) TEI is the technological energy intensity; (iv) SEI is the structural\systemic energy intensity and (v) A is the activity. For a more precise interpretation of the factors, the following conceptual equation demonstrates the different components:

$$CO_2 = \frac{CO_2}{FE} * \frac{FE}{UsefulE} * \frac{UsefulE}{ES} * \frac{ES}{pop} * pop$$

in which (i) UsefulE is the useful energy for a particular energy service (ES), as occurring in the energy conversion chain, and (ii) pop is population (GDP is often used as the main decomposition factor for commercial building emissions). Because ES is often difficult to rigorously define, and UsefulE and ES are either difficult to measure or little data are available, this chapter does not attempt a systematic quantitative decomposition, but rather focuses on the main strategic categories for mitigation based on the equation:

$$CO_2 mitigation \approx CarbonEfficiency \times TechnologicalEfficiency \times Systemic/InfrastruralEfficiency \times DemandReduction$$

whereby (i) carbon efficiency entails fuel switch to low-carbon fuels, building-integrated renewable energy sources and other supply-side decarbonisation; (ii) technological efficiency focuses on the efficiency improvement of individual energy-using devices; (iii) systemic/infrastructural efficiency encompass all efficiency improvements whereby several energy-using devices are involved, i.e. systemic efficiency gains are made, or energy use reductions due to architectural, infrastructural and systemic measures; and finally (iv) demand reduction composes of all measures that are beyond technological efficiency and decarbonisation measures, such as impacts on floorspace, service levels, behaviour, lifestyle, use and penetration of different appliances. The four main emission drivers and mitigation strategies can be further decomposed into these more distinct sub-strategies, but due to the limited space in this report and in order to maintain a structure that supports convenient comparison between different sectoral chapters, we focus on these four main identities during the assessment of literature in this chapter and this decomposition serves as the main organising/conceptual framework for Chapter 9. Table 9.1 (see Executive Summary) summarises the main findings of the chapter by these four main identities.

9.2 New developments in emission trends and drivers

9.2.1 Energy and GHG emissions from buildings

In 2009 buildings accounted for 32% of total global final energy use (IEA, 2012), being one of the largest end-use sectors worldwide (Figure 9.1). The building sector is responsible for 15% of total direct energy-related CO_2 emissions from final energy consumers, but if indirect upstream emissions attributable to electricity and heat consumption are taken into account, it is responsible of 26% of all CO_2 emissions. Figure 9.2 shows the energy use by region and building subsector (residential or commercial). Individual regions of the world contribute from 4% (Pacific OECD) to 18% (Centrally Planned Asia) of global residential building energy use. Differences in the regional contribution to commercial building energy use are greater, ranging from 1% (Africa) to 32 % (North America), with clear differences between developed and developing countries (Figure 9.1). According to (IEA, 2012), space heating represented 32-33% of the total final energy consumption in both the residential and the commercial building sub-sectors in 2010 (Figure 9.3). Moreover, in the commercial sub-sector, lighting was very important, while cooking and water heating were significant applications in residential buildings.

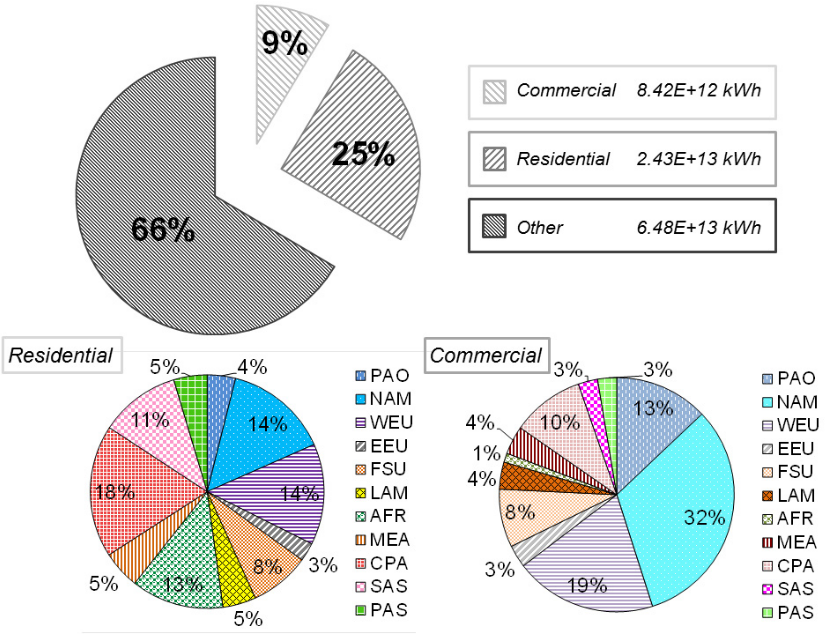


Figure 9.1. Contribution of residential and commercial buildings to the global final energy consumption, data from (IEA, 2012)

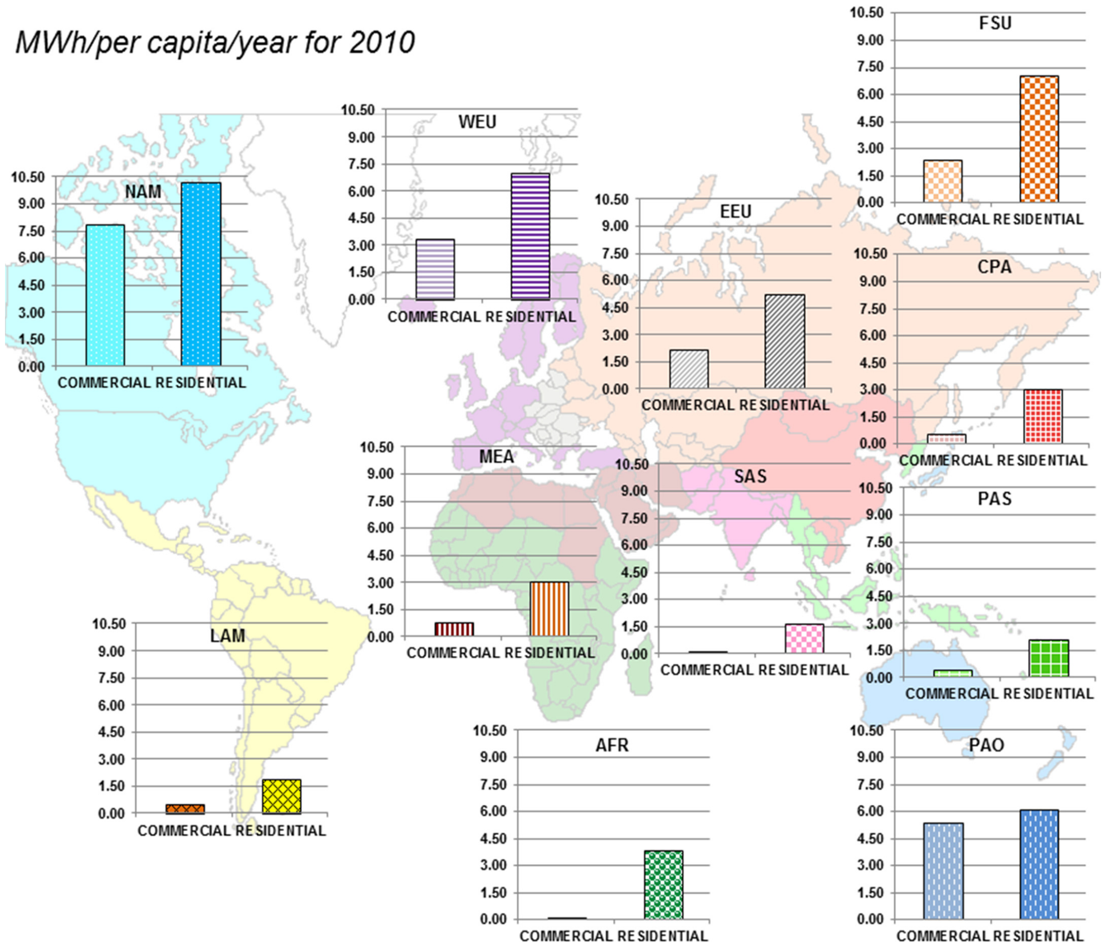


Figure 9.2. Buildings final energy use by sub-sector and region in 2010, data from (IEA, 2012)

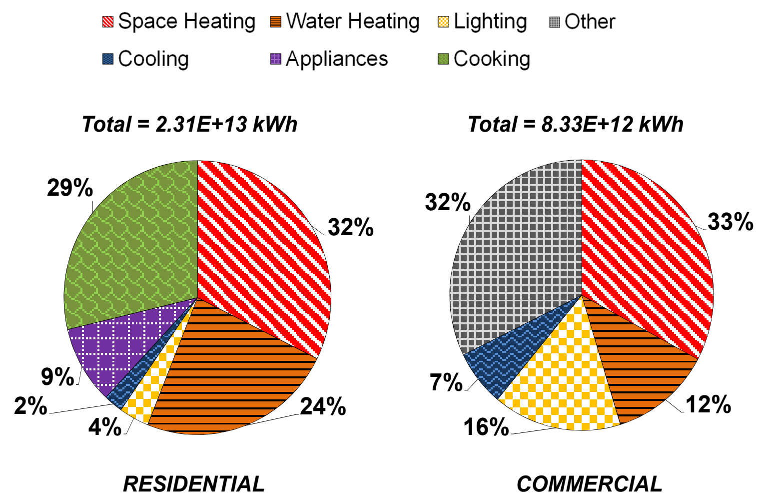


Figure 9.3. World buildings energy consumption by final use. Source: adapted from (ETP, 2012).

9.2.2 Trends and drivers of thermal energy uses in buildings

Figure 9.4 shows trends and projections of thermal energy uses in commercial and residential buildings in the regions of the world from 1980 to 2030 (Ürge-Vorsatz et al., 2013a). While energy consumption for thermal uses in buildings in the developed countries (see North America and Western Europe) accounts for most of the energy consumption in the world, its tendency is to grow little in the period shown, while developing countries show an important increase, both in the past (1980-2010) and in the projections (2010-2030). Commercial buildings represent between 10 to 30% of total building sector energy consumption in most regions of the world, except for China, where energy consumption in commercial buildings is expected to overtake that of residential buildings.

Drivers to these trends and their developments are here discussed separately for heating/cooling and other building energy services. Heating, cooling and DHW energy use in residential buildings can be decomposed by the following key identities, from (Ürge-Vorsatz et al., 2013a). For residences, the identity is $\{[energy_{resid}] = [h] * [p/h] * [area/p] * [energy/area]\}$, where *[h]* and *[p/h]* are the activity drivers, the number of households and the number of persons living in each household, respectively; *[area/p]* is the use intensity driver, the floor area (usually m2) per person; and *[energy/area]* is the energy intensity driver, ie the annual thermal energy consumption (usually kWh) per unit of floor area, also referred to as specific energy consumption. For commercial buildings, the heating and cooling use is decomposed as $\{[energy_{comd}] = [GDP] * [area/GDP] * [energy/area]\}$; where *[GDP]* or Gross Domestic Product (nominal) is the activity driver; *[area/GDP]* is the use intensity driver; and *[energy/area]* is the energy intensity driver, the annual thermal energy consumption (in kWh) per unit of floor area (in m^2), also referred to as specific energy consumption.

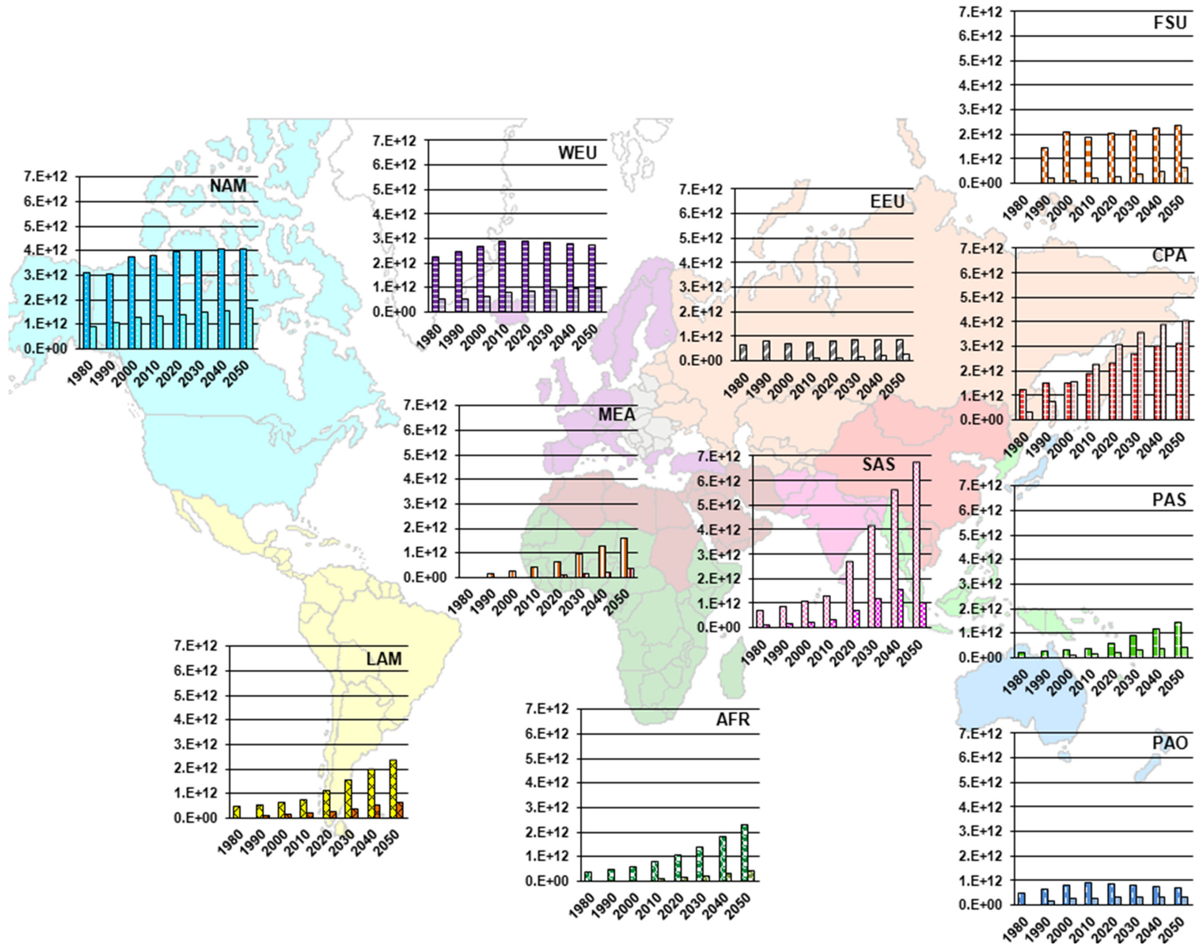


Figure 9.4. Total final thermal energy consumption trends in the building sector in the different regions of the world for residential and commercial buildings. Historical data (1980-2000) are from IEA statistics; projections (2010-2050) are based on a frozen scenario (Ürge-Vorsatz et al., 2013b)

Heating and cooling energy use grew over the period 1980-2010 by 39% and 61% in residential and commercial buildings, respectively, and is expected to grow 52% and 34%, respectively, over the period 2010-2030 (Figure 9.5) in a business-as-usual scenario. In residential buildings, both the growing number of households and the area per household tend to increase energy consumption, while the decrease in the number of persons per household and in energy intensity tend to decrease energy consumption (5% in the period 2010-2030). In commercial buildings, the projected decrease area/GDP is of 98%, while energy/area is expected to stay constant over the period 2010-2030. Different tendencies of the drivers are shown for both residential and commercial buildings in the world as whole (Figure 9.5) and in different world regions (Figure 9.6). More detail information about each driver trend can be found in (Ürge-Vorsatz et al., 2013a).

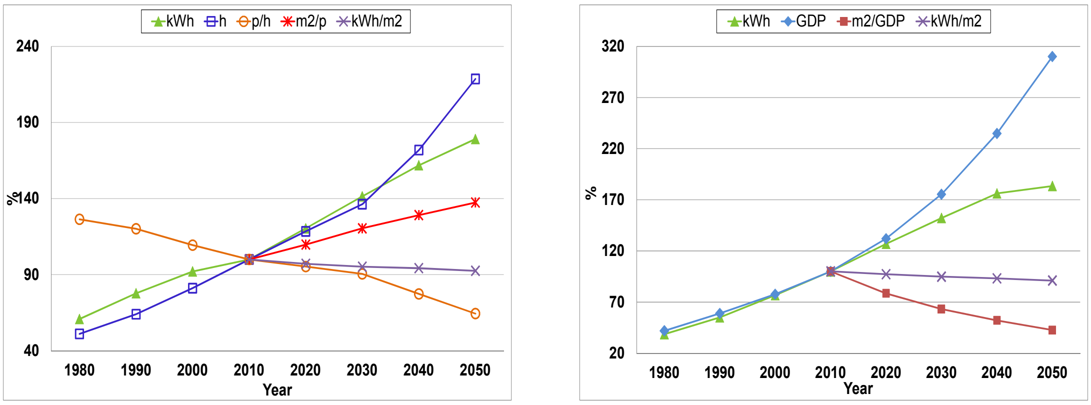
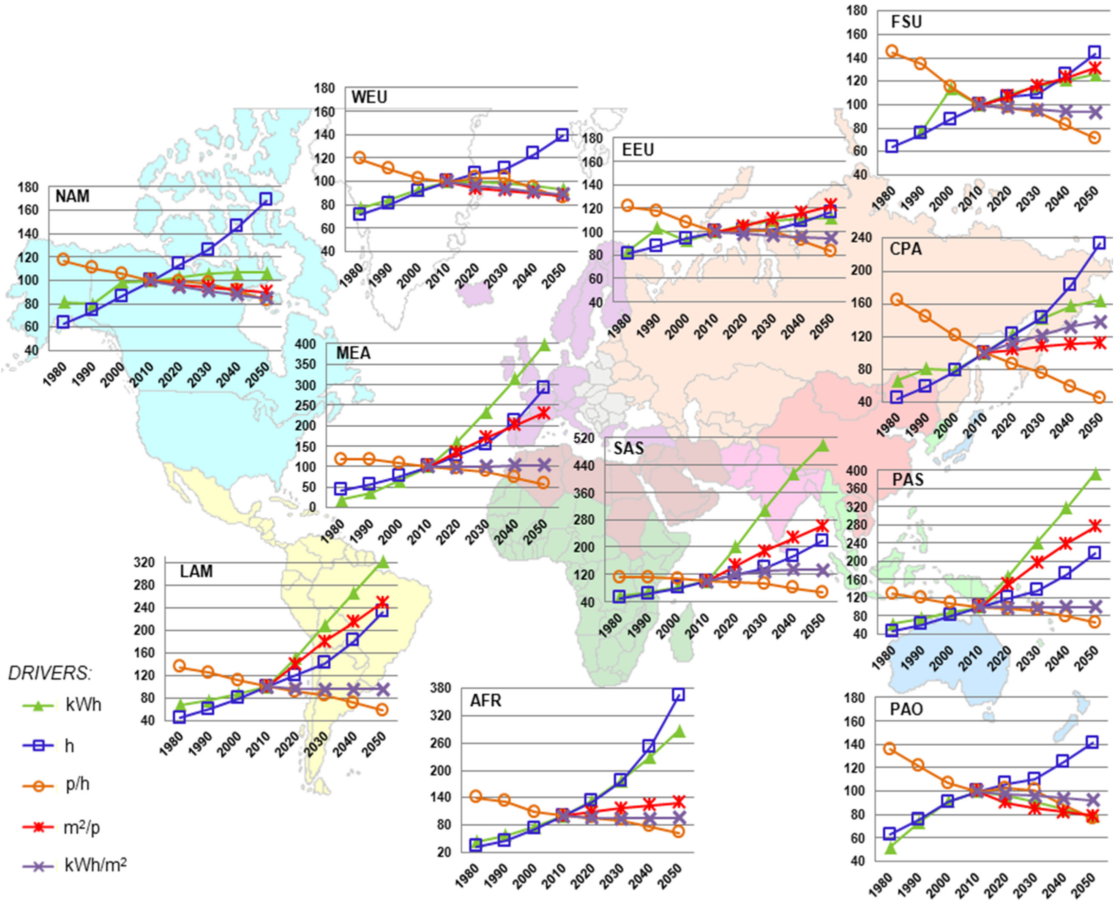


Figure 9.5. Trends of the different drivers for final thermal energy consumption in residential and commercial buildings in the world. Historic data 1980-2000 detailed in Urge-Vorsatz et al. 2013a; projections 2010-2050 data based on frozen scenario (Ürge-Vorsatz et al., 2013b)



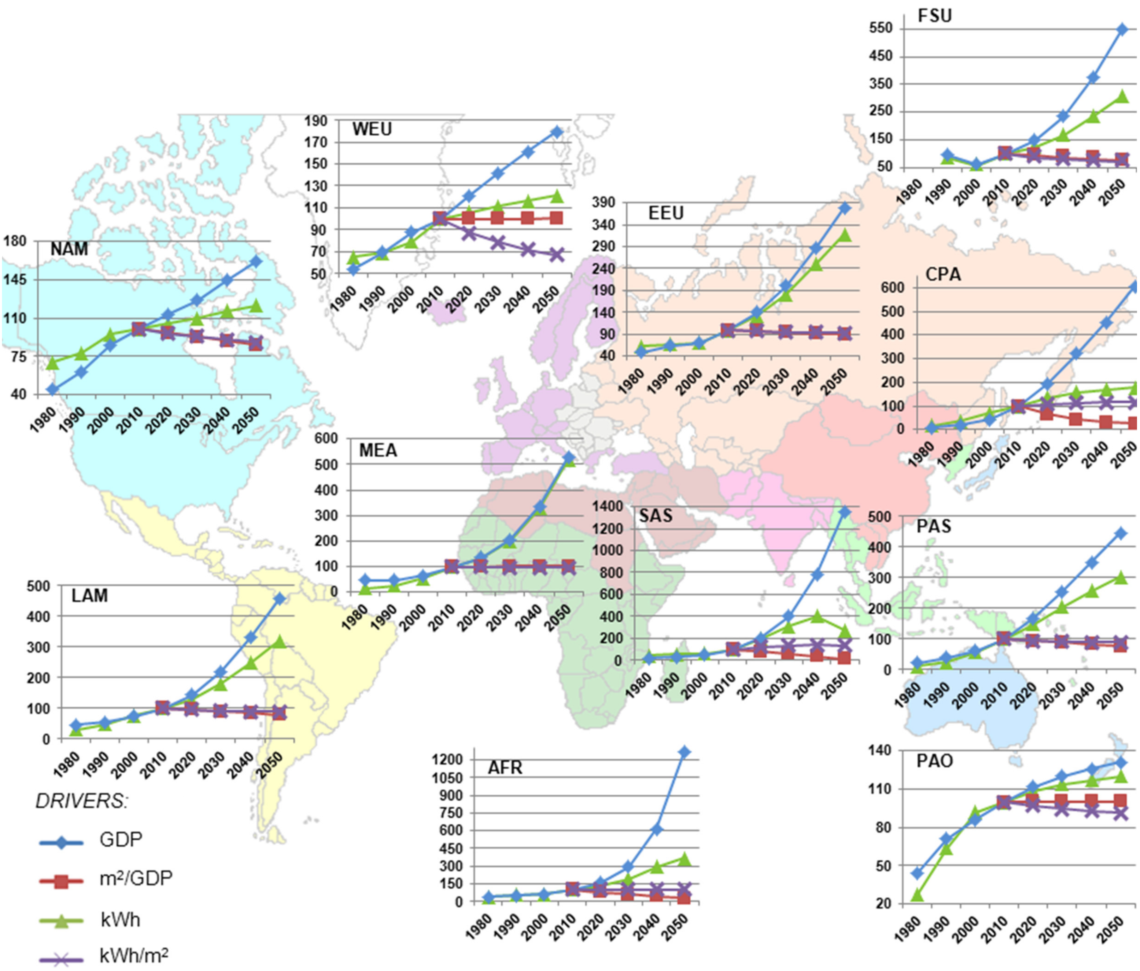


Figure 9.6. Trends of the drivers of final thermal energy consumption of residential (top) and commercial (bottom) buildings in world regions - historic data (1980-2000) from (Ürge-Vorsatz et al., 2013a) and projections (2010-2050) based on a frozen scenario (Ürge-Vorsatz et al., 2013b).

