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Chapter 9

Buildings

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Chapter 9: Buildings

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Executive Summary

In 2010 buildings accounted for 34% of total global final energy use, 24% of energy-related GHG emissions (including electricity-related ones), approximately 45% of F-gas and one-third of black carbon emissions *[medium agreement, medium evidence]*. This energy use and related emissions may double or potentially even triple by mid century due to several key trends. A very important one is increased access of billions in developing countries to adequate housing, electricity and improved cooking facilities. The ways in which these energy-related needs will be provided will significantly determine trends in building energy use and related emissions. In addition, population growth, migration to cities, household size changes and increasing levels of wealth and lifestyle changes globally will all contribute to significant increases in building energy use. The substantial new construction taking place in developing countries represents both a significant risk and opportunity from a mitigation perspective.

In contrast to a doubling, final energy use may stay constant or even decline by mid-century, as compared to today's levels, if today's cost-effective best practices and technologies are broadly proliferated *[high agreement, medium evidence]*. The technology solutions to realize this potential exist and are well demonstrated. New improved energy efficiency technologies have been developed as existing energy efficiency opportunities have been taken up, so that the potential for cost-effective energy efficiency improvement has not been diminishing. 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]*. In existing buildings 50 – 90% energy savings have been achieved throughout the world through deep retrofits *[high agreement, medium evidence]*. Energy efficient appliances, lighting, and information, communication (ICT) and media technologies can reduce the growth in the substantial increases in electricity use that are expected due to the proliferation of equipment types used and their increased ownership and use. *[high agreement, robust evidence]*.

Strong barriers hinder the market uptake of these cost-effective opportunities, and large potentials will remain untapped without adequate policies (robust evidence, high agreement). These barriers include imperfect information, split incentives, lack of awareness, transaction costs, inadequate access to financing and industry fragmentation. In developing countries corruption, inadequate service levels, subsidised energy prices and high discount rates are additional barriers. Market forces alone are not likely to achieve the necessary transformation without external stimuli. Policy intervention addressing all levels of the building and appliance lifecycle and use, plus new business and financial models are essential.

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. Dynamic developments in building-related policies in some developed countries have demonstrated the effectiveness of such instruments, as total building energy use have started decreasing while accommodating continued economic and in cases population growth. Building codes and appliance standards with strong energy efficiency requirements that are well enforced, tightened over time and made appropriate to local climate and other conditions have been among the most environmentally and cost-effective. Net zero energy buildings are technically demonstrated, but may not always be the most cost- and environmentally effective solutions. Experience shows that pricing is less effective than programs and regulation *[medium agreement, medium evidence]*. Financing 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 significant further improvements, in terms of both enhanced energy access and energy efficiency. Delivering low-carbon options raises major challenges for data, research, education, capacity building and training.

Due to the very long lifecycles of buildings and retrofits there is a very significant lock-in risk pointing to the urgency of ambitious and immediate measures *[medium agreement, robust evidence]*. Even if the most ambitious of currently planned policies are implemented, approximately 80% of 2005 energy use in buildings globally will be "locked in" by 2050 for decades, compared to a scenario where today's best practice buildings become the standard in newbuild and retrofit . As a result, the urgent adoption of state-of-the-art performance standards, in both new and retrofit buildings avoid locking-in carbon intensive options for several decades

In addition to technologies and architecture, behaviour, lifestyle and culture have a major effect on buildings energy use presently causing 3-5 times differences in energy use for similar levels of energy services *[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. Alternative development pathways exist that can moderate the growth of energy use in developing countries through the provision of high levels of building services at much lower energy inputs, incorporating certain elements of traditional lifestyles and architecture and can avoid such trends. In developed countries, the concept of "sufficiency' has also been emerging, going beyond pure "efficiency". Reducing energy demand includes rationally meeting floor space needs.

Beyond direct energy cost savings, many mitigation options in this sector have other significant and diverse co-benefits *[high agreement, robust evidence]*. Taken together, the monetizable co-benefits of many energy efficiency measures alone often substantially exceed the energy cost savings and possibly the climate benefits *[medium agreement, medium evidence]*, with the non-monetizable benefits often also being significant *[high agreement, robust evidence]*. These offer attractive entry points for action into policy-making, even in countries or jurisdictions where financial resources for mitigation are limited *[high agreement, robust evidence]*. These include, but are not limited to, energy security, less need for energy subsidies; health (due to reduced indoor and outdoor air pollution as well as fuel poverty alleviation) and environmental benefits; productivity and net employment gains; alleviated energy and fuel poverties as well as reduced energy expenditures; increased value for building infrastructure, improved comfort and services *[high agreement, medium evidence]*. However, they are rarely internalised by policies, while a number of tools and approaches are available to quantify and monetize co-benefits that can help this integration *[medium agreement, medium evidence]*.

In summary, buildings represent a critical piece of a low-carbon future and a global challenge for integration with sustainable development *[high agreement, robust evidence]*. They are the location of the biggest unmet need for basic energy services, especially in developing countries; whilst much existing energy use in buildings in developed countries is very wasteful and inefficient. Existing and future buildings will determine a large fraction of global energy demand. Current trends indicate the potential for massive increases in energy demand and associated emissions. However, this chapter shows that buildings offer immediately available, highly cost-effective opportunities to reduce (growth in) energy demand, while contributing to meeting other key sustainable development goals including poverty alleviation, energy security, and improved employment. This potential is more fully represented in sectoral models than in many integrated models, as the latter do not represent any or all of the options to reduce building energy use cost-effectively. Realizing these opportunities requires aggressive and sustained policies and action to address every aspect of the design, construction, and operation of buildings and its equipment around the world. The significant advances in building codes and appliance standards in some jurisdictions over the last decade already demonstrated to be able to reverse total building energy use trends in developed countries to its stagnation or reduction. However, in order to reach ambitious climate goals, these need to be substantially up-scaled to further jurisdictions, building types and vintages. Table 9.1 summarises some main findings of the chapter by key mitigation strategy.

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),. Fuel switching to low-carbon fuels such as electricity (9.4.1.2)Use of natural refrigerants to reduce halocarbon emissions (9.3.6). Advanced biomass stoves (9.3.8)	High-performance building envelope (HPE). Efficient appliances (EA). Efficient lighting (EL). Efficient Heating, Ventilation, and Air-Conditioning systems (eHVAC). Building automation and control systems (BACS). Daylighting, heat pumps, indirect evaporative cooling to replace chillers in dry climates, advances in digital building automation and control systems, smart meters and grids (9.3.2). Solar-powered desiccant dehumidification	Passive house standard (PHS). Nearly/net zero and energy plus energy buildings (NZEB) (9.3.3.3). Integrated Design Process (IDP). Urban planning (UP), (9.4.1). District heating/cooling (DH/C). Commissioning (C). Advanced building control systems (9.3.3.2)High efficiency distributed energy systems, co-generation, trigeneration, load levelling, diurnal thermal storage, advanced management (9.4.1.1). "Smart-grids" (9.4.1.2). Utilisation of waste heat (9.4.1.1)	Behavioural change (BC). Lifestyle change (LSC). Smart metering (9.4.1.2)
Potential reductions of identity (versus baseline BAU)	Solar electricity generation through buildings' roof-top PV installations: energy savings -15 to -58% of BAU (Table 9.4)	-9.5% to -68% energy savings of BAU (Table 9.4). Energy savings from advanced appliances: Ovens -45%, microwave ovens -75%, Dishwashers – up to 45%, Clothes washers – 28% (by 2030 globally), Clothes Dryers – factor of 2 reduction, air-conditioners -50-75%, Ceiling fans -50-57%, Office computers and monitors – 40%, Circulation pumps for hydronic heating and cooling – 40% (by 2020, EU), Residential water heaters – factor of 4 improvement (Table 9.3). Also, -30 to -60% in fuel savings, -80 to 90% in indoor air pollution levels from advanced biomass stoves as compared to open fires (9.3.8)	- 30 to -70% CO_2 of BAU. PHS & NZEB/new versus conventional building: - 83% (residential heating energy) and -50% (commercial heating&cooling energy). Deep retrofits – DRs (residential, Europe): - 40 to -80%. IDP up to - 70% final energy by 2050 (Table 9.4);. Potential global building final energy demand reduction: IAMs -5 to -27%; bottom up models: -14 to -75% (Fig. 9.21). Energy savings by building type: (i) detached single-family homes, total energy use - 50-75%; (ii) multi-family housing, space heating requirements - 80-90%, (iii) multi-family housing in developing countries, cooling energy use – 30%, heating energy – 60%; (iv) commercial buildings, total HVAC - 25-50%; (v) lighting retrofits of commercial buildings - 30-60% (9.3.4.1)	- 20 to -40% of BAU. LSC ~ - 40% electricity use (Table 9.4).
Cost-effectiveness	-	Retrofit of separate measures: CCE: 0.01-0.10 $/kWh (Fig. 9.13) …. Efficient Appliances: CCE: -0.07 €/kWh/yr (9.3.4.2)	PHS&NZEB/new (EU&US), CCE: 0.7-0.2 $/kWh (Figure 9.11, 9.12). DR with energy savings of 60-75%: CCE of 0.05-0.25 $/kWh (Fig. 9.13)	
Co-benefits, co-risks, co-costs	CB: Energy security; lower need for energy subsidies; health and environmental benefits			
	CB: Employment impact; enhanced asset value of buildings; energy/fuel poverty alleviation. CR: Energy access/fuel poverty	CB: Employment; energy/fuel poverty alleviation; improved productivity/competitiveness; asset value of buildings; improved quality of life. CR: rebound and lock-in effects	CB: Employment impact; improved productivity and competitiveness; enhanced asset values of buildings; improved quality of life. CR: Rebound effect, lower life-cycle energy use of low-energy buildings in comparison to the conventional ones (9.3.9)	
Key barriers	Suboptimal measures, subsidies to conventional fuels	Transaction costs, access to financing, principal agent problems, fragmented market and institutional structures, poor feedback	Energy and infrastructure lock-in (9.4.2), path-dependency (9.4.2) 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	C tax, feed-in tariffs extended for small capacity; soft loans for renewable technologies	public procurement, appliance standards, tax exemptions, soft loans	Building codes, preferential loans, subsidised financing schemes, ESCOs, EPCs, suppliers' obligations, white certificates, IDP into Urban Planning, Importance of policy packages rather than single instruments (9.10.1.2)	Awareness raising, education, energy audits, energy labelling, building certificates & ratings, energy or carbon tax, personal carbon allowance

9.1 Introduction

The purpose of this chapter is to update the knowledge on the sector since AR4 from a mitigation perspective. Buildings and activities in buildings are responsible for a significant share of GHG emissions, but these are also the key to mitigation strategies. In 2010, the building sector accounted for approximately 125 EJ or 34% 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 (based on HFC inventories, 82%of totals in the US and 84% in the EU-27) around 45% of F-gas emissions. The chapter argues that beyond a large emission role, mitigation opportunities in this sector are also significant, often very cost-effective, and are many times 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 - may even double by mid-century - due to several drivers. The chapter points out that certain policies have proven to be very effective and several new ones are emerging. As a result, building energy use trends have been reversed to stagnation or even reduction in some jurisdictions in recent years, despite the increases in affluence and population.

The chapter uses a novel conceptual framework, in line with the general analytical framework of WGIII 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 use 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 identities key to driving building sector emissions:

$$CO_2 emissions = CI \times TEI \times SEI \times A$$

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

$$CO_2 = \frac{CO_2}{FE} \times \frac{FE}{UsefulE} \times \frac{UsefulE}{ES} \times \frac{ES}{pop} \times pop \approx CI \times TEI \times SEI \times \frac{A}{pop} \times pop$$

in which *FE* is the final energy; *UsefulE* is the useful energy for a particular energy service (ES), as occurring in the energy conversion chain, and *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 measure, 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 relationship established in the previous equation:

$$\mathrm{CO_2 mitigation} \approx \mathrm{CEff} \times \mathrm{TEff} \times \mathrm{SIEff} \times \mathrm{DR}$$

whereby (i) CEfF, or carbon efficiency, entails fuel switch to low-carbon fuels, building-integrated renewable energy sources and other supply-side decarbonisation; (ii) TEff, or technological efficiency, focuses on the efficiency improvement of individual energy-using devices; (iii) SIEff, or 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) DR, or demand reduction, composes of all measures that are beyond technological efficiency and decarbonisation measures, such as impacts on floor space, service levels, behaviour, lifestyle, use and penetration of different appliances. The four main emission drivers and mitigation strategies can be further decomposed into 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 as the main organising/conceptual framework.

9.2 New developments in emission trends and drivers

9.2.1 Energy and GHG emissions from buildings

Greenhouse gas (GHG) emissions from the building sector have more than doubled since 1970 to reach 9.26 $GtCO_{2\text{-}e}e$ in 2010 (Figure 9.1.), representing 25% of total emissions without the AFOLU sector; and 19% of all global 2010 GHG emissions (IEA, 2012a; JRC/PBL, 2012; see Annex II.8). Furthermore, they account for at least 45% of total global fluorinated gas emissions (UNEP, 2011a; EEA, 2013; US EPA, 2013) and approximately 2/3rd of black carbon emissions (GEA, 2012).

Most of GHG emissions (6.10Gt) are indirect CO_2 emissions from electricity use in buildings, and these have shown dynamic growth in the studied period in contrast to direct emissions that have roughly stagnated during these four decades (Figure 9.1). For instance, residential indirect emissions doubled and commercial ones quadrupled.

Figure 9.2. shows the regional trends in building-related CO_2 emissions. OECD countries have the highest emissions, but the growth in this region between 1970 and 2010 was moderate. For less developed countries, the emissions are low with little growth. The largest growth has taken place in Asia where emissions in 1970 were similar to those in other developing regions but by today they are closing in on those of OECD countries.

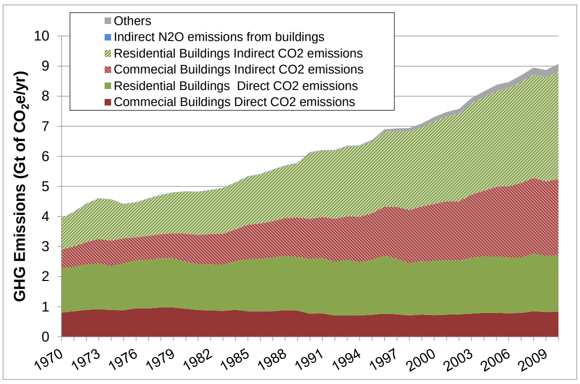

Figure 9.1. Direct and indirect emissions in the building subsectors (IEA, 2012a; JRC/PBL, 2012; see Annex II.8).

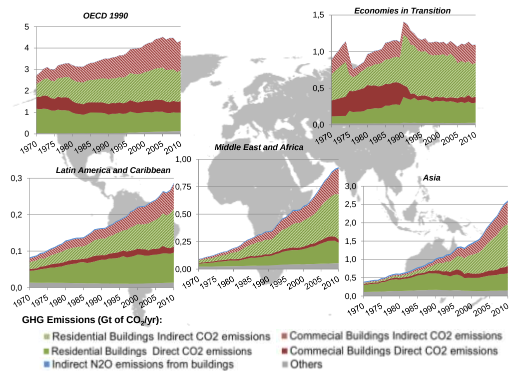

Figure 9.2. Regional direct and indirect emissions in the building subsectors (IEA, 2012a; JRC/PBL, 2012; see Annex II.8).

Due to the high share of indirect emissions in the sector, actual emission values very strongly depend on emission factors - mainly that of electricity production - that are beyond the scope of this chapter. Therefore the rest of this chapter focuses on final energy use (rather than emissions) that is determined largely by activities and measures within the sector.

In 2010 buildings accounted for 34% (25% for residential and 9% for commercial) of total global final energy use(IEA, 2013) , or 32.72 PWh, being one of the largest end-use sectors worldwide. Space heating represented 32-34% of the global final energy consumption in both the residential and the commercial building sub-sectors in 2010 (Figure 9.4). Moreover, in the commercial sub-sector, lighting was very important, while cooking and water heating were significant end-uses in residential buildings. In contrast to the very dynamically growing total emissions, per capita final energy use did not grow substantially over the two decades between 1990 and 2010 in most word regions (see Figure 9.3). This value stagnated in most regions during the period, except for a slight increase in FSU and a dynamic growth in MEA. Commercial energy use has also grown only moderately in most regions on a per capita basis, with more dynamic growth shown in CPA, SAS and MEA. This indicates that most trends to drive building energy use up have been compensated by efficiency gains. In many developing regions this can largely be due to switching from traditional biomass to modern energy carriers that can be utilised much more efficiently.