9.2.3 Trends and drivers in energy consumption of appliances in buildings

Traditional large appliances are still responsible for most household electricity consumption (ETP, 2012). However, their share is falling rapidly, as electronic home entertainment and information and communications equipment now account for more than 20% of residential electricity consumption in most countries. This rapid growth offers opportunities to roll out more efficient technologies, but this effect to date has been overwhelmed by the increased uptake of new devices. ***Energy use of appliances*** can be decomposed as shown in the following equation from (Cabeza et al., 2013a), with an example for UK: {[energy] = [Σ_a [h] * [n/h] * [energy/n]} where Σ_a is the sum over all appliances; *[h]* is the activity driver, the number of households; *[n/h]* is the use intensity driver, the number of appliances per household; and [energy] is the energy intensity driver (kWh used per appliance). The number of appliances grew all over the world (Figure 9.7 shows this tendency for China). In China, a country with an economy in transition, the growth of the stock of appliances was more influenced by the growth in GDP than in the number of households. (Cabeza et al., 2013a) shows a forecast of electricity demand for selected appliances in thirteen major economies that account for most of the world's energy consumption is carried out using the BUENAS model (Zhou et al., 2011) – this model includes OECD countries, Australia, Canada, EU, Japan, Korea, Mexico and US as well as non-OECD countries Brazil, China, India, Indonesia, Russia, and South Africa. Figure 9.8 shows that the energy consumption of major appliances in the six major non-OECD countries is already nearly equal to consumption in the OECD, due to their large populations and widespread adoption of the main white goods and lighting. Also, while fans are a minor end-use in most OECD countries, they are extremely popular in the warm developing countries, where mechanical air conditioning is largely unaffordable.

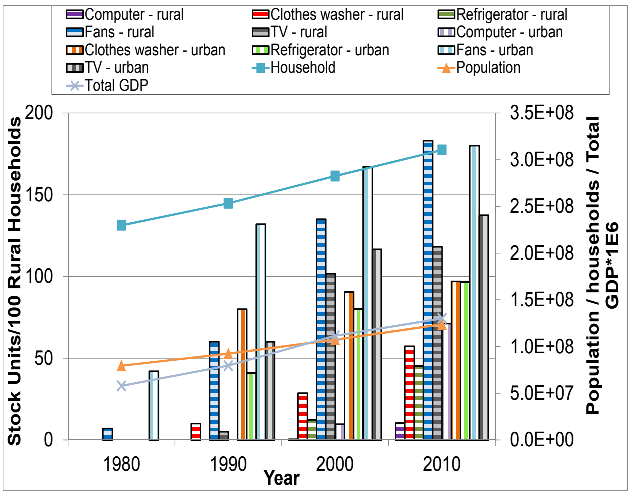


Figure 9.7. Number of appliances in urban and rural households in China (1980-2010). Source: adapted from (Cabeza et al., 2013a)

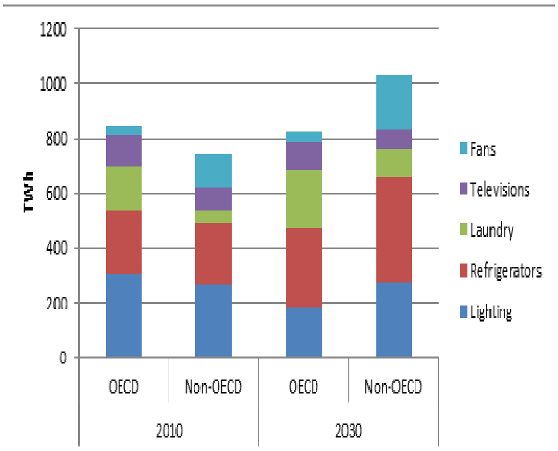


Figure 9.8.BUENAS modelled residential electricity consumption by end-use. Source: (Cabeza et al., 2013a)

Box 9.1: Least Developed Countries (LDCs)

[TSU COMMENT TO REVIEWERS: Boxes highlighting further LDC-specific issues are included in other chapters of the report (see chapter sections 1.3.1, 2.1, 6.3.6.6, 7.9.1, 8.9.3, 10.3.2, 11.7, 12.6.4, 16.8) and a similar box may be added to the Final Draft of chapters, where there is none in the current Second Order Draft. In addition to general comments regarding quality, reviewers are encouraged to comment on the complementary of individual boxes on LDC issues as well as on their comprehensiveness, if considered as a whole.]

The Least Developing Countries (LDCs) are at the fringe of new construction taking place in developing countries. These populations, as well as considerable fractions of other developing nations where high Gini-measured inequality levels prevails, amount to over 2 billion without access to modern energy carriers. Providing clean cooking facilities is one of the world's most critical development challenges (Zhang and Smith, 2007; Duflo et al., 2008; Wilkinson et al., 2009; World Health Organization, 2009, 2011; Hailu, 2012; Pachauri, 2012). Rapid economic development, accompanied by urbanization, is propelling huge building activity in developing countries, notably China and India (WBCSD, 2007, 2009; ABC, 2008; Li and Colombier, 2009). Around one third of the urban population in developing countries in 2010 did not have access to adequate housing, living in slums (UNHSP, 2010) and the number of slum dwellers is likely to rise in the near future (UN-Habitat, 2011). In order to avoid locking in carbon-intensive options for several decades, a shift to electricity and modern fuels should be accompanied by energy-saving solutions (technological, architectural), as well as renewable sources, adequate management and sustainable lifestyles (WBCSD, 2006; Ürge-Vorsatz et al., 2009; Wilkinson et al., 2009; US EERE, 2011; GEA, 2012; Wallbaum et al., 2012) (Ürge-Vorsatz et al., 2009; GEA, 2012). Modern knowledge and techniques can be used to improve vernacular designs (Foruzanmehr and Vellinga, 2011). In many parts of the world where efficient building systems – especially for housing – are not affordable, principles of low-energy design may provide comfortable conditions much of the time, thereby reducing the pressure to later install energy-intensive cooling equipment such as air conditioners. These principles are embedded in vernacular designs throughout the world, which evolved over centuries in the absence of mechanical heating and cooling systems. To promote vernacular architecture, it is necessary to consider the cultural and convenience factors and perceptions concerning "modern" approaches, as well as the environmental performance that influences the decision to adopt or abandon vernacular approaches. Beyond the direct energy cost savings, many mitigation options in this sector have significant and diverse co-benefits that offer attractive entry points for mitigation policy-making, even in countries/jurisdictions where financial resources for mitigation are limited. These co-benefits include, but are not limited to, energy security, air pollution and health benefits; productivity, competitiveness and net employment gains; increased social welfare, alleviated energy and fuel poverty, decreased need for energy subsidies and exposure to energy price volatility risks; increased value for building infrastructure, improved comfort and services, and improved adaptability to adverse climate events. However, most social benefits are non-market ones and therefore are rarely taken into consideration in financial assessments of mitigation or energy efficiency programmes (Clinch and Healy, 2001; Tirado Herrero and Ürge-Vorsatz, 2012).

9.3 Mitigation technology options and practices, behavioural aspects

This section provides a broad overview at the strategic and planning level of the technological options, design practices and behavioural changes that can achieve large reductions in building energy use (factors of 2-10 in new buildings, factors of 2-4 in existing buildings). Energy uses in buildings can be broken into those that are commonly regulated through building codes (the combination of heating, cooling, ventilation and lighting energy uses) and those that might be regulated through equipment standards (appliances, consumer electronics, office equipment). A synthesis of documented examples of large reductions in the building-code regulated energy use achieved in real, new and retrofitted buildings in a variety of different climates, and of costs at the building level, is presented here, while Section 9.4 reviews the additional savings that are possible at the community level and their associated costs, Section 9.5 considers the impact of anthropogenic global warming on building energy use, and Section 9.6 presents a synthesis of studies of the integrated potential at the national, regional, and global level.

9.3.1 Key points from AR4

AR4 (Levine et al., 2007) contains an extensive discussion of the wide range of technical and design measures that can be taken to reduce the energy use of new buildings. AR4 emphasized that the energy use of buildings depends to a significant extent on how the various energy-using devices (pumps, motors, fans, heaters, chillers, and so on) are put together as systems, rather than depending primarily on the efficiencies of the individual devices. The savings opportunities at the system level are generally many times what can be achieved at the device level, and these system-level savings can often be achieved at a net investment-cost savings (see also (Harvey, 2008)). A systems approach in turn requires an Integrated Design Process (IDP), in which the building performance is optimized through an iterative process that involves all members of the design team from the beginning (Montanya et al., 2009; Pope and Tardiff, 2011). However, the conventional process of designing a building is a largely linear process, in which the architect makes a number of design decisions with little or no consideration of their energy implications, and then passes on the design to the engineers, who are supposed to make the building habitable through mechanical systems. The design of mechanical systems is also largely a linear process with, in some cases, system components specified without yet having all of the information needed in order to design an efficient system (Lewis, 2004). This is not to say that there is no integration or teamwork in the traditional design process, but rather, that the integration is not normally directed toward minimizing total energy use through an iterative modification of a number of alternative initial designs and concepts so as to optimize the design as a whole.

As discussed in AR4, the essential steps in the design of low-energy buildings are: (i) to consider building orientation, form and thermal mass; (ii) to specify a high-performance building envelope; (iii) to maximize passive heating, cooling, ventilation, and day-lighting; (iv) to install efficient systems to meet remaining loads; (v) to ensure that individual energy-using devices are as efficient as possible, and properly sized; and (vi) to ensure that the systems and devices are properly commissioned. By focusing on building form and a high-performance envelope, heating and cooling loads are minimized, daylighting opportunities are maximized, and mechanical systems can be greatly downsized. This generates cost savings that can offset the additional cost of a high-performance envelope and the additional cost of installing premium (high-efficiency) equipment throughout the building. These steps alone can usually achieve energy savings on the order of 35-50% for a new commercial building, compared to standard practice, while utilization of more advanced or less conventional approaches has often achieved savings on the order of 50-80%. AR4 also briefly reviewed the technical potential for energy savings through comprehensive retrofits of existing buildings. The various case studies and analyses reviewed in AR4 indicate that retrofits should be able to routinely achieve savings in total energy use of 25-70%. In-depth discussions can be found at (Harvey, 2006), others, as well as at the AR4).

9.3.2 Significant technological developments since AR4

There have been important incremental improvements in the performance and reductions in the cost of several technologies since AR4, and further significant improvements are foreseen. Examples include (i) daylighting (Dubois and Blomsterberg, 2011) and electric lighting (source); (ii) household appliances (Bansal et al., 2011b); (iii) insulation materials (Baetens et al., 2011; Korjenic et al., 2011; Jelle, 2011); (iv) heat pumps (Chua et al., 2010), (v) indirect evaporative cooling to replace chillers in dry climates (Jiang and Xie, 2010); (vi) fuel cells (Ito and Otsuka, 2011); (vii) advances in digital building automation and control systems, which can cut energy use by more than half (NBI, 2011); and (viii) smart meters and grids (Catania, 2012). There has also been an increasing application of existing knowledge and technologies, both in new buildings and in the retrofitting of existing buildings. This has been driven in part by targeted demonstration programs in a number of countries, and has been accompanied by an impressive strengthening of the energy provisions of the building codes in many countries and plans for significant further tightening of building codes in the near future. In the following sections we review the literature published largely since AR4 concerning the energy intensity and cost of low-energy new buildings and of deep retrofits of existing buildings.

9.3.3 Exemplary New Buildings

This subsection presents an overview of the energy performance and incremental cost of exemplary buildings from around the world, based on the detailed compilation of high-performance buildings presented in (Harvey, 2013). The metrics of interest are the on-site energy intensity (annual energy use per square meter of building floor area) for those energy uses (heating, cooling, ventilation and lighting) that naturally scale with the building floor area, and energy use per person for those energy uses (such as service hot water, consumer electronics, appliances and office equipment) that naturally scale with population or the size of the workforce. The energy intensity of advanced buildings in comparison to conventional buildings has been estimated based on measured energy use in case-study buildings and otherwise comparable conventional buildings, or based on computer simulations of reference and case-study buildings that are calibrated against measured energy use. Costs at the building-level have been estimated based on parallel tracking of the costs of reference and actual high-performance buildings, in comparing the cost of completed high-performance buildings with the local average of otherwise comparable buildings, or based on cost models.

9.3.3.1 Energy intensity of new high-performance buildings

Table 9.2 summarizes energy intensities for buildings by climate type or region.

Table 9.2: Typical and current best case energy intensities (kWh/m²/yr) for building loads directly related to floor area

	Region	Residential		Commercial (offices, education, government)		Source
End Use		Advanced	Typical modern	Advanced	Typical modern	
Heating		15-30 (M, C)	50-150(M); 50-450(C)	15-30 (C)	75-200 (C)	[1]
Cooling		0 (T, HD), 3-5 (HH)		5 (T); 0-10 (HD); 15-30 (HH)	20-40 (T); 20-50 (HD); 50-150 (HH)	[1]
Pumps				2-5		
Ventilation		4-8 (M,C)		0-20	30-50	[1]
Lighting	OECD	2-4	5-12	5-20	30-70	[1]
Total HVAC + lighting	DE			30-110	250-300;	[2,3,4]
	UK			130-145	300-330	[5]
	US			80-120	300-400	[6,7]
	CN			30-80	70-200	[1]
	MY			50-100	100-380	[8]
	IN			54	320-430	[9]

Note: lighting energy intensity for residential buildings is based on typical modern intensities times a factor of 0.3-0.4 to account for an eventual transition to LED lighting. Pump energy is energy used to circulate hot or cold water in hydronic heating/cooling that replaces all-air heat/coldness distribution, thereby reducing ventilation energy use. Climate regions: cold (C), moderate (M), temperate (T), hot and dry (HD), hot and humid (HH). References: [1] (Harvey, 2013), *[2]* (Voss et al., 2007)*; [3]* (Kalz et al., 2009)*; [4]* (Jacobson et al., 2009) *; [5]* (Walker et al., 2007)*; [6]* (Torcellini and Crawley, 2006)*; [7]* (Torcellini et al., 2010)*; [8]* (Kristensen, 2010)*; [9]* (Singh and Michaelowa, 2004).

For ***residential buildings***, a number of voluntary standards for heating energy use have been developed in various countries (see Table 1 in LDD Harvey, 2013). The most stringent of these is the Passive House standard, originally developed in Germany based on early work in Canada in the 1970s. This standard prescribes a heating load (assuming a uniform indoor temperature of 20ºC) of no more than 15 kWh/m²/yr irrespective of the climate. Over 30,000 buildings have been constructed worldwide that comply with this standard, ranging as far north as Helsinki. As seen from Table 9.2, this standard represents a factor of 6-12 reduction in heating load in mild climates (such as southern Europe) and up to a factor of 30 reduction in cold climate regions with minimal insulation requirements. Cooling energy use is growing rapidly in many regions where, with proper attention to passive design principles, mechanical air conditioning would not be needed. This includes regions that have a strong diurnal temperature variation (where a combination of external insulation, exposed interior thermal mass, and night ventilation can maintain comfortable conditions) or a strong seasonal temperature variation (so that the ground can be used to cool incoming ventilation air). Combining insulation levels that meet the Passive House standard for heat demand in southwestern Europe (Portugal, Spain, southern France, Italy) with the above strategies, heating loads in this region can be reduced by a factor of 6-12 (from 100-200 kWh/m²/yr to 10-15 kWh/m²/yr) and cooling loads by a factor of 10 (from < 30 kWh/m²/yr to < 3 kWh/m²/yr) (Schneiders et al., 2009). With good design, comfortable conditions can be maintained ≥90% of the time (and closer to 100% of the time if fans are used) without mechanical cooling in relatively hot and humid regions such as southern China (Ji et al., 2009; Zhang and Yoshino, 2010; Lin and Chuah, 2011), Vietnam (Nguyen et al., 2011a), Brazil (Grigoletti et al., 2008; Andreasi et al., 2010; Candido et al., 2011), and the French tropical island of La Reunion (Lenoir et al., 2011). In Salamanca, Mexico, provision of air conditioning increases the total energy intensity from 46 kWh/m²/yr to 80 kWh/m²/yr in a case-study conventional house, but increases it from 37 kWh/m²/yr to only 40 kWh/m²/yr in the least-life-cycle-cost design (Griego et al., 2012) – an impact that is a factor of 10 smaller.

In ***commercial buildings***, energy intensities of modern office and retail buildings are typically 200-500 kWh/m^2/yr, whereas advanced buildings have frequently achieved energy intensities of less than 100 kWh/m^2/yr in climates ranging from cold (5000 HDD) to hot and humid. The Passive House standard for heating has been achieved in a wide range of different types of commercial buildings in Europe. Sensible cooling loads can typically be reduced by at least a factor of four compared to recent new buildings – through measures to reduce cooling loads (often by a factor of 2-4) and through more efficient systems in meeting reduced loads (often a factor of two). Latent heat cooling loads are less amenable to reduction but can be met through solar-powered desiccant dehumidification with minimal non-solar energy requirements. Advanced lighting systems that include daylighting with appropriate controls and sensors, and efficient electric lighting systems (layout, ballasts, luminaries) typically achieve a factor of two reduction in energy intensity compared to typical new systems (Dubois and Blomsterberg, 2011).

9.3.3.2 Importance of post-occupancy evaluation to energy savings

Advanced building control systems are a key to obtaining very low energy intensities in commercial buildings. It routinely takes over one year (one complete heating and cooling season) to adjust the control systems so that they deliver the expected savings, and it sometimes takes two years (Jacobson et al., 2009). This is only possible through detailed monitoring of energy use once the building is occupied.

9.3.3.3 Zero energy/carbon and energy plus buildings

Net zero energy buildings (NZEBs) refer to buildings with on-site renewable energy systems (such PV, wind turbines, or solar thermal) that, over the year, generate as much energy as consumed by the building. NZEBs can be defined in terms of a net balance of on-site energy, or in terms of a net balance of primary energy associated with fuels used by the building and avoided through the net export of electricity to the power grid (Marszal et al., 2011). (Musall et al., 2010) identify almost 300 net zero or almost net zero energy buildings, both commercial and residential. There have also been some NZE retrofits of existing buildings. Some jurisdictions have adopted legislation requiring some portion of, or all, new buildings to be NZEBs by specific times in the future (Kapsalaki and Leal, 2011). An extension of the NZEB concept is the Positive-Energy Building Concept (having net energy production) and its role in a two-way interaction with the electricity grid (Stylianou, 2011; Kolokotsa et al., 2011).

Issues related to NZEBs include (i) the feasibility of NZEBs, (ii) minimizing the cost of attaining an NZEB, where feasible, (iii) the cost of a least-cost NZEB in comparison with the cost of supplying a building's residual energy needs (after implementing energy efficiency measures) from off-site renewable energy sources, (iv) the sustainability of NZEBs, and (v) life-cycle energy use. Creation of a NZEB at minimal cost requires implementing energy saving measures in the building in order of increasing cost up to the point where the next energy savings measure would cost more than the cost of on-site renewable energy systems. In approximately one third of NZEBs worldwide, the reduction in energy use compared to local conventional buildings is about 60% (Musall et al., 2010). Attaining net zero energy use is easiest in buildings with a large roof area (to host PV arrays) in relation to the building's energy demand, so a requirement that buildings be NZE will place a limit on the allowed height and therefore on urban density. In Abu Dhabi, NZE is possible in buildings of up to 5 stories if internal heat gains and lighting and HVAC loads are aggressively reduced (Duncan Phillips et al., 2009). Space heating and service hot water has been supplied in NZEBs either through heat pumps (supplemented with electric resistance heating on rare occasions), biomass boilers, or fossil fuel-powered boilers, furnaces, or cogeneration. An NZEB in which on-site fossil fuel use is offset through PV electricity that displaces central power-plant fossil fuel use is not truly sustainable, given limitations on fossil fuel supplies, and would not result in zero net greenhouse gas emissions once the electricity grid is decarbonized. If space heating is to be supplied through electric heat pumps, then reductions in heating loads not only reduce the required size of the heat pump by reducing the peak heating loads, but also allow the heat pump to operate more efficiently (with coefficients of performance (COP) - of up to 5 for ground source heat pumps in Germany (DEE, 2011)), thereby reducing the size of the PV array needed to supply sufficient electricity to offset the heat pump electricity use.

9.3.3.4 Incremental cost

A large number of published studies of the incremental costs of specific low-energy buildings are reviewed in (Harvey, 2013). Summary conclusions from this review, along with key studies underlying the conclusions, are given here. In the ***residential sector***, several studies indicate an incremental cost of achieving the Passive House standard (< 15 $kWh/m^2/yr$ heating load) in the range of 5-16% of the construction cost (about 50-200 €/m^2) ("Google Scholar Linked Page"; Schnieders and Hermelink, 2006; Audenaert et al., 2008; Bretzke, 2008; Newman, 2011, 2012; Pickard and Pickard, 2011). For a variety of locations in the US, (Parker, 2009) indicates additional costs of houses that achieve 34-76% reduction in energy use of about \$30-162/m^2 (excluding solar PV for both savings and costs). The extra cost of meeting the 'Advanced' thermal envelope standard in the UK (which reduces heating energy use by 44% relative to the 2006 regulations) has been estimated at 7-9% (about £70-80/m^2) relative to a design the meets the 2006 mandatory regulations (which have since been strengthened) (Langdon, 2011). Several cold-climate studies indicate that, if no simplification of the heating system is possible as a result of reducing heating requirements, then the optimal (least life-cycle cost, excluding environmental externalities) level of heating energy savings compared to recent code-compliant buildings is about 20-50% (Anderson et al., 2006; Hasan et al., 2008; Kerr and Kosar, 2011; Kurnitski et al., 2011). However, there a number of ways in which costs can be reduced: if the reference building has separate mechanical ventilation and hydronic heating, then the hydronic heating system can be eliminated or at least greatly simplified in houses meeting the Passive House standard (Feist and Schnieders, 2009); perimeter heating units or heating vents can be eliminated with the use of sufficiently insulated windows, thereby reducing plumbing or ductwork costs (Harvey and Siddal, 2008); the building shape can be simplified (reducing the surface area-to-volume ratio), which both reduces construction costs and makes it easier to reach any given low-energy standard (Treberspurg et al., 2010), and, in Passive Houses (where heating cost is negligibly small), individual metering units in multi-unit residential buildings could be eliminated (Behr, 2009). As well, it can be expected that costs will decrease with increasing experience on the part of the design and construction industries. For residential buildings in regions where cooling rather than heating is the dominate energy use, the key to low cost is to achieve designs that can maintain comfortable indoor temperatures while permitting elimination of mechanical cooling systems.

The available studies indicate that the incremental cost of low-energy buildings in the ***commercial sector*** is less than in the residential sector, due to the greater opportunities for simplification of the HVAC system, and that it is possible for low-energy commercial buildings to cost less than conventional buildings. In particular, there are a number of examples of educational and small office buildings that have been built to the Passive House standard at no additional cost compared to similar conventional or less-stringently low-energy local buildings (Anwyl, 2011; Pearson, 2011). The Research Support Facilities Building in Golden, Colorado achieved a 67% reduction in energy use (excluding the solar PV offset) at zero extra cost for the efficiency measures, as the design team was contractually obliged to deliver a low-energy building at no extra cost (Torcellini et al., 2010) . (Torcellini and Pless, 2012) discuss many opportunities for cost savings such that low-energy buildings can often be delivered at no extra cost. Other examples of low-energy buildings (50-60% savings relative to standards at the time) that cost less than conventional buildings are given in (McDonell, 2003) and (IFE, 2005). (New Buildings Institute, 2012) reports some examples of net-zero-energy buildings that cost no more than conventional buildings. Even when low-energy buildings cost more, the incremental costs are often small enough that they can be paid back in energy cost savings within a few years or less (see (Harvey, 2013)). The keys to delivering low-energy buildings at zero or little additional cost are through implementation of the integrated design process (described in Section 9.3.1) and the design-bid-build process. (Vaidya et al., 2009) discuss how the traditional, linear design process leads to missed opportunities for energy savings and cost reduction, often leading to the rejection of highly attractive (from an economic perspective) energy savings measures. Even with use of the IDP for the design stage, design of the building, bidding, detailed costing and awarding of construction contracts are usually separate steps. In the design-bid-build process, a single firm performs the design, costing and construction. (Pless et al., 2011) suggest that adoption of this framework for high-performance buildings can lead to cost savings such that high-performance buildings will cost no more than conventional buildings under the usual design + bid + build process.

9.3.4 Retrofits of existing buildings

Programs to retrofit the entire building stock of a country would be an important part of any program to reduce the energy requirements of the building stock, as buildings are very long-lived and a large fraction of the total building stock that will exist in 2050 already exists today (given typical demolition rates of less than 1%/yr).

9.3.4.1 Energy savings

Numerous case studies of individual retrofit projects (in which measures, savings and costs are documented) have been published, as well as the results of national retrofit projects involving up to several dozen pilot projects each. Most published studies pertain to retrofits in developed countries. These are reviewed in detail in (Harvey, 2013), but a few broad generalizations can be presented here: (i) for detached single-family homes, the most comprehensive retrofit packages have achieved reductions in total energy use by 50-75%; (ii) in multi-family housing (such as apartment blocks), a number of projects have achieved reductions in space heating requirements by 80-90%, approaching, in many cases, the Passive House standard for new buildings; (iii) relatively modest envelope upgrades to multi-family housing in developing countries such as China have achieved reductions in cooling energy use by about one third to one half, and reductions in heating energy use by two-thirds; (iv) in commercial buildings, savings in total HVAC (heating, ventilation and air conditioning) energy use achieved through upgrades to equipment and control systems, but without changing the building envelope, are typically on the order of 25-50%, although in one study involving an office building in Los Angeles (Armstrong et al., 2006), better operation of the system alone reduces cooling energy use by 30-60%; (v) eventual re-cladding of building facades – especially when the existing façade is largely glass with a high solar heat gain coefficient, no external shading, and no provision for passive ventilation and cooling – offers an opportunity for yet further significant savings in HVAC energy use; and (vi) lighting retrofits of commercial buildings in the early 2000s typically achieved a 30-60% energy savings (Bertoldi and Ciugudeanu, 2005).

9.3.4.2 Incremental cost

Various isolated studies of individual buildings and systematic pilot projects involving many buildings, reviewed in (Harvey, 2013), indicate the potential, with comprehensive insulation and window upgrades, air sealing, and implementation of mechanical ventilation with heat recovery, to reduce heating energy requirements by 50-75% in single-family housing and by 50-90% in multi-family housing at costs of about $100-400/m^2 above that which would be required for a routine renovation. In the commercial sector, significant savings can often be achieved at very low cost simply through retro-commissioning of equipment; (Mills, 2011) evaluated the benefits of commissioning and retro-commissioning for a sample of 643 buildings in California. The study reports a 16% median whole-building energy savings through retro-commissioning of buildings in California, with a mean payback time of 1.1 years. The International Energy Agency, Solar Heating and Cooling Programme, carried out Task 37 (Advanced Housing Renovation with Solar and Conservation) between July 2006 and June 2010. Reports providing technical details of renovation

Table 9.3: Potential savings in energy consumption by household appliances and equipment

Item	Savings potential	Reference
Televisions	Average energy use of units sold in US (largely LCDs) 426 kWh/yr in Jan 2008 102 kWh/yr in Jan 2012 Further reductions (30-50% below LCD TVs) are expected with use of organic LED backlighting (likely commercially available by 2015)	(Howard et al., 2012; Letschert et al., 2012)
Refrigerator-freezer units	40% minimum potential savings compared to the best standards, 27% savings at ≤11 cents/kWh CCE (Costs of Conserved Energy)	(Bansal et al., 2011b; McNeil and Bojda, 2012)
Cooking	50% savings potential (in Europe), largely through more efficient cooking practices alone	(Oberascher et al., 2011)
Ovens	45% potential savings through advanced technology in conventional electric ovens, 75% for microwave ovens	(Bansal et al., 2011b)
Dishwashers	Typically only 40-45% loaded, increasing energy use per place setting by 77-97% for 3 dishwashers studied	(Richter, 2011)
Dishwashers	Current initiative targets 17% less electricity, 35% less water than best US standard	(Bansal et al., 2011b)
Clothes washers	Global 28% potential savings by 2030 relative to business-as-usual	(Letschert et al., 2012)
Clothes Dryers	Factor of two difference between best and average units on the market in Europe (0.27 kWh/kg vs 0.59 kWh/kg) More than a factor of 2 reduction in going from US average to European heat pump dryer (820 kWh/yr vs 380 kWh/yr)	(Werle et al., 2011)
Standby loads	Potential of < 0.005 W for adapters and chargers, < 0.05 W for large appliances ("zero" in both cases) (typical mid 2000s standby power draw: 5-15 W)	(Harvey, 2010; Matthews, 2011)for mid 2000s data
Air conditioners	COP (a measure of efficiency) of 2.5-3.5 in Europe and US, 5.0-6.5 in Japan (implies up to 50% energy savings)	(Waide et al., 2011)
Ceiling fans	50% energy savings	(Letschert et al., 2012)
Circulation pumps for hydronic heating and cooling	40% savings from projected energy use in 2020 in Europe (relative to a baseline with efficiencies as of 2004) due to legislated standards already in place	(Bidstrup, 2011)
Residential lighting	Efficacies (lm/W) (higher is better): standard incandescent, 15; CFL, 60; best currently available white-light LEDs, 100; current laboratory LEDs, 250	(Letschert et al., 2012)
Residential water heaters	Typical efficiency factor (EF) for gas and electric water heaters in US is 0.67, 0.8 in EU, most efficient heat-pump water heaters have EF=2.35, 3.0 foreseeable (factor of 4 improvement)	(Letschert et al., 2012)

techniques (related to insulation, windows, thermal bridges, air sealing, ventilation and acoustics) and lessons learned from 60 demonstration projects carried out in 9 European countries and Canada were published (Hastings, 2010; Trachte and Deherde, 2010; Herkel and Kagerer, 2011). A report (Rødsjø et al., 2010) discussing how to scale up from pilot projects to large-scale market acceptance of deep energy retrofits was also published. Among the 60 demonstration projects, the projected or measured savings in primary energy demand almost always exceeds 50%, the average savings is 76%, and 13 of the projects reached or almost reached the Passive House standard for heating energy use. Although retrofits generally entail a large upfront cost, they also generate large annual cost savings, and so are often attractive from a purely economic point of view. (Korytarova and Ürge-Vorsatz, 2012) note that shallow retrofits can result in greater life-cycle costs than deep retrofits. (Mata et al., 2010) studied 23 retrofit measures for buildings in Sweden. They report a simple technical potential for energy savings in the residential sector of 68% of annual energy use. They estimated a cost per kWh saved between -0.07 Euro/kWh/yr (appliance upgrades) and +0.34 Euro/kWh/yr (façade retrofit). (Polly et al., 2011) present a method for determining optimal residential energy efficiency retrofit packages, and report on methods to evaluate and select retrofit measures based on a. They identify near-cost-neutral packages of measures providing between 29% and 48% energy savings across 8 US locations (assuming a 3% discount rate, a 3% annual fuel escalation rate, and a 30-year time horizon). Of particular interest are studies wherein a number of similar buildings were retrofitted to different standards, and the energy use and cost associated with the different standards determined. Also of interest are simulation studies involving an archetype existing building that is assumed to have increasingly stronger sets of measures applied, again with the energy use and cost calculated at each step (Galvin, 2010). (Lewis, 2004) has compiled information from several such studies in old buildings in Europe. His compilation indicates that the total and marginal cost of conserved energy both tend to be relatively uniform for savings of up to 70-80%, but increase markedly for savings of greater than 80% or for final heating energy intensities of less than about 40 kWh/m2/yr.

9.3.5 Appliances, consumer electronics and office equipment

Table 9.3 summarizes information concerning potential reductions in unit energy by household appliances and equipment. Identified savings potentials are typically 40-50%. Aggregate energy consumption by these items is expected to continue to grow rapidly as ownership rates increase with increasing wealth, unless standards are used to induce close to the maximum technically achieved reduction in unit energy requirements.

9.3.6 Halocarbons

Building-related emissions of halocarbons occur from refrigeration and cooling equipment and from various foam insulation products. With the phase-out of CFCs following the Montreal protocol in 1990, and the planned phaseout of HCFCs (temporary replacements for CFCs), most of the halocarbons of present and future concern to climate are hydro-fluoro-carbons (HFCs), which global warming potentials (GWPs) generally over 1000 and up to 12386 on a 100-year time horizon (see Table 8.A.1 in Myhre and Shindell, 2012)**.** Progress is being made in developing substitutes with lower climate impact. For example, hydro-fluoro-olefins (HFOs), having a GWP of 4-6, are possible substitutes for HFC-134a (GWP=1430) in residential refrigerators (Bansal et al., 2011b), while foam insulations with non-halocarbon expanding agents have recently become available. There is also great potential to reduce emissions of HFCs during the operation and servicing of HFC-containing equipment (McCulloch, 2009).

9.3.7 Affordable low-energy housing

The previous case studies of high-performance buildings assume that mechanical heating, cooling, and ventilation systems are provided as needed in order to maintain building temperatures and humidities within acceptable ranges, although allowance is made for adaptive thermal comfort standards and the installed systems have been greatly downsized through the attention to passive building design features and provision of a high-performance thermal envelope. However, in many parts of the world, such systems – especially for housing – are not affordable. The goal then is to use principles of low-energy design to provide comfortable conditions as much of the time as possible, thereby reducing the pressure to later install energy-intensive cooling equipment such as air conditioners. These principles are embedded in vernacular designs throughout the world, which evolved over centuries in the absence of mechanical heating and cooling systems. For example, vernacular housing in Vietnam tested by (Nguyen et al., 2011b) experienced conditions warmer than 31°C only 6% of the time. In the hot-humid regions of Brazil, an airflow > 0.8 m/s is sufficient for a temperature of 31°C to be deemed acceptable by 90% of respondents (Cândido et al., 2011). The natural and passive control system of traditional housing in Kerala (India) maintains bedroom temperatures of 23-29°C as outdoor temperatures vary from 17-36°C on a diurnal time scale (Dili et al., 2010). However, to promote vernacular architecture, it is necessary to consider the cultural and convenience factors and perceptions concerning “modern” approaches, as well as the environmental performance, that influence the decision to adopt or abandon vernacular approaches (Foruzanmehr and Vellinga, 2011). It may also be the case that modern knowledge and techniques can be used to improve vernacular designs.

9.3.8 Uses of biomass

As noted in (Fig. 9.9) [and in the Bioenergy X-cut Section], biomass is the single largest source of energy for buildings at the global scale, playing an important role for space heating, production of SHW and for cooking in many developing countries. Advanced biomass stoves provide fuel savings of 30-60% and reduce indoor air pollution levels by 80-90% for models with chimneys, compare to open fires (Ürge-Vorsatz, Eyre, Graham, Kornevall, et al., 2012). Gasifier and biogas cookstoves have also undergone major developments.

9.3.9 Building materials lifecycle

Research published since AR4 confirms that the total life-cycle energy use of low-energy buildings is less than that of conventional buildings, in spite of generally greater embodied energy in the materials and energy efficiency features. A review of life cycle assessment (LCA), life cycle energy analysis (LCEA) and material flow analysis (MFA) in buildings (conventional and traditional) can be found in (Cabeza et al., 2013). In Switzerland, (Citherlet and Defaux, 2007) find that the life cycle energy of a low-energy house with PV and solar hot water is about half that of a house meeting the Swiss Minergie standard, which in turn is about two-thirds that of a conventional house. In Sweden, Karlsson and Moshfegh (2007) find that a low-energy house, while having 40% greater embodied energy, requires 40% less total energy over a 50-year period than a conventional Swedish house. Sartori and Hestnes (2007) find that a house built to the Passive House standard uses significantly less energy on a life-cycle basis than any alternative. (Ramesh et al., 2010) show, based on 73 case studies across 13 countries, that lower operating energy use is consistently associated with lower life cycle energy use. Recent research also confirms that wood-based wall systems entail 10-20% less embodied energy than concrete systems (Upton et al., 2008; Sathre and Gustavsson, 2009) and that concrete-framed buildings entail less embodied energy than steel-framed buildings (Xing et al., 2008). Pre-fabrication of wood frame modules can reduce wood waste by 20-40%, with a corresponding reduction in embodied energy (Monahan and Powell, 2011). Insulation materials entail a wide range of embodied energy per unit volume, and the time required to pay back the energy cost of successive increments insulation through heating energy savings increases as more insulation is added. However, this marginal payback time is less than the expected lifespan of insulation (50 years) even as the insulation level is increased to that required to meet the Passive House standard (Harvey, 2007). The use of phase-change materials is also beneficial on a life-cycle basis (De Gracia et al., 2010; Castell et al., 2012). The embodied energy of biomass-based insulation products is not lower than that of many non-biomass insulation products when the energy value of the biomass feedstock is accounted for, but is less if an energy credit can be given for incineration with cogeneration of electricity and heat, assuming the insulation is extracted during demolition of the building at the end of its life (Ardente et al., 2008).

9.3.10 Behavioural impacts

Chapter 2 discusses behavioural issues in a broad sense. In buildings, the key behavioural issues pertain to thermostat temperature settings for heating and cooling, the way in which equipment is operated, whether or not advantage is taken of opportunities for natural ventilation and passive cooling, frugality with respect to the use of hot water, and choices of lighting equipment and whether or not lighting is left on when not needed, and the number of electronic gadgets that are acquired (most of which remain plugged in and draw power even when turned off). It is now widely recognized that the indoor temperature found to be acceptable depends on the outdoor temperature, leading to an adaptive thermal comfort standard, whereby the thermostat setting varies with the outdoor temperature (Brager and De Dear, 2000). In low-energy buildings, where the heating demand is only about 1/3 of the gross heat loss, an increase in the mean indoor-to-outdoor temperature difference by 10% (by changing the thermostat setting during the heating season from 20ºC to 22ºC if the mean outdoor temperature is 0ºC) would increase the heating energy requirement by up to 30%. During the cooling season, increasing the thermostat setting from 24ºC to 28ºC 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 et al., 2004), and by a factor of two to three if the thermostat setting is increased from 23ºC to 27ºC for night-time air conditioning of bedrooms in apartments in Hong Kong (Lin and Deng, 2004). Behavioural issues – involving the cooperation of building occupants – are crucial to the correct operation of passive and hybrid ventilation systems in office buildings. Behavioural factors interact with the choice of technology. In much of Asia, air conditioning – where available – is usually done with individual room air conditioners that are turned off when the room is not occupied. Centralized chillers, while being up to twice as efficient as older room air conditioners, provide continuous rather than selective cooling to the entire building volume. As a result, they use up to 9 times more energy than small decentralized units that are used selectively (S Zhang et al. 2010).

9.4 Infrastructure and systemic perspectives

9.4.1 Urban form and energy suppy infrastructure

Land use planning influences greenhouse gas emissions in several ways, including through the energy consumption of buildings. More compact ***urban form*** tends to reduce consumption due to lower per capita floor areas, reduced building surface to volume ratio, increased shading and more opportunities for district heating and cooling systems (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012). Greater compactness has trade-offs within individual buildings in regions with significant cooling demand, as it tends to increase the urban heat island effect. However, the overall impact of increased compactness is to reduce GHG emissions. This issue is discussed in more detail in Chapter 12. Energy-using activities in buildings and their energy supply networks co-evolve. Whilst the structure of the building itself is key to the amount of energy consumed, the ***energy supply networks*** largely determine the energy vector used, and therefore the carbon intensity of supply. Changing fuels and energy supply infrastructure to buildings will be needed to deliver large emissions reductions even with the major demand reductions outlined in 9.3. This section therefore focuses on the interaction of buildings with the energy infrastructure, and its implications for use of lower carbon fuels.

9.4.1.1 District Heating and Cooling networks

Heating and cooling networks facilitate mitigation where they allow the use of higher efficiency systems or the use of waste heat or lower carbon fuels (e.g. solar heat and biomass) than can be used cost effectively at the scale of the individual building. High efficiency distributed energy systems, such as gas engine and solid oxide fuel cell cogeneration and trigeneration generate heat and electricity more efficiently than centralized power plants and heating boilers. District energy systems differ between climate zones. Large-scale district heating systems of cold-climate cities predominantly provide space heating in winter and domestic hot water throughout the year. There are also some examples that utilize non-fossil heat sources, notably waste incineration (Holmgren, 2006). Despite their energy saving benefits, fossil fuel district heating systems cannot alone deliver very low carbon buildings. In very-low energy buildings, hot water is the predominant heating load, and the high capital and maintenance costs of district heating infrastructure may be uneconomic (Thyholt and Hestnes, 2008; Persson and Werner, 2011). The literature is therefore presently divided on the usefulness of district heating to serve very low energy buildings. In regions with cold winters and hot summers, district energy systems can deliver both heating and cooling, usually at the city block scale, and primarily to commercial buildings. Energy savings of 30% can be achieved using trigeneration, load levelling, thermal storage, highly-efficient refrigeration, and advanced management (Nagota et al., 2008). Larger benefits are possible by using waste heat from incineration plants (Shimoda et al., 1998) and from water source heat pumps (Song et al., 2007).

9.4.1.2 Electricity infrastructure

Electricity grid infrastructure is ubiquitous in the developed world. Universal access to electricity remains a key development goal in developing countries. Implications for energy demand depend on generation efficiency and efficiency of use. Electricity is the dominant fuel for cooling and appliances, but energy use for heating is dominated by direct use of fossil fuels in most countries. Electrification of heating can therefore be a mitigation measure, depending on the levels of electricity decarbonisation and its end use efficiency. Heat pumps may facilitate this benefit as they allow electrification to be a mitigation technology at much lower levels of electricity decarbonisation (Lowe, 2007). Ground-source heat pumps already have a high market share in some countries with low cost electricity and relatively efficient buildings (IEA HPG, 2010). There is a growing market for low-cost air source heat pumps in mid-latitude countries (Cai et al., 2009; Howden-Chapman et al., 2009; Singh, Muetze, et al., 2010). In many cases the attraction is that there are not pre-existing whole-house heating systems and that air-source heat pumps can provide both heating and cooling. A review of scenario studies indicates heating electrification may have a key role in decarbonisation (Sugiyama, 2012), with heat pumps usually assumed to be the preferred heating technology (IEA, 2010a). This would imply a major technology shift from direct combustion of fossil fuels for building heating. Use of electricity, even at high efficiency, will increase winter peak demand (Cockroft and Kelly, 2006) with implications for generation and distribution capacity that have not been fully assessed; there are challenges in retrofitting to buildings not designed for heating with low temperature systems (Fawcett, 2011); and the economics of a high-cost heating system in a low-energy building are problematic. Significant energy demand reduction is therefore critical to facilitate electrification (Eyre, 2011), but the literature remains unclear on the potential scale of electrification of heating as a mitigation option.

9.4.1.3 Smart Energy Infrastructure

Electricity infrastructure will increasingly use information technology. Smart meters provide better information and therefore can aid demand reduction, but they also facilitate smart grids by facilitating shifts in demand. This can lead to mitigation directly through the use of lower carbon off peak electricity. Smart grids may be critical for the effective operation of electricity systems with high levels of intermittent supply (Sims et al., 2011) by facilitating the use of distributed energy resources, including small scale generation and new loads, such as electric heating and electric vehicles.

9.4.1.4 Thermal Energy Storage

Thermal energy storage can use diurnal temperature variations to improve load factors, and therefore reduce heating and cooling system size, which will be particularly important if heating is electrified. Thermal storage technologies could also be important in regions with electricity systems using high levels of intermittent renewable energy. The use of storage in a building can smooth temperature fluctuation and can be implemented by sensible heat (e.g. changing building envelope temperature), or by storing latent heat using phase change materials, in either passive or active systems (Cabeza et al., 2011). Both thermochemical energy storage (Freire González, 2010) and underground thermal energy storage with ground source heat pumps (Sanner et al., 2003) are being studied for seasonal energy storage.

9.4.2 Infrastructure costs

The costs of energy infrastructure systems represent a relatively high fraction of the costs of energy services in buildings. Much lower energy buildings offer the potential for some reduction in infrastructure cost. However, this potential will not automatically be realized, as infrastructure is frequently over-sized. Improved design and commissioning procedures may be required to ensure that infrastructure is sized to meet the needs of efficient buildings. Changing infrastructure within the existing built environment has higher costs than installation in new buildings – hence the economic barriers identified above to moving to low carbon vectors in low energy buildings.

9.4.3 Path Dependencies and lock-in

Buildings and their energy supply infrastructure are some of the longest lived components of the economy. Building lifetimes vary from a few decades to centuries; the major retrofit cycle of buildings is typically 20 to 50 years; and the lifetime of electricity, gas and heat infrastructure is similar. Buildings constructed and retrofitted in the next few years/decades will dominate the sector for many decades, without major opportunities for further change. The sector is particularly prone to lock-in, due to favoring incremental change (Bergman et al., 2008), traditionally low levels of innovation (Rohracher, 2001) and high inertia (Brown and Vergragt, 2008).

FAQ 9.2. How decisions in the buildings sector contribute to GHG emissions, direct and indirectly?

Decisions in the building sector affect GHG emissions for decades, as they last for 50-100 years, requiring carbon-intensive infrastructure for power and heat supply, transportation and most urban systems. An inefficient lock-in energy use can be exemplified by architectural options favoring the intensive installation of air conditioning and the need of parking spaces for cars. Such option brings up consequences such as consolidated cities where mass transport has little space to be developed and high demand for power supply. On the other hand, the pursuit of higher building performance can lower energy costs and significantly address climate change mitigation needs. Efficiency (including use of ICT, on-site renewable energy generation and cogeneration, integration through smart grids) improves energy security (thus reducing dependence of imports) and entails socio-environmental ancillary life cycle benefits (water reuse, dematerialization, substitution of high-GWP gases, substitution of indoor traditional solid fuel burning, job creation, increased education and induced innovation). It is crucial to influence such decisions, taking into consideration both the urgency to deal with climate change and the pace necessary to supply the booming demand for new buildings, especially in emerging economies.

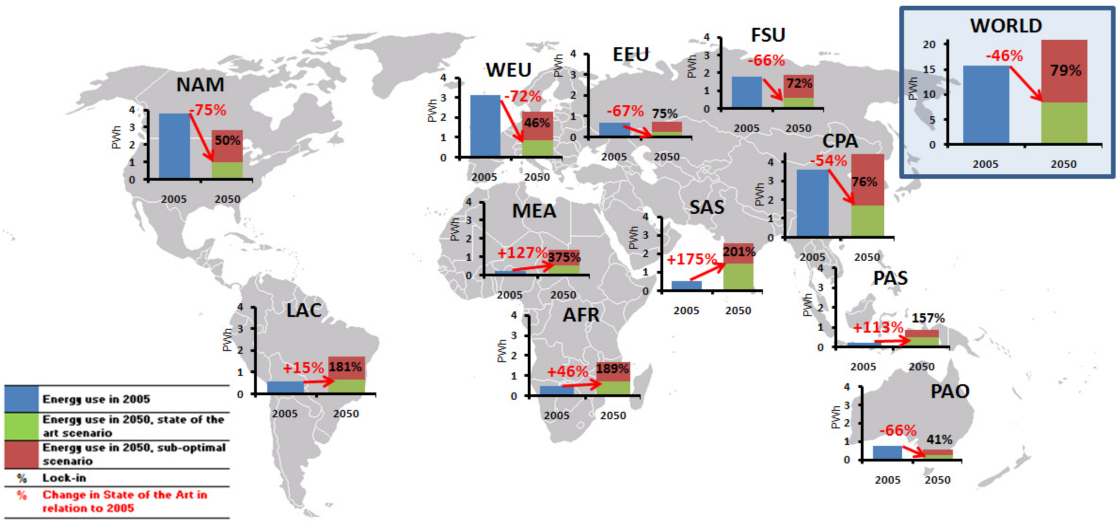


Figure 9.9. Final building heating and cooling energy use scenarios to 2050 in the Global Energy Assessment by IEA region (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012).

Notes: Green bars, indicated by red arrows and numbers; represent the opportunities through the GEA state-of-the-art scenario, while the red bars with black numbers show the size of the lock-in risk (difference from the sub-optimal scenario). Percent figures are relative to 2005 values.