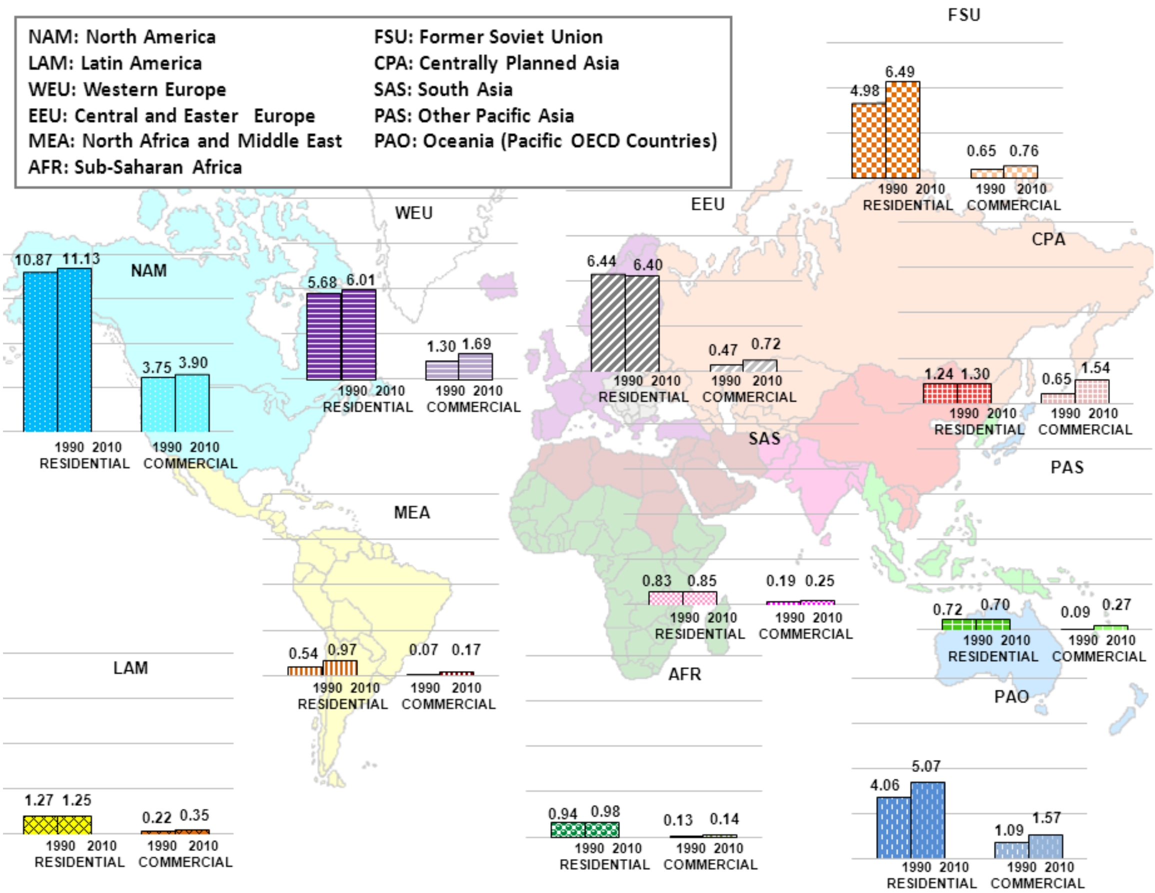

Figure 9.3. Buildings per capita final energy use by sub-sector and region [MWh/per capita/year] in 1990 and 2010.Data from (IEA, 2013) .

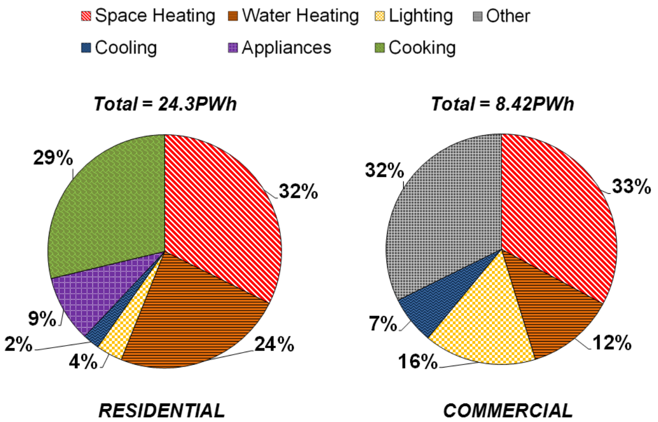

Figure 9.4. World building final energy consumption by end-use in 2010. Source: (IEA, 2013).

As shown in Section 9.9 , global building energy use may double to triple by mid-century due to several key trends. An estimated 0.8 billion people lack access to adequate housing (UN-Habitat, 2010) while 1.4 billion people lacked access to electricity in 2010 and about 3 billion people worldwide relied on highly-polluting and unhealthy traditional solid fuels for household cooking and heating (Pachauri et al., 2012; IEA, 2013). The ways these energy services will be provided will significantly influence the development of building related emissions. In addition, migration to cities, decreasing household size, increasing levels of wealth and lifestyle changes, including an increase in personal living space, the types and number of appliances and equipment and their use - these all contribute to significant increases in building energy use. Rapid economic development accompanied by urbanization and shifting from informal to formal housing is propelling significant building activity in developing countries (WBCSD, 2007) As a result, this substantial new construction taking place in these dynamically growing regions represents both a significant risk and opportunity from a mitigation perspective.

Box 9.1: Least Developed Countries (LDCs) in the context of the developing world

878 million people with an average 2 USD per day of gross national income (The World Bank, 2013) live in the Least Developed Countries (LDCs) group. Rapid economic development, accompanied by urbanization, is propelling large building activity in developing countries (WBCSD, 2007, 2009; ABC, 2008; Li and Colombier, 2009; see also Chapter 12.3). The fast growing rates of new constructions occurring in emerging economies is not being witnessed in LDCs. This group of countries is still at the fringe of modern development processes and has special needs in terms of access to housing, modern energy carriers, efficient and clean-burning cooking devices (Zhang and Smith, 2007; Duflo et al., 2008; Wilkinson et al., 2009; World Health Organization, 2009, 2011; Hailu, 2012; Pachauri, 2012). 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 needs to 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). Principles of low-energy design often provide comfortable conditions much of the time, thereby reducing the pressure to 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 active energy systems.

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; reduced pressures to expand energy generation capacities in developing regions; productivity, competitiveness and net employment gains; increased social welfare, reduced energy and fuel poverty, decreased need for energy subsidies and exposure to energy price volatility risks, improved comfort and services, and improved adaptability to adverse climate events (Table 9.7; Clinch and Healy, 2001; Tirado Herrero and Ürge-Vorsatz, 2012).

9.2.2 Trends and drivers of thermal energy uses in buildings

Figure 9.5 shows trends and projections of thermal energy uses in commercial and residential buildings in the regions of the world from 1980 to 2050 (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 (2010-2050).Commercial buildings represent between 10 to 30% of total building sector thermal energy consumption in most regions of the world, except for China, where heating and cooling energy consumption in commercial buildings is expected to overtake that of residential buildings. Drivers to these trends and their developments are discussed separately for heating/cooling and other building energy services because of conceptually different drivers.
Heating and cooling energy use in residential buildings can be decomposed by the following key identities, from (Ürge-Vorsatz et al., 2013a):

energyresid = h * [p/h] * [area/p] * [energy/area]

where [h] and [p/h] are the activity drivers, with (h) being the number of households and the (p/h) number of persons (p) living in each household, respectively. [area/p] is the use intensity driver, with 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

energycomd = 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 m2), also referred to as specific energy consumption. The following figures illustrate the main trends in heating and cooling energy use as well as its drivers globally and by region.