When a major retrofit or new construction takes place, state-of-the-art performance levels discussed in section 9.3 are required to avoid locking in sub-optimal outcomes. Sunk costs of district heating, in particular, can be a disincentive to investments in very low energy buildings. Without the highest achievable performance levels, global building energy use will rise instead of going down (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012). This implies that a major reduction in building energy use will not take place without strong policy efforts, and particularly the use of building codes that require adoption of the ambitious performance levels set out in 9.3 as soon as possible. Recent research (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012) finds that by 2050 the size of the lock-in risk is equal to almost 80% of 2005 global building heating and cooling final energy use (see Figure 9.9). This represents the gap between a scenario in which today's best cost-effective practices in new construction and retrofits become standard after a transitional period, and a scenario in which levels of building energy performance are only consistent with today's policy ambitions. The size of the lock-in risk varies significantly by region: e.g., in South-East Asia (including India) the lock-in risk is over 200% of 2005 final heating and cooling energy use.

9.5 Climate change feedback and interaction with adaptation

Buildings are sensitive to climate change, which influences energy demand and its profile. As climate warms, cooling demand increases and heating demand decreases (Day et al., 2009; Isaac and Van Vuuren, 2009b; Hunt and Watkiss, 2011), while passive cooling approaches become less effective (Artmann et al., 2008; Chow and Levermore, 2010). Under a +3.7ºC scenario by 2100, the worldwide reduction in heating energy demand due to climate change may reach 34% in 2100, while cooling demand may increase by 70%+; net energy demand would reach -6% by 2050 and + 5% by 2100; and significant regional differences, e.g. 20%+ absolute reductions in heating demand in temperate Canada and Russia; cooling increasing by 50%+ in warmer regions and even higher increases in cold regions (Isaac and Van Vuuren, 2009b). Other regional and national studies (Mansur et al. 2008; van Ruijven et al. 2011; Wan et al. 2011; Xu et al., 2012) reveal the same general tendencies, with energy consumption in buildings shifting from fossil fuels to electricity and affecting peak loads (Isaac and Van Vuuren, 2009b; Hunt and Watkiss, 2011), especially in warmer regions (Aebischer et al., 2007). Climate implications of this shift are related to the nature of the fuels and technologies locally used for power generation: a global reference scenario from Isaac and Van Vuuren (2009b) shows increases in residential CO_2 emissions of 0.3+ Gt C by 2100 (lower with electricity decarbonisation). Projected changes in heating and cooling demands can be mitigated and even offset (e.g. in some office buildings) by using more efficient equipment that reduce heat production (Jenkins et al., 2008).

There is a a wide-range of sensitivities but also many opportunities to respond to changing climatic conditions in buildings: modified design goals and engineering specifications increase resilience (Gerdes et al., 2011; Pyke et al., 2012) . There is no consensus on definitions of climate adaptive buildings, but several aims include minimising energy consumption for operation, mitigating GHG emissions, providing adaptive capacity and resilience to the building stock, reducing costs for maintaining comfort, minimising the vulnerability of occupants to extreme weather conditions, reducing risks of disruption to energy supply and addressing fuel poverty (Roaf et al., 2009), (Atkinson et al., 2009). Adaptation and mitigation effects may be different in developed and developing countries, according to the stage of urbanization. Contemporary strategies for adapting buildings to climate change still often emphasize increasing the physical resilience of building structure and fabric to extreme weather and climatic events, but this can lead to decreased functional adaptability and increased embodied energy and associated GHG emissions. Increased extremes in local weather-patterns can lead to sub-optimal performance of buildings that were designed to provide thermal comfort 'passively' using principles of bioclimatic design. In such circumstances, increased uncertainty over future weather patterns may encourage demand for mechanical space heating and/or cooling regardless of the climate-zone.

There are also several opportunities for *radiation management* (geo-engineering) through building roofs and pavements, which constitute over 60% of most urban surfaces and with co-benefits such as improved air quality (Ihara et al., 2008; Taha, 2008). Simulations estimate reductions in urban temperatures by up to 0.7 K (Campra et al., 2008; Akbari et al., 2008; Oleson et al., 2010; Millstein and Menon, 2011).. Akbari et al., 2008 estimated that changing the solar reflectance of a dark roof (0.15) to an aged white roof (0.55) results in a one-time offset of 1 tonne CO_2 per 10 m^2 of roof area through enhanced reflection. Global CO_2 offset potentials from cool roofs and pavements amount to 78Gt CO_2 (Menon et al., 2010). Increasing the albedo of a 1 m^2 area by 0.01 results in a global temperature reduction of $3x10^{-15}$ K and offsets emission of 7 kg of CO_2 (Akbari et al., 2012). Changing to cleaner fuels and using more efficient technologies also lowers the atmospheric radiative forcing by reducing *black carbon* or soot (a pollutant from incomplete combustion of coal, oil and of traditional biomass – see Bioenergy X-Cut), which is highly absorptive of solar radiation and can be transported by clouds over long-distances (Ramanathan and Carmichael, 2008).

9.6 Costs and potentials

9.6.1 Summary of literature on aggregated mitigation potentials by key identity

The chapter's earlier sections have demonstrated that there is a broad portfolio of different technologies and practices available to cut building-related emissions significantly. However, whereas these potentials are large at an individual product/building level, it is an important question to what portion of the stock they apply to, what is the overall potential if we consider the applicability, feasibility and replacement dynamics, too, with other constraints. Figure 9.10 and the corresponding Table 9.4 synthesise the literature on a selection of regional studies on potentials through different types of measures, aggregated to stocks of the corresponding products/buildings at the regional level. The studies are organised by the four key strategic identities identified at the beginning of the chapter; but it was often not possible to precisely distinguish one category from the other, therefore the binning should be treated as indicative only. The potentials illustrated in the table and figure are usually given for final energy use (if not specified otherwise) and are mostly presented as a percentage of the respective baseline energy, specified in the original source. The figure demonstrates that the high potentials at the individual product/building level translate into relatively high potentials also at a stock-aggregated levels: mitigation or energy saving potentials often go beyond 30% to even 60% of the baseline energy use/emission of the stock the measures apply to. The figure also attests that each of the key mitigation strategies relevant to buildings can bring very large reductions, although systemic efficiency seems to bring higher results than other strategies, and demand reduction has been so far estimated to bring the most modest results from among these strategies, although studies less often assess these options systematically.

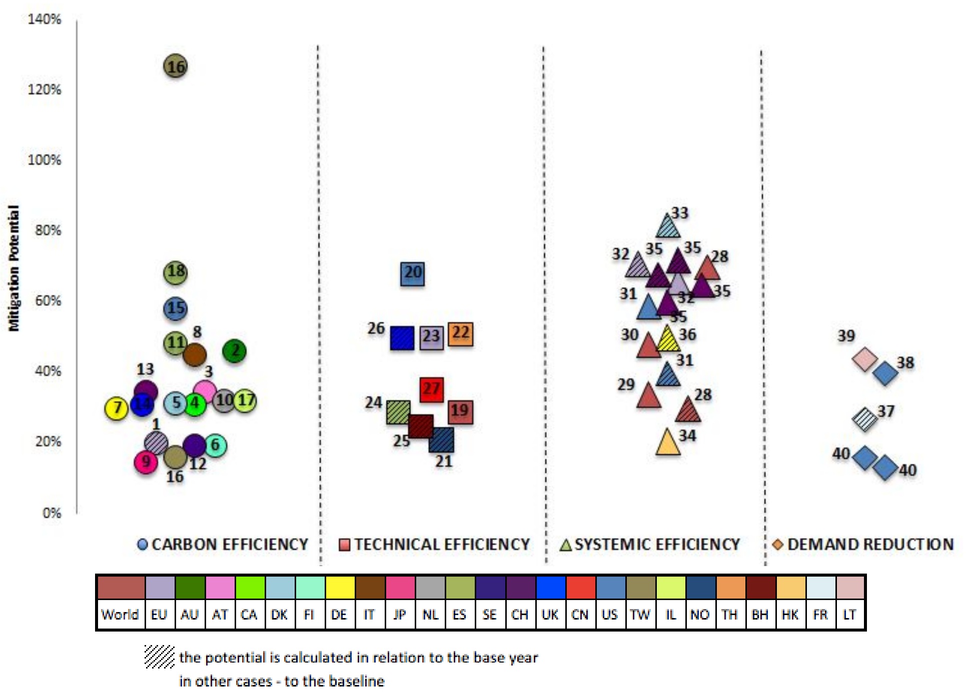


Figure 9.10. Regional studies on aggregated mitigation potentials grouped by key identity (i.e. main mitigation strategy). *Note*: *Numbers correspond to the cases in Table 9.4*

1 **Table 9.4:** Summary of literature on aggregated mitigation potentials in buildings categorized by key mitigation strategies

Reg	Description of mitigation measures/package (year)	End-uses	Type	Sector	Base-end yrs	% change to baseline	% change to base yr	No*
CARBON EFFICIENCY								
EU	Additional solar domestic hot water system	HW	T	RS	2010-20		20%, pr.e	1
AU,AT, CA,DK, FL,DE, IT,JP, NL,ES, SE,CH, UK,US	Solar electricity generation through buildings' roof-top PV installations	elect	T	BS	yearly	-46%, -35%, -31%, -32%, -19%, -30%, -45%, -15%, -32%, -48%, -20%, -35%, -31%, -58%		2 - 15
TW	Solar energy potential from solar W and PV systems on the rooftop areas of buildings	PV W	T	BS	2009	-16.3% -127.5%		16
IL	All available rooftops are accounted for producing solar energy	El.	T	BS	yearly	-32%		17
ES	An optimal implementation of the Spanish Technical Building Code and usage of 17% of the available roof surface area	W	T-E	BS	2009	-68.4%		18
TECHNICAL EFFICIENCY								
WO	Significant efforts to fully exploit the potential for EE, all cost-effective RES for heat and electricity generation, production of bio fuels, EE equipment	ALL	T	BS	2007-50	-29%		19
US	The cost-effective energy saving targets, assumed for each end-use on the basis of several earlier studies, are achieved by 2030	ALL	T-E	BS	2010-30	-68%		20
NO	Wide diffusion of heat pumps and other energy conservation measures, e.g. replacement of windows, additional insulation, heat recovery etc.	ALL	T	BS	2005-35	-9.50%	-21%	21
TH	Building energy code and building energy labeling are widely implemented, the requirements towards NZEBs are gradually strengthened by 2030	ALL	T	CS	by 2030	-51%		22
N. Eu	Improvements in lamp, ballast, luminaire technology, use of task/ambient lighting, reduction of illuminance levels, switch-on time, manual dimming, switch-off occupancy sensors, daylighting	L	T	CS	2011	-50%		23
Cat, ES	Implementation of Technical Code of Buildings for Spain, using insulation and construction solutions that ensure the desired thermal coefficients	H/C	T	BS	2005-15		-29%	24
BH	Implementation of the envelope codes requiring that the building envelope is well-insulated and efficient glazing is used	C	T	CS	1 year		-25%	25
UK	Fabric improvements, HVAC changes (incl. ventilation heat recovery), lighting and appliance improvements and renewable energy generation	ALL	T	CS	2005-30		-50% (CO_2)	26
CN	Best Practice Scenario (BPS) examined the potential of an achievement of international best-practice efficiency in broad energy use today	APPL	T	RS, CS	2009-30	-35%		27

SYSTEMIC EFFICIENCY								
WO	Today's cost-effective best practice integrated design & retrofit becomes a standard	H/C	T-E	BS	2005-50	-70%	-30%	28
WO	The goal of halving global energy-related CO_2 emissions by 2050 (compared to 2005 levels); the deployment of existing and new low-carbon technologies	ALL	T-E	BS	2007-50	-34%		29
WO	High-performance thermal envelope, maximized the use of passive solar energy for heating, ventilation and daylighting, EE equipment and systems	ALL	T	BS	2005-50	-48%		30
US	Advanced technologies, infrastructural improvements and some displacement of existing stock, configurations of the built environment that reduce energy requirements for mobility, but not yet commercially available	ALL	T-E	BS	2010-50	-59%	-40%	31
EU27	Accelerated renovation rates up to 4%; 100 % refurbishment at high standards; in 2010 20 % of the new built buildings are at high EE standard; 100% - by 2025	ALL	T	RS	2004-30	-66%	-71%	32
DK	Energy consumption for H in new RS will be reduced by 30% in 2005, 10, 15, 20; renovated RS are upgraded to the energy requirements applicable for new ones	H	T-E	RS	2005-50		-82%	33
HK	Implementation of performance-based Building Energy Code	ALL	T	CS	1 year	-20.5%		34
CH	Compliance with the standard comparable to the MINERGIE-P5, the Passive House and the standard A of the 2000 Watt society with low-carbon systems for H and W	H/W	T	RS	2000-50	-60%	-68%	35
	Buildings comply with zero energy standard (no heating demand)	H/W	T	RS	2000-50	-65%	-72%	
DE	The proportion of very high-energy performance dwellings increases by up to 30% of the total stock in 2020; the share of nearly zero and ZEBs makes up 6%	H/W	T	BS	2010-20		-25%(pr.e) -50% (CO_2)	36
DEMAND REDUCTION								
FR	EE retrofits, information acceleration, learning-by-doing and the increase in energy price. Some barriers to EE, sufficiency in H consumption are overcome	H	T	BS	2008-50	-58%	-47%	37
US	Influence of five lifestyle factors reflecting consumers' behavioral patterns on residential electricity consumption was analyzed	El.	T	RS	2005	-40%		38
LT	Change in life style towards saving energy and reducing waste	ALL	T	RS	1 year	-44%		39
US	Commissioning as energy saving measure applied in 643 commercial buildings	ALL	T	CS	1 year	-16% (exist.b.) -13% (new b.)		40

Notes: *1) The Table presents the potential of final energy use reduction (if another is not specified) compared to the baseline and/or base year for the end-uses given in the column 3 and for the sectors indicated in the column 5. 2) H – space heating; C – space cooling; W – hot water; L – lighting; APPL – appliances; ALL – all end-uses; BS – the whole building sector; RS – residential sector; CS – commercial sector; T – technical; T-E – techno-economical; EE – energy efficiency; RES – renewable energy sources; HVAC – heating, ventilation and air-conditioning; ZEB – zero-energy building; pr.e. – primary energy; EL. – electricity; red. – reduction; app. – approximately.3) Reg. – region;, WO – world, N.Eu – Northern Europe, Cat – Catalonia.*

******References:*** *1 - (Anisimova, 2011), 2-15 - (IEA, 2002), 16 - (Yue and Huang, 2011), 17 - (Vardimon, 2011), 18 - (Izquierdo et al., 2011), 19 - (GPI, 2010), 20 - (Brown, Borgeson, et al., 2008), 21 - (Sartori et al., 2009), 22 -(Pantong et al., 2011), 23 - (Dubois and Blomsterberg, 2011), 24 - (Garrido-Soriano et al., 2012), 25 -(Radhi, 2009), 26 -(Taylor et al., 2010), 27- (Zhou et al., 2011), 28 - (Ürge-Vorsatz, Petrichenko, Antal, Staniec, et al., 2012), 29 (IEA, 2010b), 30 -(Harvey, 2010), 31 -(Laitner et al., 2012) , 32 -(Eichhammer et al., 2009), 33 -(Tommerup and Svendsen, 2006), 34 -(Chan and Yeung, 2005), 35 - (Siller et al., 2007), 36 -(Schimschar et al., 2011), 37 - (Giraudet et al., 2012), 38 - (Sanquist et al., 2012), 39 -(Streimikiene and Volochovic, 2011), 40 –(Mills, 2009)*

9.6.2 Overview of option-specific costs and potentials

Since the building sector comprises a very large number of end-uses, in each of these many different types of equipment being used, for each of which several mitigation alternatives exist - giving a comprehensive account of costs and potentials of each, or even many, in the limited space of an IPCC report is not possible. Therefore, the next two sections choose to focus on selected key mitigation options and discuss their costs and potentials more in depth. This section focuses on whole-building approaches for new and retrofitted buildings, while the next section analyses a selection of representative technologies sytematically.

9.6.2.1 Costs of very high performance new construction

There is increasing evidence that very high performance new construction can be achieved at little, or occasionally even at negative, additional costs (Harvey and Ürge-Vorsatz, forthcoming; Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012). Figure 9.11 shows the resulting cost-effectiveness from a set of documented best practices from different regions measured in cost of conserved energy. The figure demonstrates well that high-performance new construction can typically be highly cost-effective; several examples attesting that even negative CCEs (Cost of Conserved Energy) can be achieved - i.e. that the project is profitable already at the investment level. The figure also shows that, while the cost range for very high performance buildings that represent a significant change from baseline technologies is increasing, the bottom of the curve does not show increasing trends. very high performance new construction projects have been done at little additional capital cost. This suggests that specific cost (i.e. investment per energy saving) does not depend on the depth of the retrofit or level of performance of newbuild, but that best practices exist to achieve very high energy savings at costs similar to less ambitious performance levels. Although converting energy saving costs to mitigation costs introduces many problems, Figure 9.12 displays the associated mitigation cost estimate of selected points from Figure 9.11. The result is a huge range of costs of conserved carbon: with many examples having triple-digit negative costs, also very high positive costs occur. There are further lines of evidence that can be applied to understand and demonstrate the cost effectiveness of whole building new construction and retrofit, including project-based incremental cost accounting, population studies, and comparative modelling such as (Kats, 2009). For commercial buildings, there are instances where there has been no additional cost in meeting standards as high as the Passive House standard, or where the cost of low-energy buildings has been less than that of buildings meeting local energy codes. Surveys of delivered full building construction costs in the United States and Australia comparing conventional and green buildings in variety of circumstances have been consistently unable to detect a significant difference in delivered price between these two categories. Rather, they find a wide range of variation costs irrespectively of performance features (Langdon, 2007; Urban Green Council and Langdon, 2010). Collectively these studies, along with evidence in 9.3 and the tables in this section indicate significant improvements in design and operational performance can be achieved today under the right circumstances at relatively low or potentially no increases, or even decreases, in total cost.

The cost and feasibility of achieving various ZNEB definitions have shown that such goals are rarely cost-effective by conventional standards; however, specific circumstances, operational goals, and incentives can make them feasible(Boehland, 2008; Meacham, 2009). Table 9.5 highlights selected published estimates of the incremental cost of net zero-energy buildings; even for these buildings, there are cases where there appears to have been little additional cost (e.g., NREL Laboratory).The costs of new ZNE buildings are heavily dependent on supporting policies, such as net metering and feed-in-tariffs, and anticipated holding times, beyond the factors described below for all buildings.Unlike residential buildings, high-performance commercial buildings can cost less to build than standard buildings, even without simplifying the design, because the cost savings from the downsizing in mechanical and electricity equipment that is possible with a high-performance envelope can offset the extra cost of the envelope. In other cases, the net incremental design and

Table 9.5: Summary of estimates for extra investment cost required for selected very low-/zero-energy buildings.

Case	Location	Type	Energy performance	Extra invest.costs	CCE	References
Passive House Projects	Central Europe	New	Passive house standard	5-8% (100-160€/m^2)	-	(Bretzke, 2005; Schnieders and Hermelink, 2006)
5 passive houses	Belgium	New	62 kWh/m^2/yr total	16% (187€/m^2	-	(Audenaert et al., 2008)
Passive House apartment block	Vienna	New	Passive house standard	5% (52€/m^2)	-	(Mahdavi and Doppelbauer, 2010)
12 very low or net zero-energy houses	US	New		7-12 cents/kWh (CCE)	-	(Parker, 2009)
10 buildings in the SolarBau programme	Germany	New	< 100 kWh/m^2/yr primary energy vs. 300-600 - conventional	Comparable to the difference in costs between alternative standards for interior finishes	-	(Wagner et al., 2004)
High performance commercial buildings	Vancouver	New	100 kWh/m^2/yr total vs. 180 - conventional	10% lower cost	-	(McDonell, 2003)
Offices and laboratory, Concordia University	Montreal	New		2.30%	-	(Lemire and Charneux, 2005)
Welsh Information and Technology adult learning centre (CaolfanHyddgen)	Wales	New	Passive House standard	No extra cost compared to BREEAM 'Excellent' standard	-	(Pearson, 2011)
Hypothetical 6,000 m^2 office building	Las Vegas	New	42% of energy savings	$12,700	-	(Vaidya et al., 2009)
10-story, 7,000 m^2 residential building	Denmark	New	14 kWh/m^2/yr (heating) vs. 45	3.4% (86 €/ m^2)	-	(Marszal and Heiselberg, 2009)
Leslie Shao-Ming Sun Field Station, Stanford University	California	New	NZEB	4-10% more based on hard construction costs	-	(NBI, 2011)
Hudson Valley Clean Energy Headquarters	New York	New	NZEB	$ 680/month in mortgage payments but saves $841/month in energy costs	-	(NBI, 2011)
IAMU Office	Ankeny, IA	New	NZEB	None	-	(NBI, 2011)
EcoFlats Building	Portland, OR	New	NZEB	None	-	(NBI, 2011)
10-story, 7,000 m^2 residential building	Denmark	New	NZEB	24% (418€/m^2)	-	(Marszal and Heiselberg, 2009)
Toronto towers	Toronto	Retrofit	194 / 95%	$ 257/m^2	0.052 $/kWh	(Kesik and Saleff, 2009)
Multi-family housing	EU	Retrofit	62-150 / 52-86%	37-87 €/m^2	0.01-0.016 €/kWh	(Petersdorff et al., 2005)
Terrace housing	EU	Retrofit	97-266/ 59-84%	63-145 €/m^2	0.09-0.016 €/kWh	(Petersdorff et al., 2005)
High-rise housing	EU	Retrofit	/ 70-81%	1.8-4.1 €/m^2/yr	0.013-0.020 €/kWh	(Waide et al., 2006)
1950s MFH	Germany	Retrofit	82-247/ 30-90	36-314 €/m^2	0.017-0.049 €/kWh	(Galvin, 2010)
1925 SFH	Denmark	Retrofit	120/	166 €/m^2	0.054 €/kWh	(Kragh and Rose, 2011)
1929 MFH	Germany	Retrofit	140-200/ 58-82%	125-255 €/m^2	0.045-0.066 €/kWh	(Hermelink, 2009)
19th century flat[1]	UK	Retrofit	192-234/ 48-59%	192-480 £/m^2	0.043-0.088 £/kWh	(United House, 2009)

[1] Uses expensive aerogel insulation. There is a big jump in cost when mechanical ventilation with heat recovery is assumed to be installed.

construction cost can be reduced to the point that the time required to payback the initial investment through operating cost savings is quite attractive.

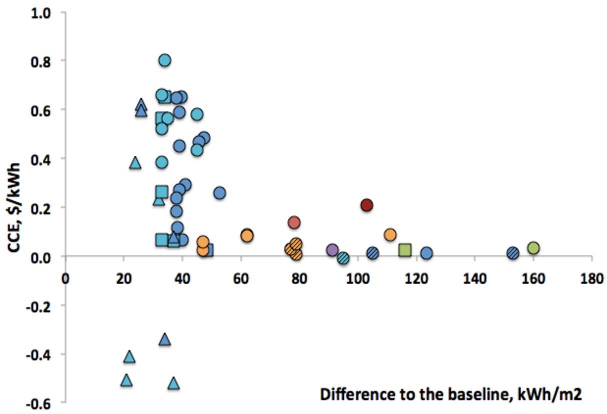


Figure 9.11. Cost of conserved energy as a function of energy performance improvement for new construction by different building types and climate zones in Europe[2]

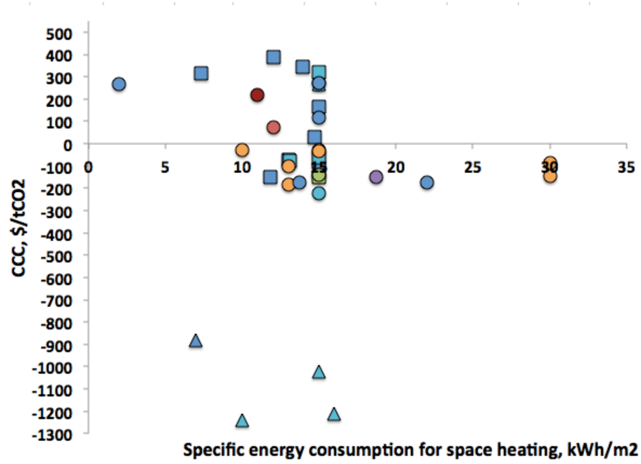
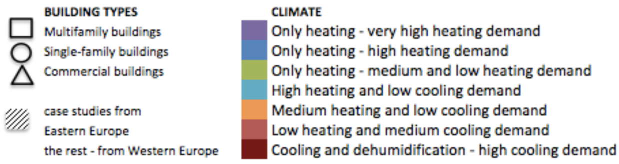


Figure 9.12. Cost of conserved carbon as a function of specific energy consumption for selected best-practices shown in Figure 9.11.