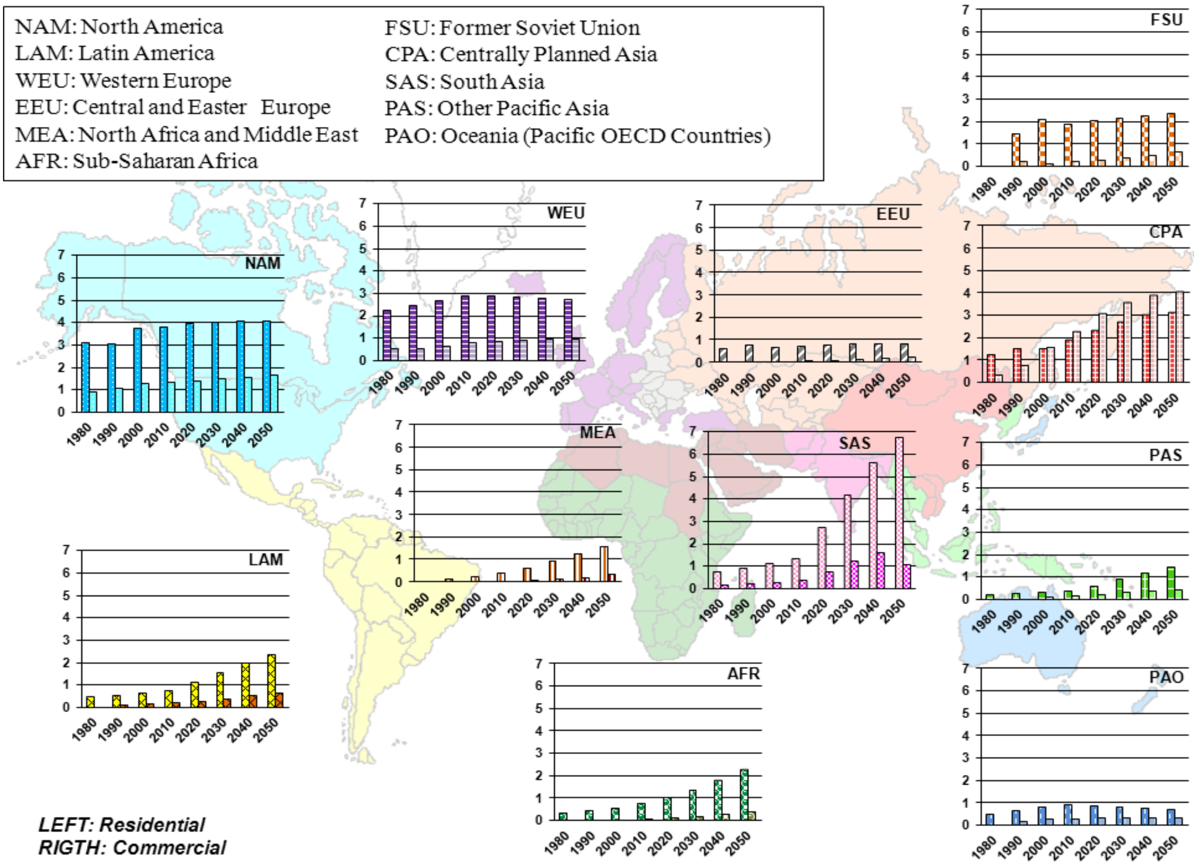

Figure 9.5. Total final thermal energy consumption [PWh] trends (y-axis) in the different regions of the world for residential and commercial buildings. Historical data (1980-2000) are from IEA statistics; projections (2010-2050) are based on a frozen efficiency scenario (Ürge-Vorsatz et al., 2013b).

Heating and cooling energy use grew by 39% and 61% in residential and commercial buildings, respectively, over the period 1980-2010, and is expected to grow by 79% and 83%, respectively, over the period 2010-2050 (Figure 9.6) 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 specific energy consumption tend to decrease energy consumption. In commercial buildings, the projected decrease area/GDP is of 57%, 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 9.6) and in different world regions (Figure 9.7). More detail information about each driver trend can be found in (Ürge-Vorsatz et al., 2013a).These figures indicate that in some regions(e.g. NAM and WEU), strong energy building policies are already resulting in declining or stagnating energy use trends despite the increase in population and service levels.

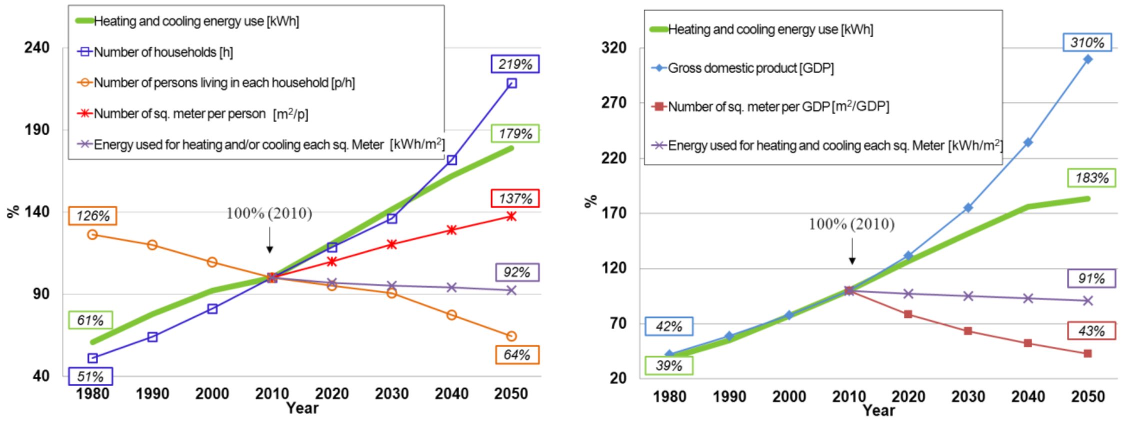

Figure 9.6. Trends of the different drivers for final thermal energy consumption in residential and commercial buildings in the world. Further details in: historic data 1980-2000 detailed in from (Ürge-Vorsatz et al., 2013a); projections: 2010-2050 data based on frozen efficiency scenario in (Ürge-Vorsatz et al., 2013b).

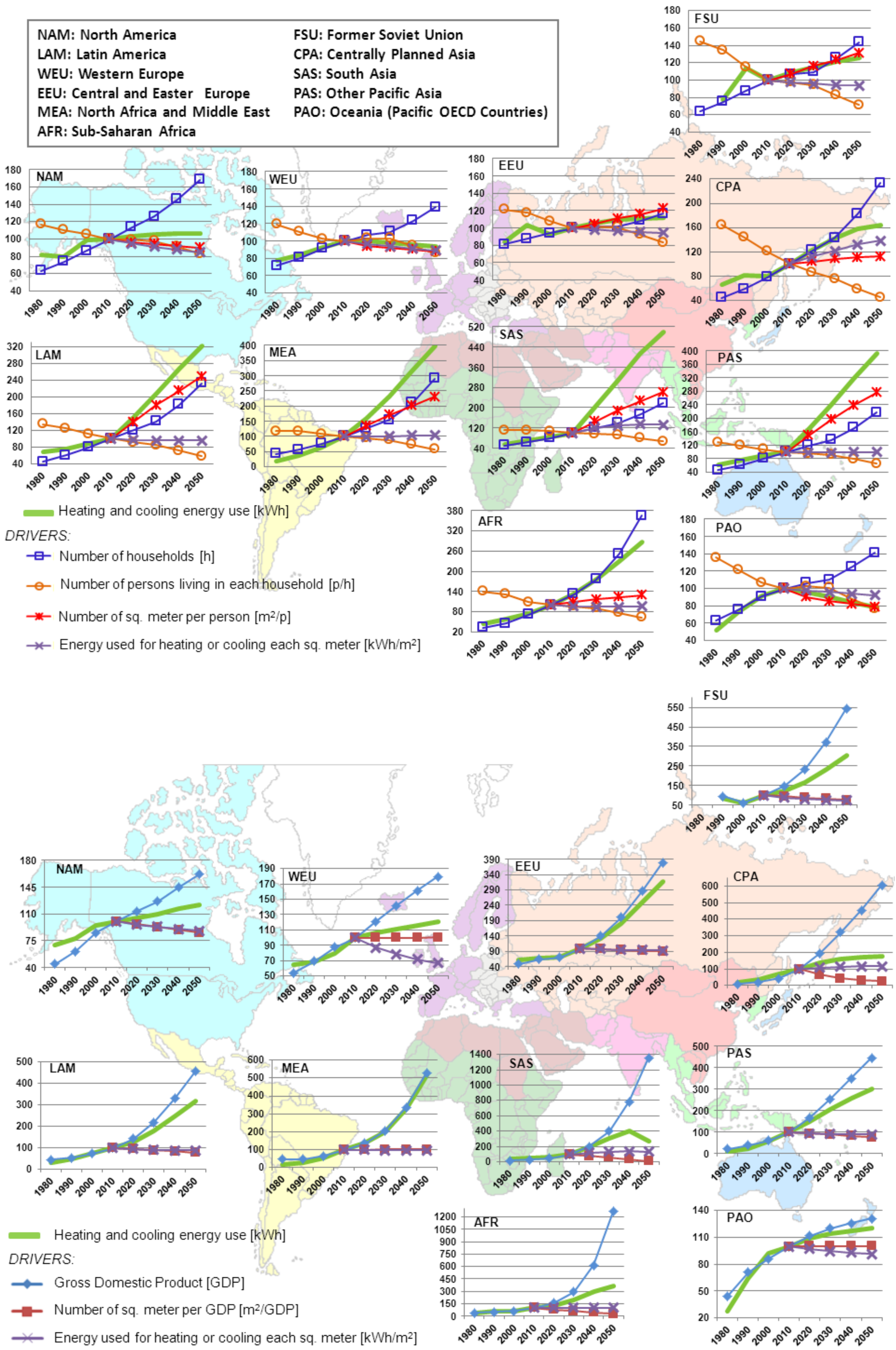

Figure 9.7. Trends of the drivers of final thermal energy consumption of residential (top) and commercial (bottom) buildings in world regions - historic data (1980-2000) from (Ürge-Vorsatz et al., 2013a) and projections (2010-2050) based on a frozen efficiency scenario (Ürge-Vorsatz et al., 2013b).

9.2.3 Trends and drivers in energy consumption of appliancesin buildings

In this chapter, we use the word "appliances" in a broader sense, covering all electricity-using non-thermal equipment in buildings, including lighting and ICT. Traditional large appliances, such as cool appliances and washing machines, are still responsible for most household electricity consumption (ETP, 2012) albeit with a falling share related to the equipments for information and communications (including home entertainment) accounting in most countries for 20%+ of residential electricity consumption (Harvey, 2008). This rapid growth offers opportunities to roll out more efficient technologies, but this effect to date has been outcompeted by the increased uptake of devices and new devices coming to the market. ***Energy use of appliances*** can be decomposed as shown in the following equation from (Cabeza et al., 2013a): $\{[energy] = [\Sigma_a\,[h] * [n/h] * [energy/n]\}$ where Σ_a is the sum overall appliances; [h] is the activity driver, the number of households; [n/h] is the use intensity driver, i.e. the number of appliances of appliance type "a" per household; and [energy] is the energy intensity driver (kWh/y used per appliance). The number of appliances grew all over the world. Figure 9.8 shows that the energy consumption of major appliances in non-OECD countries is already nearly equal to consumption in the OECD, due to their large populations and widespread adoption of the main white appliances and lighting. Also, while fans are a minor end-use in most OECD countries, they continue to be extremely important in the warm developing countries.

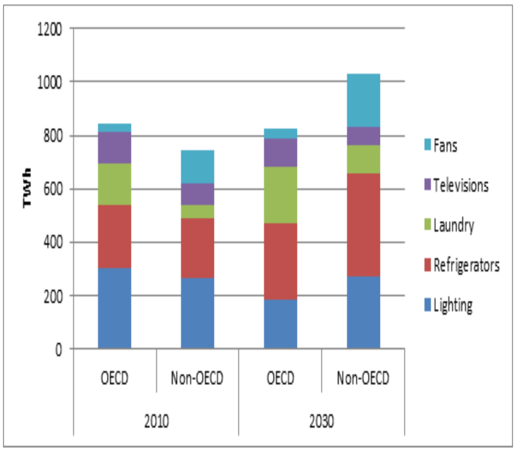

Figure 9.8. BUENAS modelled residential electricity consumption by end-use in a policy scenario. Source: (Cabeza et al., 2013a).

9.3 Mitigation technology options and practices, behavioral 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 (50%-90% in new buildings, 50%-75% in existing buildings). Table 9.2 summarizes the energy savings and CO_2 emission reduction potential according to the factors introduced in Section 9.1 , based on material presented in this section or in references given. A synthesis of documented examples of large reductions in 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, and Section 9.6 presents a synthesis of studies of the costs, their trends, and with integrated potential calculations at the national, regional, and global levels.

Table 9.2. Savings or off-site energy use reductions achievable in buildings for various end uses, due to on-site active solar energy systems, efficiency improvements or behavioral changes.

End Use	On-site C-Free Energy Supply[1]	Device Efficiency	System Efficiency	Behavioral Change
Heating	20%-95% [2]	30%[3] - 80%[4]	90%[5]	10%-30%[6]
Hot water	50%-100% [7]	60%[8]- 75%[9]	40%[10]	50%[11]
Cooling	50%-80% [12]	50%[13]-75%[14]	67%[15]	50%-67%[16]
Cooking	0-30% [17]	25-75%[18]-80%[19]		50%[20]
Lighting	10-30%	75%[21]; 83%-90%[22]; 99.83%[23]	80%-93%[24]	70%[25]
Refrigerators		40% [25a]		30%[26]; 50%[27]
Dishwashers		17+%[27a]		75%[28]
Clothes washers		30%[28a]		60%-85%[29]
Clothes dryers		50+%[29a]		10%-15%[30]-100%[31]
Office computers & monitors		40%[31a]		
General electrical loads	10%-120%[32]			

Notes [()]Only active solar energy systems. Higher percentage contributions achievable if loads are first reduced through application of device, system and behavioural efficiencies. Passive solar heating, cooling, ventilation and daylighting are considered under Systemic Efficiency.[2] Space heating. Lower value representative of combi-systems in Europe; upper value is best solar district heating systems with seasonal underground thermal energy storage, after a 5-year spinup (Sibbit et al., 2012; SAIC, 2013). [3] Replacement of 75% efficient furnace/boiler with 95% efficient unit (e.g. condensing natural gas boilers).[4] Replacement of 80% efficient furnace or boiler with ground-source heat pump with a seasonal COP for space heating of 4 (from ground-source heat pumps in well-insulated new buildings in Germany (DEE, 2011).[5] Reduction from a representative cold-climate heating energy intensity of 150 kWh/m^{2}yr to 15 kWh/m^{2}yr (Passive House standard, Section 9.3.2).[6] Typical value; 2ºC cooler thermostat setting at heating season. Absolute savings is smaller but relative savings is larger the better the thermal envelope of the building (see also Section 9.3.9).[7] Water heaters. 50-80% of residential hot water needs supplied in Sydney, Australia and Germany ((Harvey, 2007), while upper limit of 100% is conceivable in hot desert regions. [8] Replacement of a 60% efficient with a 95% efficient water heater (typical of condensing and modulating wall-hung natural gas heaters).[9] Table 9.4.[0] Elimination of standby and distribution heat losses in residential buildings (typically accounting for 30% water-heating energy use in North America ((Harvey, 2007) through use of point-of-use on- demand water heaters.[1] Shorter showers, switch from bathing to showering, and other hot-water-conserving behavior.[2] Air conditioning and dehumidification. Range for systems from central to Southern Europe with a relatively large solar collector area in relation to the cooling load ((Harvey, 2007). [3] Replacement of air conditioners having a COP of 3 (typical in North America) with others with a COP of 6 (Japanese units); Table 9.4.[4] Replacement of North American units with units incorporating all potential efficiency improvements; Table 9.4. [5] Reduction (even elimination) of cooling loads through better building orientation & envelopes, provision for passive cooling, and reduction of internal heat gains (Harvey, 2007).[6]Section 9.3.9. Fans during tolerable brief periods eliminating cooling equipments in moderately hot climates.[7] Cooking range, various ovens.[8] Range pertains to various kinds of ovens; Table 9.4.[9 Replacement of 10%-15% with 60% efficient (traditional biomass) cookstoves (Rawat et al., 2010).[20] Same recipe with different cooking practices; Table 9.4 / Section 9.3.9.[2] Replacement of 10-17 lm/W incandescent lamps with 50-70 lm/W compact fluorescent (Harvey, 2010).[22] Replacement of 15 lm/W incandescent lamps with (year 2030) LEDs, 100-160 lm/W (McNeil et al., 2006; US DOE, 2006). [23] Replacement of 0.25 lm/W kerosene lamps ((Fouquet and Pearson, 2006) with future 150 lm/W LEDs.[24] Reduction from average US office lighting energy intensity of the existing stock of 73 kWh/m^{2}yr (Harvey, 2013) to 5-15 kWh/m^{2}yr state-of-art systems (Harvey, 2013).[25] Turning off not needed lights (6000 hours/yr out of 8760 hours/yr).[25a]Table 9.4 [26]12.5 ft^{3}vs 18.5 ft^3 (350 litres, 350 kWh/yrvs 520 litres,500 kWh/yr) refrigerator-freezers or 18.5 vs 30.5 ft^3 (860 litres, 700 kWh/yr) (Harvey, 2010). [27]Elimination of a second ("beer") fridge. [27a] Table 9.4 [28]Fully loaded operation versus typical part-load operation (Table 9.4). [28a] by 2030 (Table 9.4). [29] Cold compared to hot water washing, based on relative contribution of water heating to total clothes washer energy use for the best US&EU models (Harvey, 2010).[29a] Table 9.4.[30]Operation at full load rather than at 1/3 to 1/2 load (Smith, 1997).[31]Air drying inside when there is no space heating requirement, or outside. [31a] Table 9.4. [32]Fraction of on-site electricity demand typically generated by on-site PV with low demand kept low through electricity-efficiency measures.