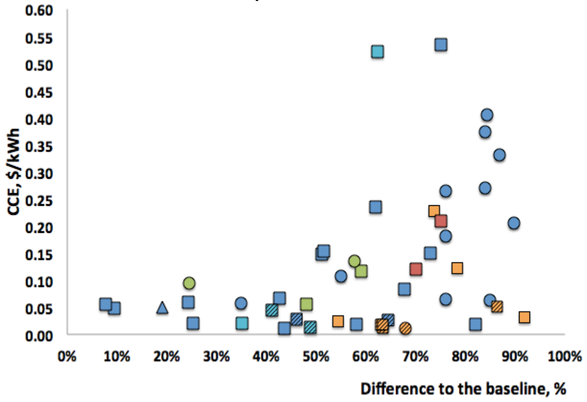


Figure 9.13. Cost of conserved energy as a function of energy saving in % for European retrofitted buildings by building type and climate zones.

9.6.2.2 Costs of deep retrofits

Studies have repeatedly indicated the important distinction between conventional “shallow” retrofits, often reducing energy use by 10-30%, and aggressive “deep” retrofits (i.e., 50% or more relative to baseline conditions. (Korytarova and Ürge-Vorsatz, 2012) evaluated a range of existing building types to characterize different levels of potential energy savings under different circumstances. They describe the potential risk for shallow retrofits to result in lower levels of energy efficiency and higher medium-term mitigation costs when compared to performance-based policies promoting deep retrofits. Figure 9.11 shows the cost-effectiveness of a few selected best practice retrofits, while Figure 9.12 presents the costs of conserved energy related to a selection of

[2] The data for the case studies presented in Figure 9.11 - Figure 9.13 are coming from various sources (e.g. PHI 2013, Lang consulting 2013, Harvey 2013, Galvin 2010, etc.). The data on total project costs or additional costs for energy efficiency measures have been obtained together with the data on building energy performance and/or energy savings. Further calculations of CCE and CCC have been performed assuming discount rate of 1.8% and the lifetime of 40 years for retrofit and 100 years for new buildings.

documented retrofit best practices (esp. at the higher end of the savings axis). The figure shows that saving energy through retrofits is typically more expensive than through new construction, but there is sufficient evidence that deep retrofits can be cost-effective in many climates, building types and cultures. The figure further shows that, while the cost range again expands with very large savings, there are many examples that indicate that deep retrofits do not necessarily need to cost more in specific cost terms than the shallow ones.

9.6.3 Assessment of key factors influencing robustness and sensitivity of costs and potentials

Costs and potentials of the measures described depend heavily on various factors and significantly influence the cost-effectiveness of the investments. While these vary with the types of measures, a few common factors can be identified.

For the cost-effectiveness of energy-saving investments the state of efficiency of the baseline is perhaps the most important determining factor. Figure 9.11, Figure 9.12 and Figure 9.13 all vary the baseline for the respective measure.

CCE figures and thus 'profitability" fundamentally depend, furthermore, on the discount rate, energy price, and CCC (Cost of Conserved Carbon) depends further on the background emission factor. Figure 9.14 illustrates, for instance, the major role discount rate, emission factor and energy price play when determining costs and cost-effectiveness. Beyond the well quantifiable influences, further parameters that contribute to the variability of the cost metrics are climate type, geographic region, building type, etc.

Figure 9.14 depicts selected studies presented in Figure 9.11 and Figure 9.13 for which CCE and CCC were calculated with variation in different parameters, as specified in the legends.

FAQ 9.3. How much could the building sector contribute to ambitious climate change mitigation goals, and what would be the costs of such efforts?

According to the GEA "efficiency" pathway, by 2050 global heating and cooling energy use could decrease by as much as 46% as compared to 2005, if today's best practices in construction and retrofit know-how are broadly deployed (Ürge-Vorsatz, Petrichenko, Antal, Staniec, et al., 2012)). This is despite the over 150% increase in floor area during the same period, as well as significant increase in thermal comfort, as well as the eradication of fuel poverty (Ürge-Vorsatz, Petrichenko, Antal, Staniec, et al., 2012). The costs of such scenarios are also significant, but according to most models, the savings in energy costs typically more than exceed the investment costs. For instance, (Ürge-Vorsatz, Petrichenko, Antal, Staniec, et al., 2012) projects an approximately EUR 18 billion in cumulative additional investment needs for realizing these advanced scenarios, but estimates an over 50 billion cumulative energy cost savings until 2050.

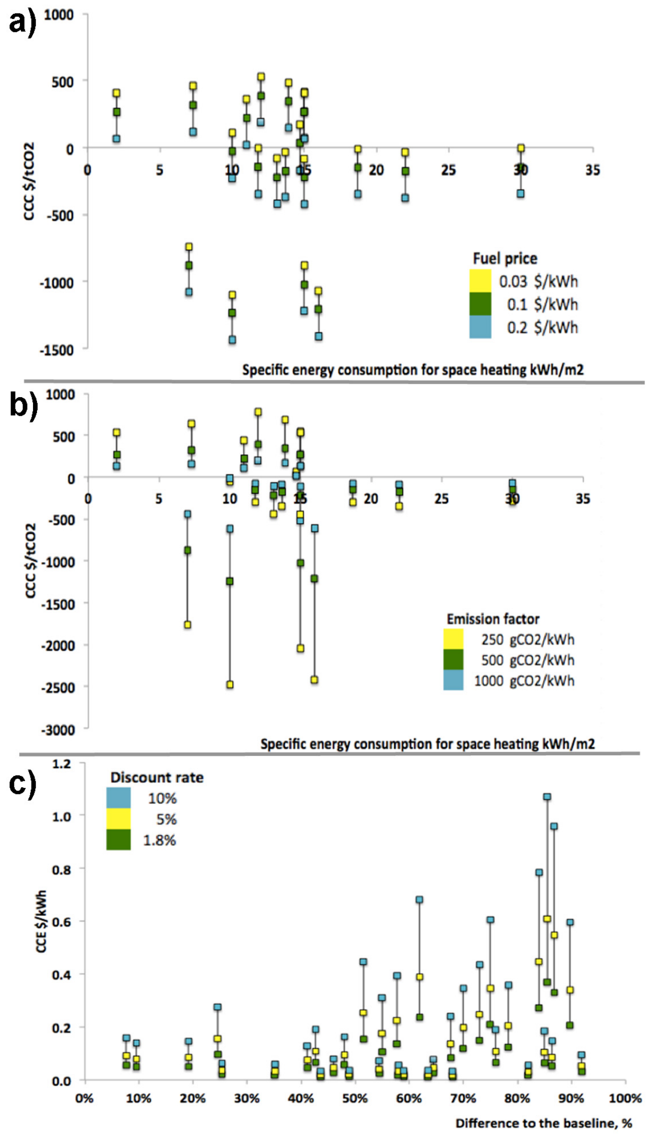


Figure 9.14. Sensitivity analysis of the key parameters: a) CCC for new buildings in response to the variation in fuel price; b) CCC for new buildings in response to the variation in emission factor; c) CCE for retrofit buildings in response to the variation in discount rate

9.7 Co-benefits, risks and spill-overs

9.7.1 Overview

Besides the economic performance of mitigation technologies, several other aspects associated with their implementation, such as co-benefits, adverse side-effects, risks, etc., can affect investment decisions and priority setting. Specifically, it has long been recognised that the implementation of GHG mitigation policies and measures in the buildings sector yields a wide spectrum of benefits beyond energy conservation and the associated reduction of GHG emissions. (Ürge-Vorsatz et al., 2009; GEA, 2012), synthesizing several previous research efforts, recognize the following major categories of co-benefits: (i) health effects (e.g. reduced mortality and morbidity from improved indoor and outdoor air quality), (ii) ecological effects (e.g. reduced impacts on ecosystems due to the improved outdoor environment), (iii) economic effects (e.g. decreased energy bill payments, employment creation, improved energy security, improved productivity), (iv) service provision benefits (e.g. elimination of energy losses during energy transmission and distribution), and (v) social effects (e.g. fuel poverty alleviation, increased comfort due to better control of indoor conditions

Table 9.6: Overview of co-benefits (+) and risks (-) associated with mitigation actions in buildings (based on (UNEP, 2011; GEA, 2012)).

Co-benefits / Risks	Residential buildings	Commercial buildings	Buildings in developed countries	Buildings in developing countries	Retrofits of existing buildings	Exemplary new buildings	Efficient equipment	Fuel switching / RES incorporation / green roofs	Behavioural changes	References
Economic										
⊕ Net employment gains	X	X	X	X	X	X	X	X		(Scott et al., 2008; Pollin et al., 2009; Ürge-Vorsatz et al., 2010; Gold et al., 2011)
⊕ Energy security	X	X	X	X	X	X	X	X	X	(IEA, 2007; Dixon et al., 2010; Borg and Kelly, 2011; Steinfeld et al., 2011)
⊕ Improved productivity		X	X	X	X	X	X			(Fisk, 2002; Kats et al., 2003; Loftness et al., 2003; Singh, Syal, et al., 2010)
⊕ Enhanced asset values of buildings	X	X	X	X	X	X		X		(Miller et al., 2008; Brounen and Kok, 2011a; Deng et al., 2012)
⊕ Lower need for energy subsidies	X	X	X	X	X	X	X	X	X	(Ürge-Vorsatz et al., 2009; GEA, 2012)
⊕ Affordability of energy sources (lower operating costs)	X		X	X	X	X	X	X		(Ürge-Vorsatz et al., 2009; GEA, 2012)
⊖ High upfront investment needed (entailing access issues, capital costs and risks)	X	X	X	X	X	X	X	X		
Social										
⊕ Fuel poverty alleviation	X		X	X	X		X	X		(Healy, 2004; Liddell and Morris, 2010; Ürge-Vorsatz and Tirado Herrero, 2012a; Hills, 2012a; Tirado Herrero and Urge-Vorsatz, 2012)
⊕ Increased comfort	X	X	X	X	X	X				(Jakob, 2006; Stoecklein and Skumatz, 2007)
⊕ Lower exposure to energy price volatility risks	X	X	X	X	X	X	X	X	X	(Ürge-Vorsatz et al., 2009; GEA, 2012)
⊕ Increased productive time for women and children (for replaced traditional cookstoves)	X			X			X	X		(Hutton et al., 2007)
Health/Environmental										
⊕ Health benefits due to:										
reduced outdoor pollution	X	X	X	X	X	X	X	X	X	(Levy et al., 2003; Aunan et al., 2004; Mirasgedis et al., 2004; Chen et al., 2007; Crawford-Brown et al., 2012)
reduced indoor pollution	X			X			X	X		(Bruce et al., 2006; Zhang and Smith, 2007; Duflo et al., 2008; Wilkinson et al., 2009; World Health Organization, 2009)
improved indoor environmental conditions	X	X	X	X	X	X			X	(Fisk, 2002; Singh, Syal, et al., 2010)
fuel poverty alleviation	X		X	X	X		X	X		(Healy, 2004; Liddell and Morris, 2010; Ürge-Vorsatz and Tirado Herrero, 2012a; Hills, 2012a; Tirado Herrero and Urge-Vorsatz, 2012)
⊕ Reduced impacts on ecosystems, cultivations, materials, etc.	X	X	X	X	X	X	X	X	X	(Aunan et al., 2004; Mirasgedis et al., 2004; Ürge-Vorsatz et al., 2009)
⊕ Reduced water consumption and sewage production	X	X	X	X	X	X	X			(Kats et al., 2005; Bansal et al., 2011a)
⊕ Reduction of heat island effect	X		X	X	X	X		X		(Cam, 2012)

and the reduction of outdoor noise, increased safety). On the other hand, the risks associated with the implementation of mitigation actions in buildings are limited.

Table **9.6** provides an overview of the co-benefits and risks associated with broad categories of mitigation actions in buildings. The IPCC AR4 (Levine et al., 2007), as well as other major studies completed recently (UNEP, 2011; GEA, 2012), provides a detailed and comprehensive presentation and analysis of these effects, highlighting the further need for their quantification and incorporation as positive welfare effects in decision analysis. Therefore, the following paragraphs review recent advances reported in the literature focusing on selected co-benefits/risks, with a view to providing methods, quantitative information and examples that can be exploited in the decision-making process.

FAQ 9.4. How significant are co-benefits associated with energy-efficiency and building-integrated renewable energy policies that provide attractive opportunities for policy integration?

Since the AR4, there have been significant advances in quantifying the co-benefits related to GHG mitigation through energy efficiency in buildings. Some examples include between 0.7 and 35.5 job-years created per $2010 1 million spent in different countries (see Figure 9.14, Section 9.8.3.1); increases in productivity by 1-9%, which are mainly attributed to reduced lost work and less work hours affected by asthma, respiratory allergies, depression and stress as well as to improved worker performance from changes in thermal comfort and lighting; cost premiums associated with higher levels of green building certification ranging from 3% to over 8% (Kats, 2009); significant health benefits, particularly in developing countries, due to reduced indoor pollution, amounting for example in India to 12,500 fewer DALYs per million population in one year as a result of the implementation of a national program promoting modern low-emission stove technologies (Wilkinson et al., 2009); welfare gains associated with fuel poverty alleviation, amounting to 30% of the total benefits of energy efficiency investments.

9.7.2 Socio-economic effects

9.7.2.1 Impacts on employment

An opportunity lies in the pursuit of so-called "green jobs" - employment that contributes to protecting the environment and reducing humanity's carbon foot-print. Specifically, an increasing number of studies find that greater use of renewables and energy efficiency in the building sector results in positive economic effects through job creation, economic growth, increase of income and reduced needs for capital stock in the energy sector (see for example (Scott et al., 2008; Pollin et al., 2009; Kuckshinrichs et al., 2010); these conclusions, however, have been criticized on grounds that include, among others, the accounting methods used, the efficacy of using public funds for energy projects instead of for other investments and the possible inefficiencies of investing in labour-intensive activities (Alvarez et al., 2009; Carley et al., 2011; Gülen, 2011). These effects can be classified as: (i) direct (i.e. the jobs created, particularly in the construction industry, for retrofitting homes etc.); (ii) indirect, in the sectors of the economy that supply materials and services for the implementation of the mitigation measures; and (iii) induced, as a result of the additional income that will be available to workers and/or households, which will be spent to other activities (Jeeninga et al., 1999; Scott et al., 2008). Focusing on the labour market, several approaches (Scott et al., 2008; Ürge-Vorsatz et al., 2010) can be implemented for quantifying the impact of interventions to address climate change: (i) indices and multipliers from specific case studies; (ii) input-output analysis; (iii) computable general equilibrium analysis; and (iv) transfer of results from previous studies. In the context of this assessment, a review of the literature on quantification of the employment effects of energy efficiency and GHG mitigation measures in the building sector was conducted and the main results are presented in Figure 9.15. The bulk of the studies reviewed, which concern mainly developed economies, point out that the implementation of GHG mitigation interventions in buildings generates between 0.7 and 35.5 job-years per $2010 million spent. This range does not change if only studies from our sample estimating net employment effects are considered. Two studies (Scott et al., 2008; Gold et al., 2011) focus on cost savings from unspent energy budgets that can be redirected in the economy, estimating that the resulting employment effects range between 6.0 and 10.2 job-years per $2010 million spent. Several studies (Pollin et al., 2009; Ürge-Vorsatz et al., 2010; Wei et al., 2010; Carley et al., 2011) agree that building retrofits and investments in clean energy technologies are more labour-intensive than conventional approaches (i.e. energy production from fossil fuels, other construction activities etc.). However, to what extent spending a given amount of money on clean energy investments creates more employment compared to conventional activities depends also on the structure of the economy in question, the level of the wages and to what extent the production of the necessary equipment and services for developing these investments occurs inside the economy under consideration or elsewhere. To this end, the estimation of net employment benefits instead of gross effects is of particular importance for an integrated analysis of energy efficiency implications on the economy. It is also worth mentioning that investing in clean technologies would create new job activities (e.g. in solar industry, in the sector of new building materials etc.), but the vast majority of jobs will be in the same areas of employment that people already work today (Pollin et al., 2009). Monetization of employment effects through techniques based on the total fiscal cost per unemployed worker, the public expenditures for creating one extra year of employment, the opportunity cost of labour etc. (Markandya, 2000; Tourkolias et al., 2009; Kuckshinrichs et al., 2010), can accelerate their incorporation in decision-making process.

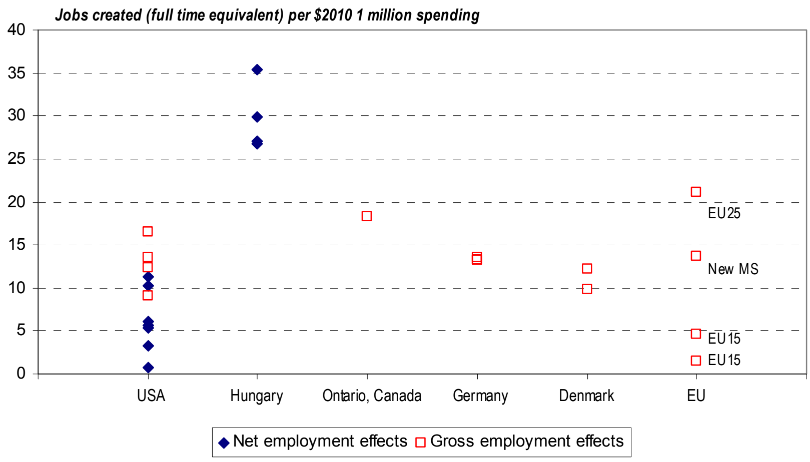


Figure 9.15. Employment effects attributed to GHG mitigation initiatives in the building sector.[3]

9.7.2.2 Energy security

Implementation of GHG mitigation measures in the buildings sector can play an important role in increasing the energy security by: (i) strengthening power grid reliability, through the enhancement of properly managed on-site generation and the reduction of the overall demand, which result in

[3] Notes: For developing this Figure the following sources have been used: USA: (Scott et al., 2008; Bezdek, 2009; Hendricks et al., 2009; Pollin et al., 2009; Garrett-Peltier, 2011; Gold et al., 2011). All the studies for the USA include the direct, indirect and induced effects of energy conservation initiatives considered. In (Gold et al., 2011) and (Scott et al., 2008) the induced effects from energy savings are also taken into account. Hungary: (Ürge-Vorsatz et al., 2010). The direct, indirect and induced effects including those associated with energy savings are taken into account. Ontario, Canada: (Pollin and Garrett-Peltier, 2009). The direct, indirect and induced effects are taken into account. Germany: (Kuckshinrichs et al., 2010). It is not specified what type of employment effects are included in the analysis. Denmark: (Ege et al., 2009). The direct and indirect effects are taken into account. EU: (ETUC, 2008). Only the direct effects are taken into account.

reduced power transmission and distribution losses and constraints (Kahn, 2008; Passey et al., 2011); (ii) reducing cooling-related peak power demand and shifting demand to off-peak periods; however, this reduction in peak demand may be significantly lower compared to electricity savings (Borg and Kelly, 2011; Steinfeld et al., 2011); and (iii) increasing the diversification of energy sources as well as the share of domestic energy sources used in a specific energy system (see for example (Dixon et al., 2010). There is a relative dearth of studies and tools aiming at quantifying these benefits. An International Energy Agency study (IEA, 2007) explored the interactions between climate policies and energy security through two quantitative energy security indices, addressing: (i) to what extent energy prices are allowed to adjust in response to changes in demand and supply; and (ii) the physical unavailability of energy. This approach was implemented in 5 European OECD countries and demonstrated that promotion of energy efficiency in electricity uses has positive impacts of similar magnitude on energy security. Specifically a 5% reduction in countries' emissions from baseline by 2030 through improved end-use efficiency was shown to result in commensurate improvements of both energy security indices (by 2.5% to 4.3% of the price indicator and by 2.3% to 37% of the index addressing the physical unavailability of energy). Monetization of the welfare impacts of energy insecurity (usually expressed with the index Value of Lost Load – VOLL) or alternatively the assessment of willingness to pay (WTP) to improve security of supply are also powerful tools for incorporating energy security issues in decision making process. To this end, the methodologies used worldwide can be grouped into three main categories (Leahy and Tol, 2011): (i) stated preferences, based on customer surveys (see for example (Damigos et al., 2009; Chou et al., 2010); (ii) proxy methods, such as the production function approach (see for example (De Nooij et al., 2007; Leahy and Tol, 2011); and (iii) case studies, based on collection of data immediately after the occurrence of large-scale power supply interruptions.

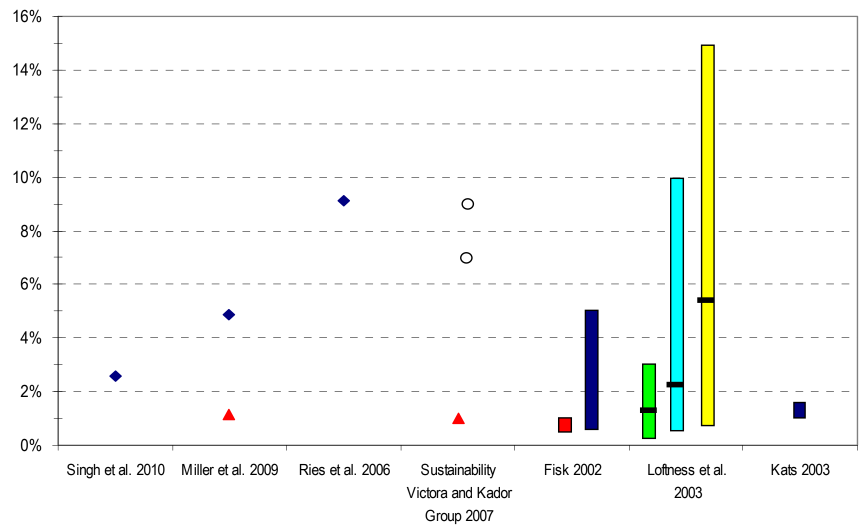


Figure 9.16. Potential productivity gains (%) associated with better indoor environmental conditions in buildings.[4]

[4] Notes: (Fisk, 2002), (Loftness et al., 2003) and (Kats et al., 2003) are review studies showing the range of productivity gains associated with energy efficient buildings after a meta-analysis of the results presented in several original studies. (Loftness et al., 2003) also give an average estimate of these productivity gains.(Ries et al., 2006; Sustainability Victoria and Kador Group, 2007; Miller et al., 2009; Singh, Syal, et al., 2010) have examined specific case studies. The productivity increase derived by (Ries et al., 2006) concern the most conservative scenario, while other scenarios in this study show productivity gains up to 25%; however these gains cannot be fully attributed to green building features. The dark blue bars and points in the diagram concern productivity gains attributed to improved worker performance from changes in thermal comfort and/or lighting. The red bars and points concern productivity gains attributed to health benefits. The blank bullets concern productivity gains for specific activities in a company. In (Loftness et al., 2003) productivity

9.7.2.3 Benefits related to workplace productivity

Energy conservation and management, which relies solely on the patience of office users significantly lowers productivity in the workplace (Wargocki et al., 2006; Tawada et al., 2010). Investment in low-carbon technologies related to air conditioning and wall thermal properties during construction or renovation can be effectively recouped from improved workplace productivity as evidenced by a meta-analysis of several studies (Fisk, 2002; Kats et al., 2003; Loftness et al., 2003; Ries et al., 2006; Sustainability Victoria and Kador Group, 2007; Miller et al., 2009; Singh, Syal, et al., 2010). On average, energy efficient buildings may result in increased productivity by 1-9% or even higher for specific activities or case studies (Figure 9.16). The productivity gains are attributed to: (i) reduced working days lost to asthma and respiratory allergies; (ii) fewer work hours affected by asthma, respiratory allergies, depression and stress; and (iii) improved worker performance from changes in thermal comfort and lighting.