9.3.1 Key points from AR4

AR4 (Levine et al., 2007) contains an extensive discussion of the wide range of techniquesl and designs to reduce energy use in new buildings. A systemic approach is more relevant to energy use than individual devices efficiencies of the individual devices (pumps, motors, fans, heaters, chillers, and so on) efficiencies, as are relatednet investment-cost savings – usually several times higher. (Levine et al., 2007; Harvey, 2008). Integrated Design Process (IDP) allows for the systemic approach, optimizing building performance iteratively, involving from the start all design team members (Montanya et al., 2009; Pope and Tardiff, 2011). However, the conventional process of designing and constructing a building and its systems is largely linear, in which, design elements and system components are specified, built and installed without consideration of optimisation opportunities in the following design and building phases, thus losing key opportunities for the optimisation of whole buildings as systems (Lewis, 2004). As discussed in AR4, essential steps in the design of low-energy buildings are: (i) building orientation, thermal mass and shape; (ii) high-performance envelope specification; (iii) maximization of passive features (day-lighting, heating, cooling, ventilation)d; (iv) efficient systems meeting remaining loads; (v) highest possible efficiencies and adequate sizing of individual energy-using devices; and (vi) proper commissioning of systems and devices . Cost savings can substantially offset additional high-performance envelope and higher-efficiency equipment costs, on around 35-50% compared to standard practices of new commercial buildings (or 50-80% with more advanced approaches) Retrofits can routinely achieve 25-70% savings in total energy use (Levine et al., 2007; Harvey, 2009).

9.3.2 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 and electric lighting (Dubois and Blomsterberg, 2011); (ii) household appliances (Bansal et al., 2011); (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 (NBI, 2011); and (viii) smart meters and grids as a means of reducing peak demand and accommodating intermittent renewable electricity sources (Catania, 2012). Many of these measures can, individually, reduce the relevant specific energy use by half or more. 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 a progressive strengthening of the energy provisions of the building codes in many countries, as well as plans for significant further tightening of these in the near future (see also Section 9.10). In the following sections we review the literature published largely since AR4 concerning the energy intensity 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 increase 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 increase with population or the size of the workforce.

9.3.3.1 Energy intensity of new high-performance buildings

Table 9.3 summarizes the specific energy consumption for floor-area driven final energy uses by climate type or region.

Table 9.3. Typical and current best case specific energy consumption (kWh/m^{2}yr) for building loads directly related to floor area (Harvey, 2013).

End Use	Climate Region	Residential		Commercial	
		Advanced	Typical	Advanced	Typical
Heating	Cold	15-30	60-200	15-30	75-250
Heating	Moderate	10-20	40-100	10-30	40-100
Cooling	Moderate	0-5	0-10	0-15	20-40
Cooling	Hot-dry	0-10	10-20	0-10	20-50
Cooling	Hot-humid	3-15	10-30	15-30	50-150
Ventilation	All	4-8	0-8	0-20	10-50
Lighting	All	2-4	3-10	5-20	30-80

Notes: 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. Definitions here for climate regions for heating: Cold_> 3000 HDD; Moderate 1000-3000 HDD. Similarly for cooling: moderate < 750 CDD; hot-dry > 750 CDD; hot-humid > 750 CDD. HDD=heating degree days (K-day) and CCD=cooling-degree days (K-day). Energy intensity ranges for commercial buildings exclude hospitals and research laboratories

For ***residential buildings***, a number of voluntary standards for heating energy use have been developed in various countries (see Table 1 in Harvey, 2013). The most stringent of these with regard to heating requirements is the Passive House standard which prescribes a heating load (assuming a uniform indoor temperature of 20ºC) of no more than 15 kWh/m^{2}yr irrespective of the climate. It typically entails a high-performance thermal envelope combined with mechanical ventilation with heat recovery to ensure high indoor air quality. Approximately 57,000 buildings complied with this standard in 31 European countries in 2012, covering 25.15 million square metres (Feist, 2012) with examples as far north as Helsinki, with significantly more that meet or exceed the standard but have not been certified due to the higher cost of certification. As seen from Table 9.3, 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. Where buildings are not currently heated to comfortable temperatures, adoption of a high-performance envelope can aid in achieving comfortable conditions while still reducing heating energy use in absolute terms. Cooling energy use is growing rapidly in many regions where, with proper attention to useful components of vernacular design combined with modern 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) or which are dry, thereby permitting evaporative cooling or hybrid evaporative/mechanical cooling strategies to be implemented. Combining insulation levels that meet the Passive House standard for heat demand in Southern Europe with the above strategies, heating loads can be reduced by a factor of 6-12 (from 100-200 kWh/m^2/yr to 10-15 kWh/m^2/yr) and cooling loads by a factor of 10 (from < 30 kWh/m^2/yr to < 3 kWh/m^2/yr) (Schneiders et al., 2009). With good design, comfortable conditions can be maintained ≥80% 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),Vietnam (Nguyen et al., 2011a), Brazil (Grigoletti et al., 2008; Andreasi et al., 2010; Candido et al., 2011), and the tropics (Lenoir et al., 2011).

In ***commercial buildings***, specific energy consumption of modern office and retail buildings are typically 200-500 kWh/m^2/yr including all end-uses, whereas advanced buildings have frequently achieved less than 100 kWh/m^2/yr in climates ranging from cold 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). Dehumidification energy use is 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, luminaires) typically achieve a factor of two reduction in energy intensity compared to typical new systems (Dubois and Blomsterberg, 2011).

9.3.3.2 Monitoring and commissioning of new and existing buildings

Commissioning is the process of systematically checking that all components of building HVAC (Heating, Ventilation and Air Conditioning) and lighting systems have been installed properly and operate correctly. It often identifies problems that, unless corrected, increase energy use by 20% or more, but is often not done (Piette et al., 2001).. Advanced building control systems are a key to obtaining very low energy intensities in commercial buildings. It routinely takes over one year or more to adjust the control systems so that they deliver the expected savings(Jacobson et al., 2009) through detailed monitoring of energy use once the building is occupied. Wagner et al., (2007) give an example where monitoring of a naturally ventilated and passively cooled bank building in Frankfurt, Germany, lead to a reduction in primary energy intensity from about 200 kWh/m2yr during the first year of operation to 150 kWh/m2yr during the third year (with a predicted improvement to 110 kWh/m2yr during the fourth year). Post-construction evaluation also provides opportunities for improving the design and construction of subsequent buildings (Wingfield et al., 2011).

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 have varying definitions around the world, but these typically refer to 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 constructed worldwide, both commercial and residential. There have also been some NZE retrofits of existing buildings. Several 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) (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, (v) life-cycle energy use, (vi) impact on energy use of alternative uses or treatments of roofs. 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 NZEB will place a limit on the achievable height and therefore on urban density. In Abu Dhabi, NZEB is possible in office buildings of up to 5 stories if internal heat gains and lighting and HVAC loads are aggressively reduced (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.

9.3.3.4 Incremental cost of low-energy buildings

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, with Table 9.4 presenting a small selection of these to illustrate some messages of this section. In the ***residential sector***, several studies indicate an incremental cost of achieving the Passive House standard in the range of 6-16% of the construction cost (about EUR 50-200 /m^2) as compared to standard construction. 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 USD 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 GBP 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 are several 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 and large-scale implementation 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 and emissions 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), see also Table 9.4. 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 energy savings measures.

Table 9.4: 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€/m²)	-	(Bretzke, 2005; Schnieders and Hermelink, 2006)
5 passive houses	Belgium	New	62 kWh/m²/yr total	16% (187€/m²	-	(Audenaert et al., 2008)
Passive House apartment block	Vienna	New	Passive house standard	5% (52€/m²)	-	(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 SolarBauprogramme	Germany	New	< 100 kWh/m²/yrprimary 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/m²/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 m² office building	Las Vegas	New	42% of energy savings	$12,700	-	(Vaidya et al., 2009)
10-story, 7,000 m² residential building	Denmark	New	14 kWh/m²/yr (heating) vs. 45	3.4% (86 €/ m²)	-	(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 m² residential building	Denmark	New	NZEB	24% (418€/m²)	-	(Marszal and Heiselberg, 2009)
Toronto towers	Toronto	Retrofit	194 / 95%	$ 257/m²	0.052 $/kWh	(Kesik and Saleff, 2009)
Multi-family housing	EU	Retrofit	62-150 / 52-86%	37-87 €/m²	0.01-0.016 €/kWh	(Petersdorff et al., 2005)
Terrace housing	EU	Retrofit	97-266/ 59-84%	63-145 €/m²	0.09-0.016 €/kWh	(Petersdorff et al., 2005)
High-rise housing	EU	Retrofit	/ 70-81%	1.8-4.1 €/m²/yr	0.013-0.020 €/kWh	(Waide et al., 2006)
1950s MFH	Germany	Retrofit	82-247/ 30-90	36-314 €/m²	0.017-0.049 €/kWh	(Galvin, 2010)
1925 SFH	Denmark	Retrofit	120/	166 €/m²	0.054 €/kWh	(Kragh and Rose, 2011)
1929 MFH	Germany	Retrofit	140-200/ 58-82%	125-255 €/m²	0.045-0.066 €/kWh	(Hermelink, 2009)
19th century flat	UK	Retrofit	192-234/ 48-59%	192-480 £/m²	0.043-0.088 £/kWh	(United House, 2009)

9.3.4 Retrofits of existing buildings

As buildings are very long-lived and a large fraction of the total building stock existing today will still exist in 2050 in developed countries, retrofitting the existing stock is key to a low-emission building sector.

9.3.4.1 Energy savings

Numerous case studies of individual retrofit projects (in which measures, savings and costs are documented) are reviewed 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%,; (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 (for a small selection of these see Table 9.4). 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 across the US and reports a 16% median whole-building energy savings in California, with a mean payback time of 1.1 years. (Rødsjø et al., 2010) showed that among the 60 demonstration projects reviewed, the average primary energy demand savings was 76%, and 13 of the projects reached or almost reached the Passive House standard. 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 and 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 (appliance upgrades) and +0.34 Euro/kWh (façade retrofit). (Polly et al., 2011) present a method for determining optimal residential energy efficiency retrofit packages in the US, and identify near-cost-neutral packages of measures providing between 29% and 48% energy savings across 8 US locations. (Lewis, 2004) has compiled information from several studies in old buildings in Europe and 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/m^2yr.

Table 9.5: 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) was426 kWh/yr in 2008 and 102 kWh/yr in 2012. Further reductions (30-50% below LCD TVs) are expected with use of organic LEDbacklighting (likely commercially available by 2015)	(Howard et al., 2012; Letschert et al., 2012)
Televisions	Energy savings of best available TVs compared to market norms are 32-45% in Europe, 44-58% in North America, and 55-60% in Australia	(Park, 2013)
Computer monitors	70% reduction in on-mode power draw expected from 2011 to 2015	(Park et al., 2013)
Computing	At least a factor of 10 million potential reduction in the energy required per computation (going well beyond the so-called Feynman limit).	(Koomey et al., 2013)
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., 2011; McNeil and Bojda, 2012)
Cooking	50% savings potential (in Europe), largely through more efficient cooking practices alone	(Fechter and Porter, 1979; Oberascher et al., 2011)
Ovens	25% and 45% potential savings through advanced technology in natural gas and conventional electric ovens, respectively, and 75% for microwave ovens	(Mugdal, 2011; Bansal et al., 2011)
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., 2011)
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/yrvs 380 kWh/yr)	(Werle et al., 2011)
Standby loads	Potential of < 0.005 W for adapters and chargers,< 0.05 for large appliances ("zero" in both cases) (typical mid 2000s standby power draw: 5-15 W)	(Matthews, 2011), (Harvey, 2010) 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)
Air conditioners	COP of 4.2-6.8 for air conditioners such that the cost of saving electricity does not exceed the local cost of electricity, and a potential COP of 7.3-10.2 if all available energy-saving measures were to be implemented (implies a 50-75% savings for a given cooling load and operating pattern).	Shah et al. (2013)
Ceiling fans	50-57% energy savings potential	(Sathaye et al., 2010; Letschert et al., 2012)
Package of household appliances in Portugal	60% less energy consumption by best available equipment compared to typically-used equipment	(da Graca et al., 2012)
Office computers and monitors	40% savings from existing low-to-zero cost measures only	(Mercier and Morrefield, 2009)
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-using fixtures	50-80% reduction in water use by water-saving fixtures compared to older standard fixtures	(Harvey, 2010)
Residential water heaters	Typical efficiency factor (EF) for gas and electric water heaters in US is 0.67 and 0.8 in EU, while the most efficient heat-pump water heaters have EF=2.35 and an EF of 3.0 is foreseeable (factor of 4 improvement)	(Letschert et al., 2012)

9.3.5 Appliances, consumer electronics, office equipment and lighting

Residential appliances have dramatically improved in efficiency over time, particularly in OECD countries (Barthel and Götz, 2013; Nicola and Paolo, 2013) due to polices (efficiency standards, labels and subsides) and technological progress. Improvements are also appearing in developing (e.g. China, Barthel and Götz, 2013) and less developed countries (e.g. Ghana) (Antwi-Agyei, 2013). Cold appliances consume 650 TWh worldwide, which is almost 14% of total residential electricity consumption (Barthel and Götz, 2013).

Table 9.5 summarizes potential reductions in unit energy by household appliances and equipment through improved technologies. Identified savings potentials for individual equipment are typically 40-50%. Indeed, energy use by the most efficient appliances available today is often 30-50% less than required by standards; the European A+++ model refrigerator, for example, consumes 50 % less electricity than the current regulated level in the EU (Letschert, Can, et al., 2013), while the most efficient TVs awarded under the "Super-efficient Equipment and Appliance Deployment (SEAD" initiative use 33-44% less electricity than otherwise similar TVs (Ravi et al., 2013). Aggregate energy consumption by these items is expected to continue to grow rapidly as the types and number of equipment proliferate and ownership rates increase with increasing wealth, unless standards are used to induce close to the maximum technically achievable reduction in unit energy requirements. Despite projected large increase in the stock of domestic appliances, especially in developing countries, total appliance energy consumption could be reduced if the best available technology were installed (Barthel and Götz, 2013; Letschert, Desroches, et al., 2013). This could yield energy savings of 2600 TWh/yr by 2030 between the EU, US, China and India (Letschert, Can, et al., 2013). Ultra-low-power micro-computers in a wide variety of appliances and electronic equipment also have the potential to greatly reduce energy use through better control (Koomey et al., 2013). Conversely, new types of electronic equipment for ICT (e.g. satellite receivers, broadband home gateways, etc.), broadband and network equipment ,and dedicated data centre buildings are predicted to increase their energy consumption (Fettweis and Zimmermann, 2008; Bolla et al., 2011; Bertoldi, 2012).Solid State Lighting (SSL) is revolutionizing the field of lighting. In the long term, inorganic light emitting diodes (LEDs) are expected to become the most widely used light sources. White LEDs have shown a steady growth in efficacy for more than fifteen years, with average values of 65-70 lm/W (Schäppi and Bogner, 2013) and the best products achieving 100 lm/W(Moura et al., 2013). LED lighting will soon reach efficacy level above all the other commercially available light source (Aman et al., 2013), including high efficiency fluorescent lamps.

9.3.6 Halocarbons

In the US and EU-27, buildings were responsible in 2010 for around 45% of total emissions of fluorine-containing gases in terms of $CO_{2\text{-eq}}$ (based on (UNEP, 2011a; EEA, 2013; US EPA, 2013). Building-related emissions occur from refrigeration and cooling equipment and from various foam insulation products. Some of these have global warming potentials (GWPs) of more than 1000. HFC as an expanding agent in polyurethane foam has been banned in the EU since 2008, but by 2005, 85% had already been shifted to hydrocarbons (having a GWP of 1). In Germany, almost all new refrigerators use natural refrigerants (isobutane, HC-600a, and propane, HC-29) in place of HCF-134a (Rhiemeier and Harnisch, 2009). There is also great potential to reduce emissions of HFCs during the operation servicing of HFC-containing equipment (McCulloch, 2009). Finally, measures to eliminate the need for mechanical cooling altogether (through passive design) will reduce cooling-related halocarbon emissions.