9.7.2.4 Rebound effects

Improvements in energy efficiency in buildings, as in other economic activities, can be offset by increases in demand for energy services due to the "rebound effect" (sometimes known as "takeback"). This has been extensively studied, including two major reviews (Greening et al., 2000; Sorrell, 2007). The effect has two components: direct rebound effects caused by the reduced cost of the energy service for which the energy efficiency has been improved, and indirect rebound effects caused by the re-spending of savings in the wider economy. Direct rebound effects have been studied empirically and tend to be in the range 0-30% for major energy services in buildings such as heating and cooling (Sorrell et al., 2009; Ürge-Vorsatz, Eyre, Graham, Kornevall, et al., 2012). For energy services where energy is a smaller fraction of total costs, e.g. from electrical appliances, there is less evidence, but lower values are expected. The rebound effect declines with saturation of demand for a particular energy service. It is therefore dependent on income, with somewhat higher rebound levels found for lower income groups (Roy, 2000; Hens et al., 2009), implying that rebound contributes positively to energy affordability and development. However there is limited evidence about rebound effects outside OECD countries (Roy, 2000; Ouyang et al., 2010) and further research is required here. *Indirect effects* are more controversial. Empirical studies for household energy savings tend to show low values, e.g. 7% for thermostat changes (Druckman et al., 2011). Rebound effects specified in terms of GHG emissions are broadly similar in size, e.g. the sum of direct and indirect effects for UK household efficiency measures is 5-15% (Chitnis et al., 2013). Analyses based on economic modelling, e.g.(Barker et al., 2007; Turner and Hanley, 2011), have diverging and uncertain predictions, depending critically on assumptions about the role of energy efficiency in total factor productivity, and therefore in economic growth. Some claims have been made that indirect rebound effects may be very large (Brookes, 2000; Saunders, 2000), even exceeding 100% so that energy efficiency improvement would increase energy use. These claims may have had some validity for critical 'general purpose technologies' such as steam engines during intensive periods of industrialisation (Sorrell, 2007). With some macroeconomic assumptions, negative rebound effects are conceptually possible (Turner, 2009). However, there is no empirical evidence to support large or negative rebound effects for energy efficiency in buildings. Modestly declining energy intensities in developed countries with strong policies for energy efficiency in buildings are indicative of the opposite conclusion. Many analyses of rebound effect assume energy prices are set in markets with no effective public policy for climate mitigation. Further research on rebound in different policy environments is required. However, effective energy efficiency policies can reduce rebound (Binswanger, 2001), and therefore some existing analysis may be invalid in real policy environments. Rebound effects should be taken into account in energy efficiency policies and programmes, but are

gains are attributed to improved thermal comfort (green bar), improved ventilation and indoor environmental quality (light blue bar) and efficient lighting (yellow bar).

unlikely to alter conclusions about their importance and cost effectiveness in climate mitigation (Sorrell, 2007).

9.7.2.5 Fuel poverty alleviation

Fuel (or energy) poverty is a condition in which a household is unable to guarantee a certain level of consumption of domestic energy services (especially heating) or suffers disproportionate expenditure burdens to meet these needs (Boardman, 1991; BERR, 2001; Healy and Clinch, 2002; Buzar, 2007; Ürge-Vorsatz and Tirado Herrero, 2012b). As such it has a range of negative effects on the health and welfare of fuel poor households. For instance, indoor temperatures that are too low affect vulnerable population groups like children, adolescent or elders (Liddell and Morris, 2010; Marmot Review Team, 2011) and increase excess winter mortality rates (The Eurowinter Group, 1997; Wilkinson et al., 2001; Healy, 2004). A more analytical discussion on the potential health impacts associated with fuel poverty is presented in Section 9.7.3.1. Improving the thermal performance of buildings to very high (such as Passive house) levels can largely alleviate fuel poverty. However, this, along with most social benefits are non-market ones and therefore are rarely taken into consideration in financial assessments of mitigation or energy efficiency programmes. Several studies have shown that fuel poverty-related welfare gains make up over 30% of the total benefits of energy efficiency investments and are more important than those arising from avoided emissions of greenhouses gases and other harmful pollutants like SO_2, NO_x and PM_{10} (Clinch and Healy, 2001; Tirado Herrero and Ürge-Vorsatz, 2012).

9.7.3 Environmental and health effects

9.7.3.1 Health co-benefits due to improved indoor conditions

The implementation of energy efficiency interventions in buildings improves indoor conditions (e.g. air quality, control of indoor temperature, thermal comfort, etc.), resulting in significant co-benefits for public health, through: (i) reduction of indoor air pollution, (ii) improvement of indoor environmental conditions and (iii) reduced cost of the required energy and particularly for heating in cold regions. In developing countries inefficient combustion of traditional solid fuels in households produces significant gaseous emissions, known as products of incomplete combustion (PICs), and results in significant health impacts, particularly for women and children who spend longer periods at home (Zhang and Smith, 2007; Duflo et al., 2008; Wilkinson et al., 2009). According to (World Health Organization, 2009), indoor air pollution from the use of biomass and coal was responsible for 2 million premature deaths and 41 million disability-adjusted life-years (DALYs) worldwide in 2004. Several climate mitigation options such as improved cookstoves, switching to cleaner fuels, behavioural changes, etc. would address not only climate change but also public health issues. (Wilkinson et al., 2009) showed that the implementation of a national program promoting modern low-emissions stove technologies in India could result in significant health benefits amounting to 12,500 fewer DALYs per million population in one year. (Bruce et al., 2006) investigated the health benefits (basically acute lower respiratory infections and chronic obstructive pulmonary diseases) and the costs associated with the implementation of selected interventions aiming at reducing indoor air pollution in various world regions. The results are summarized inTable 9.7.

Table 9.7: Healthy years gained per US$2010 million spent in implementing interventions aiming at reducing indoor air pollution. (Source: (Bruce et al., 2006))

Intervention	Sub-Saharan Africa	Latin America and Caribbean	Middle East and North Africa	Europe and Central Asia	South Asia	East Asia and the Pacific
Access to cleaner fuels: LPG	1297-1788	658-1186	~1213	704-759	1704-2973	546-9299
Access to cleaner fuels: Kerozene	11087-15393	1463-8771	~9725	5066-5557	14819-25794	4112-79504
Improved stoves	36714-45856	843-982	2028-2519	n.a.	62361-70669	1575-3112

In both developed and developing countries, better insulation, ventilation and heating systems in buildings improve the indoor conditions and result in fewer respiratory diseases, allergies and asthma as well as reduced Sick Building Syndrome symptoms (Fisk, 2002; Singh, Syal, et al., 2010). Of particular importance is the alleviation of fuel poverty in buildings, which, as already mentioned in Section 9.7.2.5, is associated with excess mortality and morbidity effects. It is estimated that over 10% to as much as 40% of excess winter deaths in temperate countries is related to inadequate indoor temperatures (Clinch and Healy, 2001; Marmot Review Team, 2011; Hills, 2012b). This in countries such as Poland, Germany or Spain amounts to several thousand – up to 10,000 – excess annual winter deaths. These figures suggest that, in developed countries fuel poverty may be causing premature deaths per year similar to or higher than that of road traffic accidents (Bonnefoy and Sadeckas, 2006; Ürge-Vorsatz, Wójcik-Gront, Herrero, Labzina, et al., 2012; Tirado Herrero et al., 2012). Improved residential insulation is expected to reduce illnesses associated with room temperature thus providing non-energy benefits, such as reduced medical expenses and reduced loss of income due to unpaid sick leave from work. (Ikaga et al., 2011) conducted a health survey of 10,000 residents who lived in poorly insulated houses and then moved into houses with better insulation. The results demonstrate that for a new- construction investment of 1 million yen (i.e. $2010 11,390) for a house with advanced thermal-insulation, the investment return period is estimated at 29 years assuming only the reduced air-conditioning costs ($2010 399 per annum), but declines to 16 years when related health benefits ($2010 308 per annum) are included and to 11 years if health insurance payment reductions are also taken into account. Such findings make addressing fuel poverty issues and the resulting health impacts in developing nations even more important, as a greater share of the population is affected (World Health Organization, 2011).

9.7.3.2 Health and environmental co-benefits due to the reduced outdoor air pollution

The implementation of GHG mitigation measures in the building sector reduces the consumption of fossil fuels and electricity, thus improving the outdoor air quality and resulting in: (i) reduced mortality and morbidity, particularly in developing countries and big cities (Harlan and Ruddell, 2011); and (ii) less stresses on natural and anthropogenic ecosystems. Quantification and valuation of these benefits is possible allowing them to be integrated into cost-benefit analysis. Particularly for health impacts, a great number of studies, primarily in North America and Europe and more recently in some developing countries, provide quantitative concentration-response functions that link changes in outdoor PM, ozone and other pollutant concentrations to changes in rates of mortality and various morbidity effects, often for different age groups, allowing for a quantification of the relative co-benefits associated with energy efficiency measures (Jack and Kinney, 2010). Based on concentration-response functions from these and similar works, many studies (see for example (Levy et al., 2003; Aunan et al., 2004; Mirasgedis et al., 2004; Chen et al., 2007; Crawford-Brown et al., 2012) have monetised the health and environmental benefits attributed to reduced outdoor air pollution due to the implementation of energy efficiency measures in buildings. The magnitude of these benefits is in the order of 8-22% of the value of energy savings in developed countries (Levy et al., 2003; Næss-Schmidt et al., 2012), and even more important in developing nations. (Markandya et al., 2009), assuming only the mortality impacts associated with $PM_{2.5}$ emissions, estimated that the health benefits per ton of CO_2 not emitted from power plants, through for example the implementation of electricity conservation interventions, are in the range of $2010 2 in EU, $2010 7 in China and $2010 46 in India.

9.7.3.3 Other environmental benefits

The implementation of energy efficiency measures in buildings results in several other environmental benefits. Specifically, using energy efficient appliances such as washing machines and dishwashers in homes, results in considerable water savings (Bansal et al., 2011b). More generally, a number of studies show that green design in buildings is associated with lower demand for water. For example, (Kats et al., 2005) evaluated 30 green schools in Massachusetts and found an average water use reduction of 32% compared to conventional schools, achieved through the reuse of the rain water and other non-potable water as well as the installation of water efficient appliances (e.g. in toilets) and advanced controls. Also, the implementation of green roofs, roof gardens, balcony gardens and sky terraces as well as green facades/walls in buildings, results in: (i) reducing heat gains for buildings in hot climates; (ii) reducing the heat island effect; (iii) improving air quality; (iv) enhancing urban biodiversity, especially with the selection of indigenous vegetation species; (v) absorbing CO2 emissions, etc. (Cam, 2012).

9.7.4 Public perception: integrating co-benefits into decision-making frameworks

Co-benefits included in analyses of energy efficiency and fuel switching policies and in particular mature methodologies from the efforts of early moving states such as the European Union, the United States, and Japan have gained interest from policy makers. Faster policy uptake is especially important in developing countries because ongoing development efforts that do not consider co-benefits may lock in suboptimal technologies and infrastructure and result in high costs in future years. According to (Williams et al., 2012), over the past two decades, studies have repeatedly documented that non-climate change related benefits of energy efficiency and fuel conversion efforts, as a part of GHG mitigation strategies, can be from between 30% to over 100% of the costs of such policies and programs. However, policies and programs face resistance in part because of the difficulty of quantifying their benefits and dealing with different perceptions caused by uncertainties. Co-benefits (e.g. improved health, agricultural productivity, reduced damage to infrastructure, and local ecosystem improvements) are generally near term and local. Avoided health risks may differ by type of health event and age, which is attributable more so to the public perception of harm rather than actual harm posed.

9.8 Barriers and opportunities

Barriers and opportunities are conditions that hinder or facilitate the implementation of mitigation measures. Technology available today can achieve dramatic improvements in building energy efficiency, but strong barriers hinder the market uptake of these cost-effective opportunities, and large potentials will remain untapped without adequate policies and challenging professionals. Barriers and related opportunities vary considerably by location, building type, culture and stakeholder groups, as vary options to overcome these, such as policies, measures and innovative financing schemes. A vast literature on barriers and opportunities in buildings, (Brown, Chandler, et al., 2008) and (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012) enumerates and describes these factors. Barriers include imperfect information, transaction costs, limited capital, externalities, subsidies, risk aversion, principal agent problems, fragmented market and institutional structures, poor feedback, poor enforcement of regulations, cognitive and behavioural patterns, weak patent protection and inadequate technology transfer. In developing countries, lack of awareness, of financing, of qualified personnel, economic informality and insufficient service levels lead to suboptimal policies and measures causing perverse lock-in effects in terms of greenhouse gas emissions. For corporate behaviour, see also Chapters 10 and 12. Opportunities beyond contributing to climate change mitigation include reduced local environmental impacts, improvements in energy security and sovereignty, net job creation, improved health and better comfort, social welfare, better productivity, new business opportunities, stimulation of higher skill levels in building profession and trades, rate subsidies avoided, and improved values for real estate. Examples of barriers can be divided into three main groups. Firstly technological barriers were reported in the EU (Power, 2008), UK (Lomas, 2009), Belgium (Mlecnik, 2010), US (Short, 2007), India (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012); while technological opportunities described in the US (Greden, 2006), (Short, 2007), UK (Lomas, 2009), Germany (Hegner, 2010). Secondly, financial barriers were found in several developing countries (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012), UK (Stevenson, 2009), (Pellegrini-Masini and Leishman, 2011), EU (Power, 2008), US (Greden, 2006); financial opportunities in the EU (Power, 2008) and US (Greden, 2006), US (Collins, 2007). Finally, institutional, cultural and legal cases for barriers were identified in the US (Short, 2009), (Collins, 2007), (Lomas, 2007), (Houghton, 2011), EU (Kwok, 2010), (Power, 2008), UK (Stevenson, 2009), Belgium (Mlecnik, 2010), Brazil and India (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012); as were related opportunities in the UK (Stevenson, 2009; Pellegrini-Masini and Leishman, 2011), US (Short, 2007), Norway (Amundsen, 2010) and Finland (Monni, 2008).

9.9 Sectoral implication of transformation pathways and sustainable development

9.9.1 Introduction

The purpose of this section is to review both the integrated assessment as well as sectoral bottom-up literature from the perspective of what main trends can be observed in the future building emissions and energy use developments, and which major mitigation strategies can be pinpointed. The section complements the analysis in Chapter 6 with more details on findings from the building sector. The two key pillars of the section are (a) a statistical analysis of a large population of IAM scenarios (665 scenarios in total) grouped by climate category, complemented by the analysis of sectoral models (grouped by baseline and advanced scenario, since often these do not relate to climate goals); and a more detailed analysis of a small selection of IAMs and end-use models. The source of the IAMs is the AR5 Scenario Database (see section 6.3.3 for details), and those of the sectoral models are (WBCSD, 2009; GPI, 2010; Harvey, 2010; WEO, 2011; Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012; ETP, 2012; Laustsen, 2012).

9.9.2 Overview of building sector energy projections

The projected development in building final energy use is markedly different in the sectoral (bottom-up) and integrated assessment modelling literature, as illustrated in Figure 9.17. The IAM literature foresees an increase in building energy consumption in most scenarios; whereas the vast majority of ambitious scenarios from the bottom-up/sectoral literature see opportunities for the reduction of, or, in the worst case, a stagnation in, total global building energy use until the middle of the century, despite the increases in wealth, floorspace, service levels and increasing amenities (see section 9.2). Scenarios without action, in contrast, project slightly higher levels of building energy use than the most relaxed IAM scenarios examined. Therefore we can state that, in general, the sectoral literature is more optimistic about the opportunities in the building sector than IAM models.

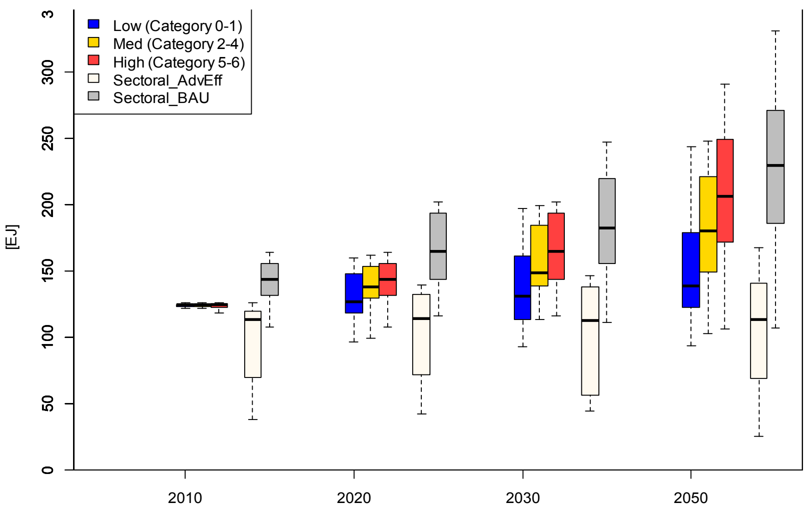


Figure 9.17. The development of global building final energy demand until 2050 in the integrated assessment modeling literature (grouped by the level of climate ambition: 277 Low, 230 Med, 158 High—for category descriptions see Chapter 6.3.3) and sectoral/bottom-up literature (13 BAU scenarios and 13 advanced scenarios). Sources as indicated in Section 9.9.1.

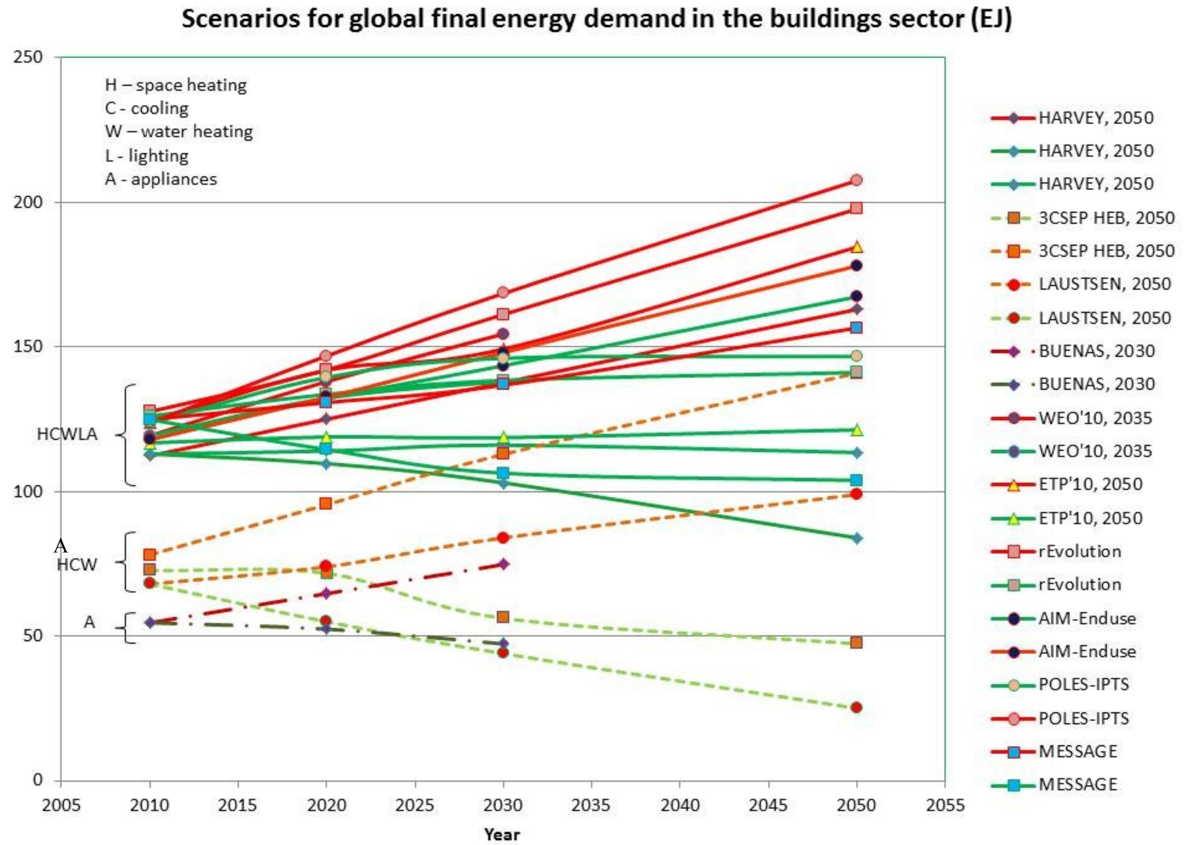


Figure 9.18. Global final energy demand development in the building sector by 2050 in selected sectoral models, baseline and advanced scenarios,for total energy (HCWLA, top solid lines),thermal energy (HCW, dashed lines, incl. heating/cooling/hot water), and appliances (A); compared to selected IAMs. Red shades are reference scenarios, green shades are advanced ones. Sources as indicated in Section 9.9.1.

The demand for energy services related to buildings tends to increase even stronger than suggested by the final energy use suggests, because the increasing service demand is typically accompanied by a transition from traditional fuel use (mostly biomass, but also coal) to modern energy carriers (oil products, electricity) with substantially higher conversion efficiencies that partly compensated the service demand increase (Krey et al., 2012). The picture is substantially different in industrialized countries where the analysis even under baseline assumptions shows stagnating or decreasing final energy use in the buildings sector while the increase in emerging economies and developing countries is significantly stronger (see section 9.2 too). As the focus on selected scenarios in Figure 9.18 suggests, thermal energy use can be reduced more strongly than energy in other building end-uses: reductions in the total are typically as much as, or less than, decreases in heating and cooling (sometimes with hot water) energy use scenarios. This indicates that non-thermal end-uses become an increasingly important target of mitigation policies with the advance of time, especially in advanced heating and cooling scenarios where this energy use can be successfully pushed down to a fraction of its 2005 levels.These findings confirm the more theoretical discussions in this chapter, i.e. that in thermal end-uses deeper reductions can be expected while appliance energy use will be more difficult to reduce or even limit its growth. For instance (Ürge-Vorsatz, Wójcik-Gront, Herrero, Labzina, et al., 2012) show a 46% reduction in heating and cooling energy demand as compared to 2005 despite the business-as-usual increase in wealth and amenities assumed. Another general finding is that studies show larger reduction potentials by 2050 than by 2030, pointing to the fact that this sector needs a medium-term, strategic policy planning, since it takes a long time while the building infrastructure can be fully modernized from a climate change mitigation perspective. In fact, 2020 figures in most of these studies and scenarios show energy growth, with the decline starting later, suggesting that “patience” and thus policy permanence is vital for this sector in order to be able to exploit its large mitigation potentials.

Figure 9.19 confirms the earlier finding that sectoral models are typically more optimistic about the energy use reduction opportunities in the sectors than IAMs. Several ambitious sectoral scenarios achieve energy demand reductions as high as 75% of their respective baselines.

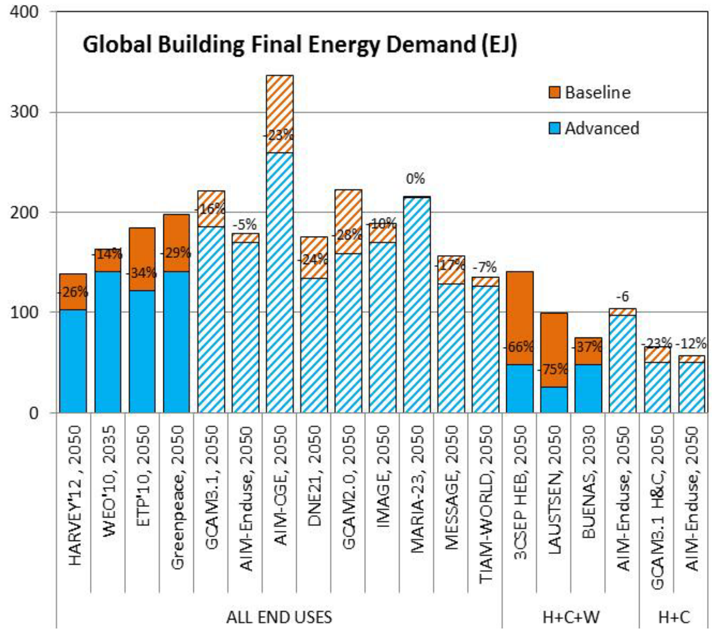


Figure 9.19. Building final energy use (total or heating/cooling, as indicated) in 2050 (2030 for the Buenas model) in advanced scenarios as compared to reference ones. Solid bars are IAMs, striped ones are bottom-up models. Sources as indicated in Section 9.9.1.

9.9.3 Key mitigation strategies as highlighted by the pathway analysis

The diversity of the development in final energy demand even among the most ambitious climate scenarios suggest that different models take different foci for their building mitigation strategies. While most stabilisation and advanced bottom-up scenarios approximately stagnate or reduce global final building energy use, a few transformation pathways achieve stabilization from rather high final energy demand levels., thereby focusing on energy supply side measures for reducing emissions. These scenarios have about twice as high per capita final energy demand levels in 2050 as the lowest stabilization scenarios. This suggests a focus on energy supply side measures for decarbonisation.

Fuel switch to electricity that is increasingly being decarbonised is a dominating mitigation strategy as shown in Chapter 6. However, as Figure 9.20 indicates, this is not true in the buildings sector. The total share of electricity in this sector depends little on climate policy except for the least ambitious scenarios: it increases from an app. 28% of final energy to app. 50% of it in almost all scenarios. Figure 9.20b suggests the higher electricity growth rates in the models is associated with the generally higher rates of energy growth, whose proportional share takes place in power consumption. Figure 9.21 confirms that climate policy does not force electrification in the building sector: there is little influence of scenario choice on the share of electricity within the same model. Figure 9.22 shows the evolution of fuel shares in the different models and scenarios.

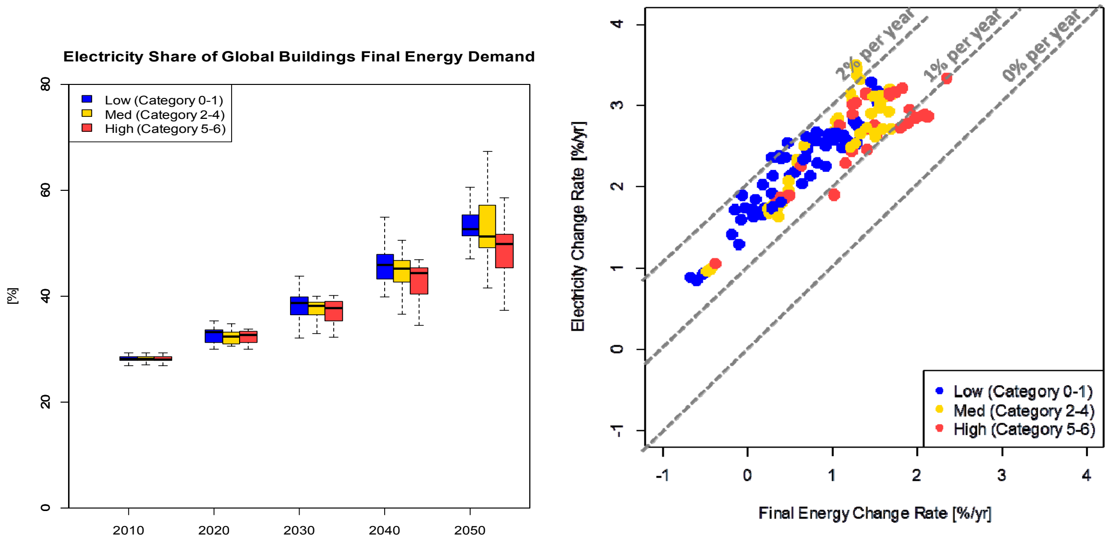


Figure 9.20. (a) The development in the share of electricity in global final energy demand until 2050, and **(b)** decomposition of the annual change into electricity demand share in final energy demand change rate and electricity demand change rate (each gray line indicates a set of points with the same annual change in electricity demand share). Sources as indicated in Section 9.9.1.

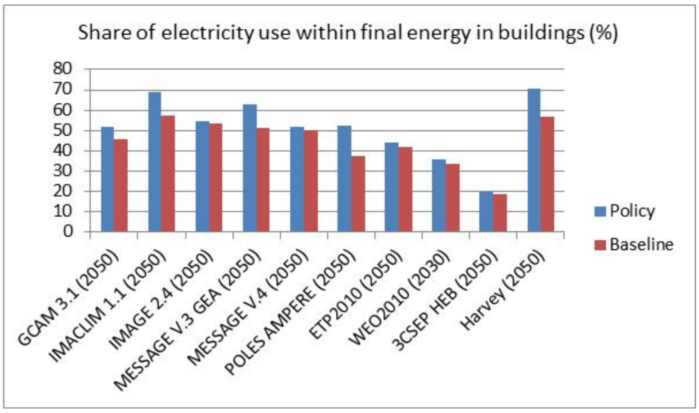


Figure 9.21. Share of electricity in final energy mix in the reference and ambitious scenarios. Sources: indicated in Section 9.9.2.

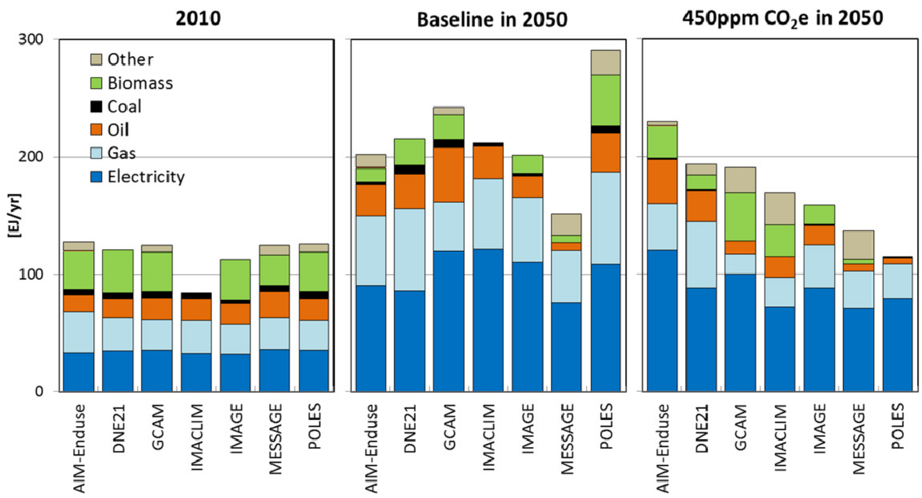


Figure 9.22. Global buildings final energy demand by fuel in baseline and 450ppm scenarios (all from AMPERE model comparison project conducted with harmonized assumptions, for details see (Riahi et al., 2013)).

Nevertheless, Figure 9.23 demonstrates clearly that most IAM models attribute the largest share of emission reduction in the building sector to electricity decarbonisation, and typically bottom-up models place a significantly more important role on reductions in energy use.

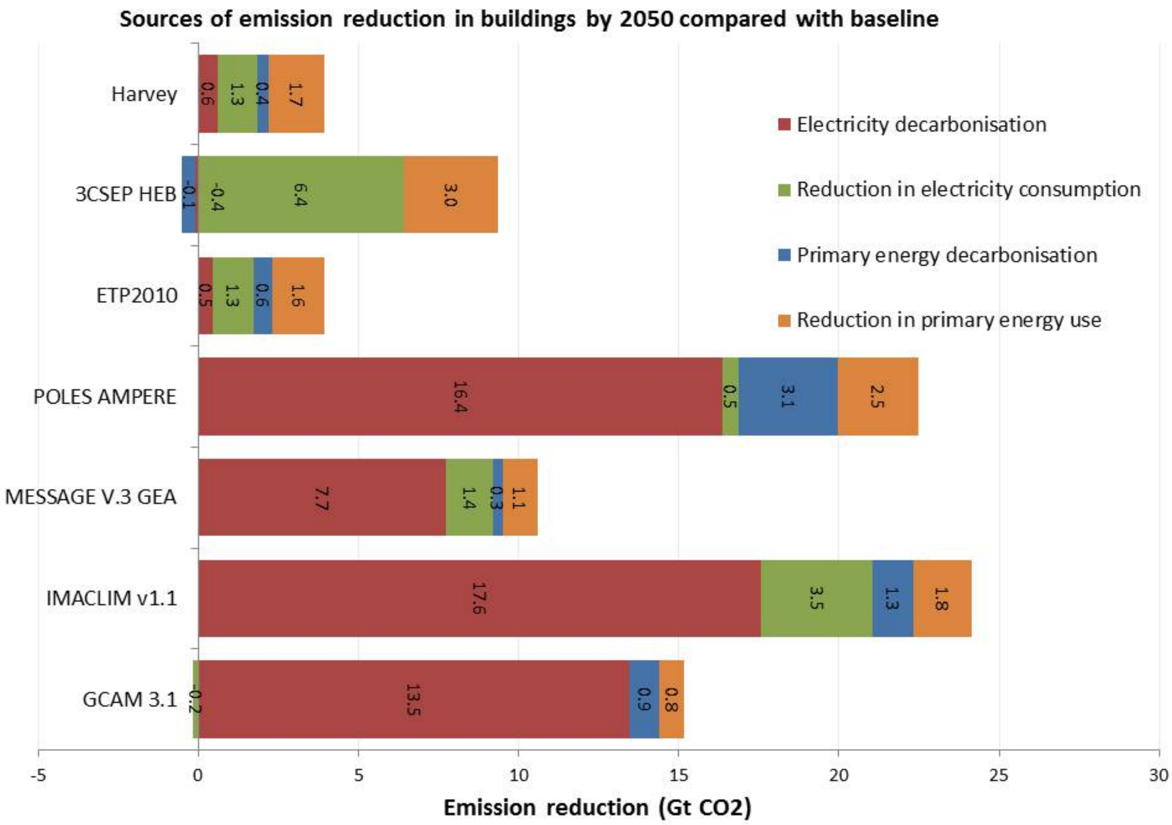


Figure 9.23. Emission reduction in ambitious/stabilisation scenarios attributed to key mitigation strategies in selected IAMs and sectoral models. Note: 3CSEP HEB is for heating/cooling/thermal use only and does not model fuel splits, therefore decarbonisation does not appear. Sources as indicated in Section 9.9.2.

9.10 Sectoral policies

9.10.1 Policies for Energy Efficiency in Buildings (highlighting new developments)

The previous sections demonstrated that many strong barriers prevent the full uptake of energy saving measures. Market forces alone will not achieve the necessary transformation towards low carbon buildings without external policy intervention. However, in order to achieve this, policy intervention needs to be complemented by new business and financial models that overcome the first-cost hurdles, one of the key barriers to energy efficiency. There is a broad portfolio of effective policy instruments available to remove the barriers, with many of them implemented in developed countries, but more recently also in developing countries, showing reductions of emissions at large negative costs. When policies are dynamically developed and implemented in a long term coordinated manner, including RD&D, incentives and financing, they can be effective in reversing growing energy consumption (as example UK residential gas consumption declined for the last 5 years – source Digest of UK Energy Statistics 2010 (UKES, 2010), as results of more efficient boilers and increased building insulation). Beside technological improvement (improvement in energy efficiency), which has been so far the main focus of most polices, recently policy makers attention has been drawn to the need of changing consumer behavior and lifestyle, based on the concept of sufficiency. It is estimated that in the EU existing building stock is renewed at the rate of 1.2 % annually (European Union, 2012) and more than 60% of this will still be standing in 2050 (Lewis,

2010)). Therefore any policy package designed to reduce emissions in buildings should include policies spefically targeting the existing stock, e.g. policies aiming at accelerating the rates of refurbishment and at the same time avoiding locked-in savings with suboptimal retrofits. This is also becoming true for some developing countries, for example, energy efficiency retrofits of existing residential buildings (EERERB) in northern China have been observed as having a great potential to provide significant social and environmental benefits (Dongyan, 2009). Policies require periodic revision to follow technical developments and market transformation, in particular they need regular strengthening, for example for equipment minimum efficiency standards (Siderius and Nakagami, 2013) or building codes, such as the German Energy Conservation Act (EnEV) (Weiss et al., 2012) . Recently a lot of attention has been placed on proper enforcement and implementation, which is needed if countries are to achieve the full potential of implemented or planned policies (Ellis et al., 2009; Weiss et al., 2012) , Weiss 2012). The most common policies for the building sector are summarised in Table 9.8, which includes some examples of the results achieved. Policy instruments for energy efficiency in buildings have been classified in the following categories: (i) ***Regulatory measures*** such as building codes and appliance standards are one of the most effective and cost-effective instruments in the analysed sample of policies (Boza-Kiss et al., forthcoming) if properly enforced (Weiss et al., 2012). This is also confirmed by other authors (Koeppel and Ürge-Vorsatz, 2007; McCormick and Neij, 2009). Economic Instruments including fiscal and financial instruments, such as low interest loans (e.g KfW loans in Germany), grant and subsidies and tax deduction can induce large savings (e.g. tax deductions in Italy). Incentives are very effective in enlarging the market for new efficient products and to overcome first cost barriers for deep retrofits, however they can be less cost-effective (McGilligan et al., 2010). (ii) Among the ***economic instruments*** there are the so-called market-based instruments such as tradable white certificates, which have been introduced only recently, but have so far proven to be very cost-effective (Bertoldi et al., 2010). (iii) The effectiveness of ***voluntary programme***s (e.g. branch sector agreements) depends on the local context and on accompanying policy measures (rather successful in the Netherlands) (Bertoldi 2011). (iv) ***Information instruments*** (e.g. labelling, public information campaigns) are relatively effective on their own depending on their design, but they can support other instruments, in particular in combination with standards. These policy instruments are evaluated and the highest GHG emission reductions were achieved by equipment standards, building codes, suppliers' obligations, and tax exemptions. Among the most cost-effective instruments were appliance standards, suppliers' obligations, public benefit charges and labelling. Most of these are regulatory and control instruments. Most of these instruments are also effective in developing countries, where it is essential that the co-benefits of energy-efficiency policies, such as energy security, poverty alleviation or improved social welfare, reduced mortality and morbidity or improved health, job creation and improved industrial productivity are well-mapped, quantified and well understood by the policy- makers (Ryan and Campbell, 2012) (Koeppel and Ürge-Vorsatz, 2007). Policy integration with other policy domains is particularly effective to leverage these co-benefits in developing countries, and energy-efficiency goals can often be pursued more effectively through other policy goals than climate mitigation, which have much higher ranking in political agendas and thus may enjoy much more resources and a stronger political momentum.

9.10.2 Emerging policy instruments in buildings

Since recent reports have reviewed building-related policy instruments comprehensively (IPCC, 2007; GEA, 2012)), this chapter provides insights only into recent developments in emerging or important instruments.

FAQ 9.5. Which policy instrument(s) have been particularly effective and/or cost-effective in reducing building-sector GHG emission (or their growth, in developing countries)?

Policy instruments in the building sector have proliferated since the AR4, with new instruments such as white certificates, preferential loans, grants, progressive building codes based on principles of cost-optimum minimum requirements of energy performance and life cycle energy use calculation, energy saving feed-in tariffs as well as suppliers' obligations and other measures introduced in several countries (UNEP SBCI, 2007). Among these, regulation-based instruments seem the most environmentally effective, due to the strong barriers that prevail in the building sector. Among them, appliance standards are often the most cost- and environmentally effective, and building codes can result in large emission reductions but can be less cost-effective and need strong enforcement and regular strengthening.

9.10.2.1 Policy instruments to encourage sufficiency

While technical efficiency improvements are still needed and important to reduce energy demand, due to the rebound effect (Alcott, 2008), the need for energy services (especially in developing countries) and increased usage of energy due to increased built space per capita and additional equipment, policies need to influence consumer behaviour and lifestyle (Herring, 2006; Sanquist et al., 2012). To this end the concept of sufficiency has recently been introduced in the energy efficiency policy debate (Herring, 2006; Oikonomou et al., 2009). Policies to target sufficiency aim at capping or discouraging constant increase in energy use due to increased floor space, comfort levels (e.g. over cooling buildings in summer), and additional equipment. Policy instruments in this category include: personal carbon allowances (to include also reduction in transport needs) - this policy instrument has not yet been introduced (The Carbon Trust, 2012) and the social acceptability and implementation has to be further demonstrated; property taxation (have a non-linear taxation based on building's CO2 emissions); progressive appliance standards and building codes. Policies can introduce absolute maximum consumption limits rather than efficiency requirements for equipment and buildings (e.g. kWh/person year rather than kWh/m2/year) (Harris et al., 2007). In order to reduce energy demand policies may address meeting needs for space in an effective manner, including promoting density, high space utilization, and efficient occupant behaviour, as increased floor space entails more energy use. A recent example are incentives based on reduction of energy consumption (or energy savings), the so-called energy saving feed-in tariff (Bertoldi et al., 2010; Eyre, 2013), (Bertoldi 2013).

9.10.2.2 New developments in building codes (ordinance, regulation or by-laws)

The EU has introduced in 2010 a new law (Directive 2010/31/EU on energy performance of buildings, "recast EPBD", EU 2010) requiring its Member States to introduce building codes set at the cost optimal point using a life cycle calculation and net present value methods both for new and buildings undergoing major renovation (Delegated Regulation (EU) No. 244/2012, EC 2012). As a result of the same Directive in the EU by the end of 2020 all new buildings must be nearly zero energy by law. Many Member States (Denmark, Germany, etc.) have announced progressive building codes to gradually reduce the energy consumption of buildings towards net zero energy. The city of Brussels has mandated that all new social and public buildings must meet Passive house levels from 2013, while all new buildings have to meet these norms from 2015.

9.10.2.3 Energy efficiency 'white' certificates

White certificates as incentive schemes have been applied in some member states of the European Union (Bertoldi et al., 2009) and Australia (Crossley, 2008), although there are more recent uses in Brazil and India. White certificates evolved from non-tradable obligations on monopoly energy utilities, also know as suppliers' obligations or energy efficiency resources standands, largely but not only in the USA. Market liberalisation initially led to a reduction in such activity (Ürge-Vorsatz, Eyre, Graham, Kornevall, et al., 2012), driven by a belief that such approaches were not needed in or incompatible with competitive markets, although this is not correct (Vine et al., 2003). Their main use has been in regulated markets driven by obligations on energy companies to save energy (Bertoldi and Rezessy, 2008) .The use of tradable obligations began in the UK in 2000, and these obligations are now significant in a number of EU countries, notably UK, France and Italy (Eyre et al., 2009). Energy supplier obligation schemes form a key part of future proposed EU policy for energy efficiency, with new EU legislation in the area of energy efficiency (European Union, 2012) for energy efficiency, with new EU legislation requiring all EU Member States to introduce this policy instrument. Precise objectives, traded quantity and rules differ across countries in which white certificates are used. Cost effectiveness is typically very good. However, white certificates tend to have incentivised low cost, mass market measures rather than deep retrofits, and therefore there are concerns that this policy approach may not be best suited to the future energy efficiency policy objectives (Eyre et al., 2009).

9.10.2.4 A holistic approach

A holistic approach implies considering the whole lifespan of the building, and includes master planning, life cycle analysis, and integrated building design to obtain the broadest impact possible in the building industry. Energy efficiency in buildings needs to begin at the neighbourhood or city level. In the holistic approach, integrated and regionally adequate codes, design, operation and maintenance must be coordinated in order to reduce emissions. Continuous monitoring of buildings' real performance and dynamic codes allow closing the gap with the efficiency potential and achieving the co-benefits. The use of modern technologies to provide feedback on consumption in real time, allowing adjustment of energy performance also as a function of external energy supply, is important. Dynamic information can also be used for energy certificates and databases to disclose building energy performances (for example this is required for public buildings in Denmark). Delivering low carbon buildings requires solving major challenges in education, capacity building and training of a specialised workforce.

9.10.2.5 Single instruments

Table 9.8 attests that there is a broad portfolio of cost effective policy instruments available to remove the barriers, with many of them being implemented widely, including in developing countries, saving emissions at large negative costs. The above polices have been evaluated for their environmental effectiveness and economic effectiveness (cost-effectiveness and economic efficiency), two other important evaluation criteria (distributional equity and broader social impacts) and institutional, political, and administrative feasibility and flexibility, are not analysed here.

Table 9.8: Policies for energy efficiency in buildings, their environmental effectiveness, i.e. emission reduction impact and societal cost-effectiveness. Based on Boza-Kiss et al. forthcoming.

Policy title and brief definition	Further information, comments	Environmental effectiveness (selected best practices of annual CO2 emission reduction)	Cost effectiveness of CO2 emission reduction (selected best practices, $2010/tCO2 per yr)	References
Building codes are sets of standards for buildings or building systems determining minimum requirements of energy performance.	Lately standards have also been adopted for existing buildings (Desogus et al., 2013). Traditionally typical low enforcement has resulted in lower than projected savings. Building codes need to be regularly strengthened to be effective.	EU: 35-45 MtCO2 (2010-2011) LV: 0.002 MtCO2/yr in 2016 (estimated in 2008) ES: 0.35 MtCO2/yr in 2012 UK : 0.02 MtCO2/yr by 2020 (estimated in 2011)	EU region: <36.5 $/tCO2 ES: 0.17$/tCO2 LV: -206 $/tCO2	(EC, 2002; Koeppel and Ürge-Vorsatz, 2007; DECC, 2011; Gov't of Latvia, 2011)
Appliance standards (MEPS) are rules or guidelines for a particular product class that set a benchmark, and usually prohibit the sale of underperforming products.	Voluntary agreements with equipment manufacturers are considered as effective alternatives in some jurisdictions. The Japanese Top Runners Schemes have proven as successful as MEPS (Siderius and Nakagami, 2013)(). Developing countries may suffer a secondary effect, receiving products banned from other markets or inefficient,second hand products.	JP: 0.1 MtCO2/yr in 2025 (Top Runner Scheme, 2007) US: 158 MtCO2 cumulative in 2030 (2010), updating the standard – 18 MtCO2/yr in 2040 (2010) KE: 0.3 MtCO2/yr (for lighting only) BF: 0.01 MtCO2/yr (lighting only)	JP: 51 $/tCO2 (Top Runner) Mor: 13 $/tCO2 AU: -52 $/tCO2 US: -82 $/tCO2 EU: -245 $/tCO2	(Kainou, 2007; AHAM, 2010; En.lighten, 2010; US EERE, 2010)
Energy labelling is the mandatory (or voluntary) provision of information about the energy/other resource use of end-use products at the point of sale.	Examples include voluntary endorsment labelling (e.g. Energy Star) and mandatory energy labelling (e.g. the EU energy label). Technical specifications for the label should be regularly updated to adjust to the best products on the market. MEPS and labels are usually co-ordinated policy measures with common technical analysis.	EU: 237 MtCO2 (1995-2020) OECD N-Am: 792 MtCO2 (1990-2010) OECD Eu: 211 MtCO2 (1990-2010) NL: 0.11 MtCO2/yr (1995-2004) DK: 0.03 MtCO2/yr (2004)	AU: -38 $/tCO2	(IEA, 2003; Wiel and McMahon, 2005; Luttmer, 2006)
Building labels and certificates rate buildings related to their energy performance and provide credible information about it to users/buyers.	Building labels could be mandatory (for example in the EU) or voluntary (such as BREEAM, CASBEE, Effinergie, LEED, European GreenBuilding label, Minergie and PassivHaus). Labels are beginning to influence market prices(Brounen and Kok, 2011b) (.	SK: 0.05 MtCO2 (during 2008-2010) for mandatory certification SK: 0.001 MtCO2 (during 2008-2010) for promoting voluntary certification and audits	EU: 27 $/tCO2 (2008-2010) for mandatory certification DK: almost 0 $/tCO2	(Gov't of Slovakia, 2011)Gov't of Slovakia, 2011) [369]
Mandatory energy audits measure the energy performance of existing buildings and identify cost-effective improvement potentials.	Audits should be mandatory and subsidized (in particular for developing countries). Audits are reinforced by incentives or regulations that require the implementation of the cost-effective recommended measures.	SK: 0.001 MtCO2 (during 2008-2010) for promoting voluntary certification and audits FI: 0.036 MtCO2 (2010)	FI: 27.7 $/tCO2 (2010) mandatory audit programme	(Koeppel and Ürge-Vorsatz, 2007; Gov't of Slovakia, 2011; Government of Finland, 2011)
Sustainable public procurement is the organized purchase by public bodies following pre-set procurement regulations incorporating energy performance /sustainability requirements.	Setting a high level of efficiency requirement for all the products that the public sector purchases, as well as requiring energy efficient buildings when renting or constructing them, can achieve a significant market transformation, because the public sector is responsible for a large share of these purchases and investments.	SK: 0.01 MtCO2 (introduction of sustainable procurement principle) (2011-2013) CN: 3.7 MtCO2 (1993-2003) MX: 0.002 MtCO2 (2004-2005) UK: 0.34 MtCO2 (2011) AT: 0.02 MtCO2 (2010)	SK: 0.03 $/tCO2 CN: -10$/tCO2	(FI, 2005; Van Wie McGrory et al., 2006; Gov't of Slovakia, 2011; LDA, 2011)
Promotion of energy services (ESCOs) aims to increase the market and quality of energy service offers, in which savings are guaranteed and investment needs are covered from cost savings.	Energy performance contracting (EPC) schemes enable ESCOs or other players to offer innovative contracts guaranteeing the level of services and the energy savings to the customer (Duplessis et al. 2012). Many countries have recently adopted policies for the promotion of EPC delivered via ESCOs (Marino et al., 2011).	EU:40-55MtCO2 by 2010 AT: 0.016 MtCO2/yr in 2008-2010 US: 3.2 MtCO2/yr Cn: 34 MtCO2	EU: mostly at no cost AT: no cost HU: <1 $/tCO2 US: Public sector: B/C ratio 1.6, Private sector: 2.1	(Koeppel and Ürge-Vorsatz, 2007; AEA, 2011; MNDH, 2011)
Energy Efficiency Obligations and White Certificates set, record and prove that a certain amount of energy has been saved at the point of end-use. Schemes may incorporate trading.	Suppliers' obligations and white certificates have been introduced in Italy, France, Poland, the UK, Denmark and the Flemish Region of Belgium and in Austrlia. In all the White Certificates schemes the targets imposed by governments have been so far exceeded (Bertoldi et al., 2010).	FR: 6.6 MtCO2/yr (2006-2009) IT: 21.5 MtCO2 (2005-2008) UK: 24.2 MtCO2/yr (2002-2008) DK: 0.5 MtCO2/yr (2006-2008) Flanders (BE): 0.15 MtCO2 (2008-2016))	FR: 36 $/tCO2 IT: 12 $/tCO2 UK: 24 $/tCO2 DK: 66 $/tCO2 Flanders (BE): 201 $/tCO2	Dunstan 2010 (Lees, 2006, 2008, 2011; Pavan, 2008; Bertoldi and Rezessy, 2009; Togeby et al., 2009; Bertoldi et al., 2010; Giraudet et al., 2011)

Policy title and brief definition	Further information, comments	Environmental effectiveness (selected best practices of annual CO2 emission reduction)	Cost effectiveness of CO2 emission reduction (selected best practices, $2010/tCO2 per yr)	References
Carbon markets limit the total amount of allowed emissions. Carbon emission allowances are then distributed and traded.	Carbon cap and trade for the building sector is an emerging policy instrument (e.g. the "Tokyo CO2 Emission Reduction Program", which imposes a cap on electricity and energy emissions for large commercial buildings), although the program is currently under change due to the special measure for the Great East Japan Earthquake.	CDM: 1267 MtCO2 (average cumulative saving per project for 32 registered CDM projects on residential building efficiency, 2004-2012) JI: 699 MtCO2 (cummulative) from the single JI project on residential building enegy efficiency (2006-2012)	CDM end-use energy efficiency projects, In: -113 to 96$/tCO2 JI projects (buildings): between 122 and 238 USD/tCO2	(BETMG, 2012; UNEP Risoe, 2012)
Energy and carbon tax is levied on fossil fuels or on energy using products, based on their energy demand and/or their carbon content respectively.	Fiscal tools can be powerful, because the increased (relative) price of polluting energy sources or less sustainable products is expected to cause a decrease in consumption. However, depending on price electicity, the tax typically should be quite substantial to have an effect on behaviour and energy efficiency investments.	SE: 1.15 MtCO2/yr (2006) DE: 24 MtCO2 cummulative (1999-2010) DK: 2.3 MtCO2 (2005) NL: 3.7 -4.85 MtCO2/yr (1996-2020)	SE: 8.5 $/tCO2 DE: 96 $/tCO2 ee NL: -421 to -552 $/tCO2 (2000-2020)	(Knigge and Görlach, 2005; Price et al., 2005; EPC, 2008; IEA, 2012)
Use of taxation can be considered as a type of subsidy, representing a transfer of funds to investors in energy efficiency.	Examples include reduced VAT, accelerated depreciation, tax deductions, feebates etc.	TH: 2.04 MtCO2 (2006-2009) IT: 0.65 MtCO2 (2006-2010) FR: 1 MtCO2 (2002) US: 88 MtCO2 (2006)	TH: 26.5 $/tCO2	(GMCA, 2009; APERC, 2010; BPIE, 2010)
Grants and subsidies are economic incentives, in the form of funds transfer.	Incentives (e.g. grants and subsidies)) for investments in energy efficiency, as provided for building renovation in Estonia.	DK: 170 MtCO2 cummulative (1993-2003) UK: 1.41 MtCO2 (2008-2009) CZ: 0.05 MtCO2 (2007) AU: 0.7 MtCO2 (2009-2011) FR: 0.4 MtCO2 (2002-2006)	DK: 0.5 $/tCO2 UK: 84.8 $/tCO2 FR: 17.9 $/tCO2	(DPMT, 2009; GMCA, 2009; BPIE, 2010; Missaoui and Mourtada, 2010; Hayes et al., 2011)
Soft loans (including preferential mortgages) are given for carbon-reduction measures with low interest rates.	Typically the government provides a fiscal incentive to the bank, which in turn offers a preferential interest rate to its customers, e.g. in Germany.	TH: 0.3 MtCO2 (208-2009) LT: 0.33 MtCO2/yr (2009-2020) PL: 0.98 MtCO2 (2007-2010)	TH: 108 $/tCO2 (total cost of loan)	(BPIE, 2010)
Voluntary and negotiated agreements are tailored contracts between an authority and another entity, aimed at meeting a predefined level of energy savings.	Voluntary programmes can be also applied in the built environment as in the Netherlands and Finland, where housing association and public property owners agree on energy efficiency targets with the government.	FI: 9.2 MtCO2 NL: 2.5 MtCO2 (2008-2020) DK: 0.09 MtCO2/yr (1996)	FI: 0.15 $/tCO2 NL: 14 $/tCO2 DK: 39 $/tCO2	(Koeppel and Ürge-Vorsatz, 2007; Rezessy and Bertoldi, 2010; Government of Finland, 2011; MIKR, 2011)
Awareness raising and information campaigns, are programs transmitting general messages to the whole population**.** ***Individual feedback*** is characterized by the provision of tailored information.	Information campaigns to stimulate behavioural changes (e.g. to turn down the thermostat by 1 C during the heating season) as well as investments in energy efficiency technologies; new developments are seen in the area of smart metering and direct feedback.	BR: 6-12 MtCO2/yr (2005) UK: 0.01 MtCO2/yr (2005) EU: 0.0004 MtCO2 (2009) FI: 0.001 MtCO2/yr (2010) UK: 0.25% household energy saving/yr, that is 0.5 MtCO2/yr (cumulated 2011-2020) (billing and metering)	BR: -69 $/tCO2 UK: 8.4 $/tCO2 EU: 40.2 $/tCO2 US: 20-98 $/tCO2	(Koeppel and Ürge-Vorsatz, 2007; Uitdenbogerd et al., 2009; CPI, 2011; UK DE, 2011; CB, 2012)
Public Leadership Programmes are public practices going beyond the minimum requirements in order to lead by example and demonstrate good examples.		IE: 0.033 MtCO2 (2006-2010) BR: 6.5-12.2 MtCO2/yr	ZA: 25 $/tCO2 BR: - 125 $/tCO2	(Koeppel and Ürge-Vorsatz, 2007; Government of Ireland, 2011)

Country codes (ISO 3166): AT-Austria; AU-Australia; BE- Belgium; BF- Burkina Faso; BR- Brazil; CN- China; CZ-Czeck Republic; DE- Germany; DK- Denmark; ES- Spain; EU- European Union; FI- Finland; FR-France; HU- Hungary; IE- Ireland; IN-India; IT-Italy; JP- Japan; KE- Kenya; LT- Lithuania; LV- Latvia; Mor – Morocco; MX- Mexico; NL-The Netherlands; OECD EU- OECD countries in Europe; OECD N-Am: OECD countries in North-America; PL- Poland; SE-Sweden; SK- Slovak Republic; SL- Slovenia; TH- Thailand; UK- United Kingdom; US- United States; ZA South Africa. [AUTHORS: THIS TABLE CAN BE REDUCED IN SIZE IF REFERENCES ARE NUMBERED AND REFERRED TO IN THIS ENDNOTE]

9.10.2.6 Policy packages

There is agreement among experts and it is widely reported in literature (Harmelink et al., 2008; Tambach et al., 2010; Weiss et al., 2012; Murphy et al., 2012) , that no single policy is enough to achieve the potential energy savings and that a number of coordinated and complementary policies are very effective (and cost-effective). As example in the EU the Energy Efficiency Directive (European Union, 2012) () requires Member States to describe the co-ordinated packages of policies in the National Energy Efficiency Action Plans (NEEAPs), which have to be prepared every 3 years since 2008. Among the most common energy efficiency packages adopted by several developed countries are equipment MEPS, energy labels and financial incentives for the most efficienct equipment (e.g Energy Star or Class A) all based on a common technical analysis (e.g. phasing out in time the lowest classes of the energy label, and giving incentives for the highest efficiency class; this was very successful for the market transformation of domestic appliances in the EU), supported by an effective communication campaign for end-users. In many cases, policy measures for appliances are used in combination to increase their impact. There are numerous examples, such as "MEPS and performance labels", "Endorsement labels and procurement policies" and "Labels, retailer programmes and customer incentives". There is no one single model to employ; rather, each program varies in terms of structure, funding, and implementation. The specific policies, regulations, programs, and incentives needed are highly dependent on the nature of the target product or the technological area and conditions (e.g. market structure, resources, institutional capacity) of the target market area (e.g. national, state, regional grouping), and the background of each country such as its history, culture, custom, economical development, national awareness, etc. Other packages of measures for the retrofitting of existing buildings are mandatory audits and financial incentives linked to the implementation of the audit findings or to the minimum efficiency requirements (the financial incentives could be also proportional to the achieved efficiency level indicated in the building certificates). An interesting example is the Singapore government's green building policy packages, termed as Green Building Master Plan. In other jurisdictions the financial incentives are provided by suppliers' obligation or white certificates. Other policy packages include voluntary programmes coupled with tax exemptions and other financial incentives (Murphy et al., 2012). Suppliers'obligations and white certificates are usually introduced with equipment labelling and MEPS are used to promote products beyond the standards requirements, in France this policy instrument is used in conjuction with tax credits (Bertoldi et al., 2010)).

9.10.3 Financing opportunities

9.10.3.1 New financing schemes for energy efficiency (for deep retrofits)

Energy efficiency (EE) is not a single market: it covers measures in a diverse range of end-user sectors, end-use equipment and technologies and consists of very large numbers of small, dispersed projects with a diverse range of decision makers. As the chapter has demonstrated, many EE technologies in the building sector are proven and economic: if properly financed, the investment costs are paid back over short periods from energy cost savings. However, many potentially attractive energy investments do not meet the short-term financial return criteria of businesses, investors and individuals, or there is no available financing or there is no information about it. While significant savings are possible with relatively modest investment premiums, a first-cost sensitive buyer, or one lacking financing, will never adopt transformative solutions. Major causes of this gap are the lack of EE finance and of delivery mechanisms that suit the specifics of EE projects and the lack – in some markets – of pipelines of bankable energy efficiency projects. One solution is that energy utilities, businesses and financial institutions develop creative business models that overcome the first-cost hurdle, such as energy services companies (ESCOs). One innovative example is energy-efficiency investment funds capitalizing on the lower risk of mortgage lending on low-energy housing; the funds to provide such investment could be attractive to socially responsible investment funds. In Germany through the KfW development bank energy efficiency loans with low interested rate are offered making it attractive to end-users, the scheme has triggered many building refurbishments (Harmelink et al., 2008) (Harmelink et al., 2008).

The ***UK 'Green Deal'*** is a new initiative by the UK government designed to facilitate the retrofitting of energy saving measures to all buildings across the UK. The scheme enables private firms to offer consumers energy efficiency improvements to their building, and to recoup payments through a charge in instalments on the electricity bill. The finance will be tied to the energy meter rather than the building owner. The UK government does not plan to subsidise the loan interest rate charged to homeowners, and current commercial rates may not be attractive to end-users. The Green Deal is expected to finance short payback measures (e.g.cavity wall insulation) previously covered by the suppliers'obligation. In areas of the US with ***PACE*** (Property Assessed Clean Energy) legislation in place, municipality governments offer a specific bond to investors and then using this to finance lending to consumers and businesses to for energy retrofits (Headen et al., 2010). The loans are repaid over the assigned term (typically 15 or 20 years) via an annual assessment on their property tax bill.

ESCOs projects provide comprehensive solutions for improving energy efficiency in building by guaranteeing that energy savings are able to repay the efficiency investment, thus overcoming financial constraints to energy efficiency investments. The ESCO model has been found to be effective in developed countries such as Germany (Marino et al., 2011) and the USA, and rather less in developing countries (UNEP SBCI, 2007). However, in the last decade ESCOs have been created in number of developing countries (e.g. China, Brazil, and South Korea) supported by international financial institutions and their respective governments (UNEP SBCI, 2007; Da-li, 2009). Since the introduction of an international cooperation project in the field of energy conservation by Chinese government and World Bank in 1998, the market-based EPC mechanism and ESCO industry has developed in China (Da-li, 2009). The Chinese government has supported and aggressively pushed this industry since its establishment. Policies for the support of ESCOs in developing countries include the creation of a Super ESCOs (Limaye and Limaye, 2011) by governmental agencies. Financing environments for ESCOs need to be improved to ensure they operate optimally and sources of financing, such as debt and equity, need to be located. Possible financing sources are commercial banks, venture capital firms, equity funds, leasing companies and equipment manufacturers (Da-li, 2009). In social housing in Europe, funding can be provided through the Energy Performance Contracts (EPC), in which an ESCO invests in a comprehensive refurbishment (building insulation and renovation of the heating systems), and repays itself through the generated savings. In the FRESH project, social housing operators and ESCO from France, United Kingdom, Italy and Bulgaria have established the legal, financial and technical framework for EPC's in social housing. Interesting results using the ESCO models in multifamily buildings were also achieved in Hungary (Milin and Bullier, 2011) Labanca 2013).

Taxes such as energy and carbon (CO_2) taxes have increasingly been implemented to accelerate energy efficiency (UNEP SBCI, 2007). They have an advantage of complementing and reinforcing the effectiveness of other policy instruments such as standards. Energy taxes imposed on the building sector can reduce GHG emissions in three ways: increase the end user energy price to foster reduced energy demand, shorten pay back periods for investment in energy efficiency and governments can reinvest tax revenues into energy efficiency interventions (UNEP SBCI, 2007). Tax exemptions and reductions, if appropriately structured, can provide a more effective mechanism than energy taxes (UNEP SBCI, 2007). In Italy a tax deduction of 55% for building retrofits (windows, boilers, insulation), has been in force since January 2007; this represents one of the most generous system of incentives ever established to promote energy efficiency. The results have been successful; since 2007, over 600,000 requests for deduction have been submitted, during the first three years about 8 billion Euro were invested by taxpayers, over 4,400 GWh of energy saved per year, roughly one million tons of CO_2 emissions avoided (Valentini and Pistochini, 2011). Another option is value-added tax (VAT) exemption, hence stimulating uptake of energy efficiency technologies in new homes and commercial buildings. Tax policies are used to incentivize the implementation of EERERB in China in a form of tax relief on VAT, property tax and land use tax in cities and towns (Dongyan, 2009). Certified carbon emissions reductions from CDM projects are exempted from normal (company) tax in South Africa (RSA, 2009).

9.10.3.2 Opportunities in Financing for Green Buildings

Regarding ***global trends for eco-friendly real estate***, the existing global green building market is valued at approximately $550 billion and is expected to grow through to 2015, with Asia anticipated to be the fastest growing region (Lewis, 2010). According to results of a survey carried out by the United Nations Environment Programme Finance Initiative Property Working Group (UNEP FI, 2009) on responsible property investing (RPI), covering key markets around the world, it is possible to achieve a competitive advantage and greater return on property investment by effectively tackling environmental and social issues when investing in real estate (UNEP FI and PRI signatories, 2008). In Japan, new rental-apartment buildings equipped with solar power systems and other energy-saving devices had significantly higher occupancy rates (occupancy rate is about 100%) than the average rate of 81.3% for other properties in the neighbourhood, and investment return rates were also higher (MLIT, 2010a; b). According to results of a survey comparing rent and vacancy rates of buildings certified by the U.S. Building Council LEED and those not certified (Watson, 2010), rents for LEED certified buildings were consistently higher than for uncertified buildings, although vacancy rates varied according to market conditions. In many municipalities in Japan, assessment by the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and notification of assessment results are required at the time of construction for buildings. Several financial products are available that provide a discount of more than 1% on housing loans, depending on the grade received by the CASBEE assessment. This has been contributing to the diffusion of green buildings through financial schemes (IBEC, 2009). In addition, a housing eco-point system was implemented in 2009 in Japan. The eco-point system was broadly divided between a home appliances eco-point system and a housing eco-point system; in the housing eco-point system, housing which satisfies the Top Runner-level standards are targeted. The housing eco-point system targets newly constructed as well as existing buildings. There were 160,000 applications for subsidies for newly constructed buildings, accounting for approximately 20% of newly constructed buildings in 2010. This program has contributed to the promotion of green buildings in the market. Regarding existing buildings, the number of window replacements has increased, and has attracted much attention (MLIT, 2012).

9.10.3.3 Financing opportunities in developing countries

Economic instruments and incentives are recognised as very important means to encourage stakeholders and investors in building sector to adopt more energy efficient approaches at the stages of design, construction and operation of buildings (Huovila, 2007). This section provides an overview of financial instruments commonly applied in the developing world to promote emissions reduction in building sector.

In terms of ***Carbon markets***, the Clean Development Mechanism (CDM) has a great potential to promote energy efficiency and lower emissions in building sector. The CDM is regarded as one of the important international market mechanisms to finance emissions reduction projects in developing countries, and with its strong financial and technology transfer incentives it puts the building sector in a good position to be a target for project developers (Huovila and UNEP, 2009). Carbon finance can provide an additional revenue stream that can facilitate project financial closure (UNEP FI, 2009). There are barriers for financing energy efficiency projects with flexible mechanisms under Kyoto Protocol due to the size of the projects and the M&V criteria (Huovila and UNEP, 2009). Carbon markets are divided into two categories: the compliance market (such as CDM), which is influenced by policies and regulations, and the voluntary market based on 'willing' market participants (Chaurey and Kandpal, 2009). In the voluntary market, Verified Emissions Reductions (VER) are traded instead of Certified Emissions Reductions (CER), which are carbon assets generated by CDM projects. As an example, emerging voluntary markets, such as retail carbon markets that sell emissions reductions to individuals and companies willing to reduce their carbon footprints, can also be a potential source of financing for household interventions such as solar home systems (SHS) (Chaurey and Kandpal, 2009). The World Bank has established a Community Development Carbon Fund (CDCF) that supports projects having twin objectives of community development and emissions reduction whilst improving the quality of life of the poor and their local environment (Chaurey and Kandpal, 2009). CDCF is also one of the funds that can provide carbon financing to SHS type projects.

Public benefits charges are incentive mechanisms meant to raise funds for energy efficiency measures and to accelerate market transformation in both developed and developing countries (UNEP SBCI, 2007). In a developing country like Brazil, all energy distribution utilities are required to spend a minimum of 1% of their revenue on energy efficiency interventions while at least a quarter of this fund is expected to be spent on end-user efficiency projects (UNEP SBCI, 2007). Utility ***demand side management (DSM)*** may be the most viable option to implement and finance energy efficiency programs in smaller developing countries (Sarkar and Singh, 2010). In developing country context, it is common practice to house DSM programmes within the local utilities due to their healthy financial means, strongest technical and implementation capacities, for example, in Argentina, South Africa, Brazil, India, Thailand, Uruguay and Vietnam (Winkler and Van Es, 2007; Sarkar and Singh, 2010). Eskom, South African electricity utility uses its DSM funds mainly to finance load management and energy efficiency improvement including millions of free issued compact fluorescent lamps(CFLs) that have been installed in the households of South Africa (Winkler and Van Es, 2007).

Capital subsidies, grants and subsidized loans are among the most frequently used instruments for the implementation of increased energy efficiency projects in buildings. These are common in residential sector to overcome financial barrier of initial capital costs (UNEP SBCI, 2007). Financial subsidy is used as the primary supporting fund in the implementation of EERERB in China (Dongyan, 2009). In recent years, the World Bank Group (WBG) has steadily increased energy efficiency lending. This includes the highest lending ever in the fiscal year of 2009 to reach US$3,3 billion and US$1,7 billion committed investments in the same year alone (Sarkar and Singh, 2010). Examples include energy efficient lighting programmes in Mali, energy efficiency projects in buildings in Belarus, carbon finance blended innovative financing to replace old chillers (air conditioning) with energy efficient and CFC-free chillers in commercial buildings in India (Sarkar and Singh, 2010). The Government of Nepal has been providing subsidies in the past few years to promote the use of solar home systems (SHS) in rural households (Dhakal and Raut, 2010). The certified emission reductions (CERs) accumulated from this project were expected to be traded in order to supplement the financing of the lighting program. The Global Environmental Facility (GEF) has directed a significant share of its financial resources to SHS and the World Bank similarly has provided a number of loans for SHS projects in Asia (Wamukonya, 2007). The GEF has provided a grant of $210 million to finance 23 off-grid SHS projects in 20 countries (Wamukonya, 2007).

Implementation and enforcement of policies is a key component of policy design. It is the only way to ensure that the expected results of the policy are achieved. Developed countries are now raising the importance of proper implementation and enforcement (Jollands et al., 2010), to survey equipment efficiency when MEPS are in place and to check compliance with building codes. (There is still evidence in some EU Member States that the compliance of new buildings with building code is quite low, as it is based on the building design and it is not checked when the buildings is declared fit for occupancy; recommendations include a mandatory check of building performace when the building is operated and the use of sanctions). As an example the EPBD recast (European Union, 2012) requires EU Member States to develop independent control systems for their EPC schemes (Article 18, Annex II of Directive 2010/31/EU). Public money invested in implementation and enforcement will be highly cost effective (Tambach et al., 2010), as it contributes to the overall cost-effectiveness of energy efficiency policies. Implementation and enforcement is still a major challenge for developing countries which lack much of the capacity (e.g. testing laboratories for checking equipment efficiency) and knowledge to implement policies such as standards, labels and building codes. In addition to enforcement, proper ex-post evaluation of the policies is needed to assess the real impact of the policy and eventually review the policy design and stringency, or to complement it with other policy instruments. Another challenge is the need to develop the skills and training for delivering low carbon buildings. To implement the large number of energy saving projects (building retrofits or new construction) will need a large, skilled workforce to carry out high-quality work at relatively low cost. This could also be a great employment creation.

9.11 Gaps in knowledge and data

A lack of adequate bottom-up data is a major gap, leading to a dominance of top down and supply-focused decisions about energy systems. Misinformation and simplified techniques are risks to the understanding of integrated and regionally adequate building systems, leading to fragmented actions and poorer results. Poor information about opportunities and costs affects optimal decisions and appropriate allocation of financial resources. Energy indicators should also include those related to sufficiency and not only efficiency. Improved and more comprehensive databases on real, measured building energy use, capturing behaviour and lifestyles, are needed to develop exemplary practices from niches to standard. Continuous monitoring and dynamic modification of performance and dynamic of codes allows implementation to catch up with the potential for efficiency improvements and co-benefits. It also provides better feedback to the policymaking process, as well as education, capacity building and training. Positive and negative externalities over the building life cycle are not seldom quantified and monetized, and are thus not well integrated into decision-making processes.

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