9.3.7 Avoiding mechanical heating, cooling and ventilation systems

In many parts of the world, high-performance mechanical cooling systems – especially for residential 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. 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

Biomass is the single largest source of energy for buildings at the global scale, playing an important role for space heating, production of hot water 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). An advanced cook stove with an efficiency of 60%, has been used in place of traditional cookstoves with an efficiency of 6-8% in the state of Arunachal Pradesh, India (Rawat et al., 2010) . Gasifier and biogas cookstoves have also undergone major developments. Biomass is the single largest source of energy for buildings at the global scale (IEA, 2012c) 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 Embodied energy and 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 (Citherlet and Defaux, 2007; GEA, 2012). However, the embodied energy and carbon in construction materials is especially important in regions with high construction rates, and the availability of affordable low-carbon, low-energy materials that can be part of high-performance buildings determines construction-related emissions substantially in rapidly developing countries. (Sartori and Hestnes, 2007; Karlsson and Moshfegh, 2007; Ramesh et al., 2010). A review of life cycle assessment, life cycle energy analysis and material flow analysis in buildings (conventional and traditional) can be found in (Cabeza et al., 2013). Recent research indicates that wood-based wall systems entail 10-20% less embodied energy than traditional 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). 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 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 and lifestyle impacts

Chapter 2 discusses behavioural issues in a broad sense. There are substantial differences in building energy use in the world driven mainly by behaviour and culture. Factors of 3 to 10 differences can be found worldwide in residential energy use for similar dwellings with same occupancy and comfort levels (Zhang et al., 2010), and up to 10 times difference in office buildings with same climate and same building functions with similar comfort and health levels (Batty et al., 1991; Zhaojian and Qingpeng, 2007; Zhang et al., 2010; Grinshpon, 2011; Xiao, 2011). The major characteristics of the lower energy use buildings are openable windows for natural ventilation, part time & part space for indoor environment (thermal and lighting), and variable indoor thermal parameters (temperature, humidity and outdoor air). These are traditional approaches to obtain suitable indoor climate and thermal comfort. However since the spread of globalised supply of commercial thermal conditioning heating/cooling solutions tend towards fully controlled indoor climates through mechanic systems and these typically result in a significantly increased energy demand (TUBESRC, 2009). An alternative development pathway to the ubiquitous use of fully conditioned spaces by automatically operated mechanical systems is to integrate key elements of the traditional lifestyle in buildings, in particular the "part time & part space" indoor climate conditioning, passive design for indoor thermal and lighting and take mechanic system only for the remaining needs when the passive approaches cannot meet the comfort demand. By relative innovation technologies towards further improvements in indoor service levels, such pathways can reach the energy use levels below 30 kWh_e/m^2yr on world average (TUBESRC, 2009; Murakami et al., 2009), as opposed to the 30 ~ 50 kWh_e/m^2yr achievable through presently taken building development pathways utilising fully automatised full thermal conditioning (Murakami et al., 2009; Yoshino et al., 2011).

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). Thermostat settings are also influenced by dress codes and cultural expectations towards attires, and thus major energy savings can be achieved through changes in these, such as the relaxation of certain business dress codes such as initiatives in Japan (GEA, 2011). However, behaviour and lifestyle are crucial drivers of building energy use in more complex ways, too. Figure 9.9 shows the electricity use for summer cooling in apartments of the same building (occupied by households of similar affluence and size) in Beijing (Zhaojian and Qingpeng, 2007), ranging from 0.5 to 14.2 kWh/m^2yr. This is mainly caused by different operating hours of the split air-conditioner units. Opening windows during summer and relying on natural ventilation can reduce the cooling load while maintaining indoor air quality in most warm climate countries (Batty et al., 1991), compared to solely relying on mechanical ventilation (Yoshino et al., 2011). Buildings with high-performance centralized air-conditioning can use much more energy than decentralized split units that operate part time and for partial space cooling, with a factor of 9 found by (Zhaojian and Qingpeng, 2007; Murakami et al., 2009), as also illustrated in Figure 9.10. There are similar findings for other energy end-uses, such as clothes dryers (the dominant practice in laundering in the USA) consuming about 600-1000 kWh/year, while drying naturally is dominant in developing and even in many developed countries (Grinshpon, 2011).

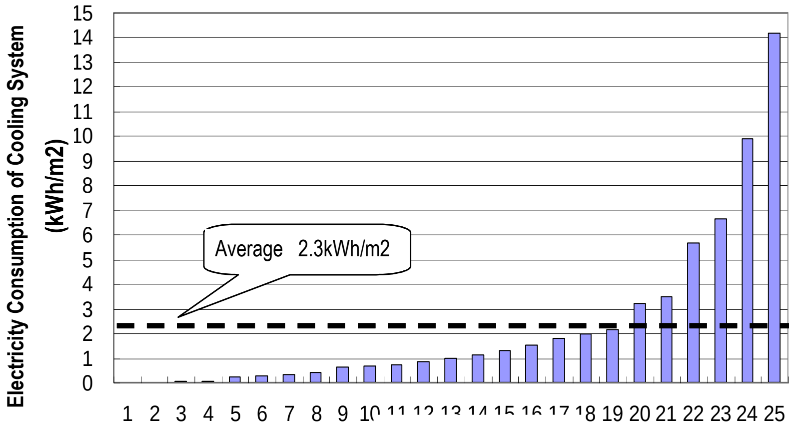

Figure 9.9. Measured electricity for cooling in an apartment block in Beijing (Peng et al., 2012).

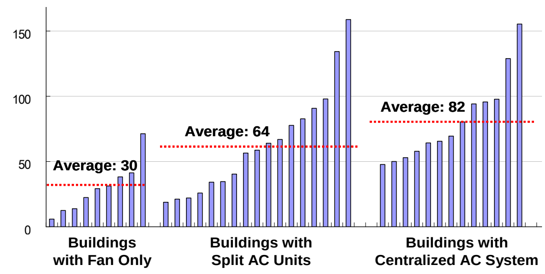

Figure 9.10. Annual unit area electricity use of buildings in Campus A (Beijing), 2006 (unit: kWh/m^{2}yr).

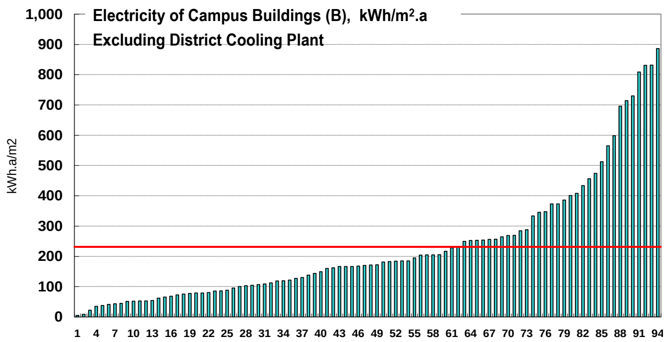

Figure 9.11. Annual unit area electricity use of buildings in Campus B (Philadelphia), 2006.

Quantitative modeling of the impact of future lifestyle change on energy demand shows that, in developed countries where energy service levels are already high, lifestyle change can produce substantial energy use reductions. In the USA, the short term behavioural change potential is estimated to be at least 20% (Dietz et al., 2009) and over long periods of time, much more substantial reductions (typically 50%) are possible, even in those developed countries with relatively low consumption (Fujino et al., 2008; Eyre et al., 2010). Similar absolute reductions are not possible in developing countries where energy services demands need to grow to satisfy development needs. However, the rate of growth can be reduced by lower consumption lifestyles (Wei et al., 2007; Sukla et al., 2008).

Energy use of buildings of similar functions and occupancies can vary by a factor of 2- 10, depending on culture and behaviour. For instance, Figure 9.10 and Figure 9.11 show the electricity usage of the HVAC system at two university campuses (in Philadelphia and Beijing) with similar climates and functions. The differences arise from: operating hours of lighting and ventilation (24h/day versus 12 h/day); full mechanical ventilation in all seasons versus natural ventilation for most of the year; and district cooling with selective re-heating versus seasonal decentralized air-conditioning. When the diversity of users' activities is taken into account, different technologies may be needed to satisfy the energy service demand .Therefore, buildings and their energy infrastructure need to be designed, built and used taking into account culture, norms and occupant behaviour. One universal standard of 'high efficiency' based on certain cultural activities may increase the energy usage in buildings with other cultural backgrounds, raising costs and emissions without improving the living standards. This is demonstrated in a recent case study of 10 "low-energy demonstration buildings" in China built in international collaborations. Most of these demonstration buildings use more energy in operation than ordinary buildings with the same functions and service levels (Xiao, 2011) . Although several energy saving technologies have been applied, occupant behaviours were also restricted by, for instance, using techniques only suitable for full time and full space cooling.

9.4 Infrastructure and systemic perspectives

9.4.1 Urban form and energy supply 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 often has trade-offs 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. Broader issues of the implications of urban form and land use planning for emissions are discussed in Chapter 12.5. 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 Section 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, generate heat and electricity more efficiently than the combination of centralized power plants and heating boilers, where heat can be used effectively. District energy systems differ between climate zones. Large-scale district heating systems of cold-climate cities predominantly provide space heating and domestic hot water. There are also some examples that utilize non-fossil heat sources, for example biomass and 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, diurnal 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 heat or cold from water source heat pumps (Song et al., 2007).

9.4.1.2 Electricity infrastructure interactions

Universal access to electricity remains a key development goal in developing countries. The capacity, and therefore cost, of electricity infrastructure needed to supply any given level of electricity services depends on the efficiency of electricity 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 attractions are 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 capital cost heating system, such as a heat pump, in a low-energy building are problematic. The literature is inconclusive on the role and scale of electrification of heating as a mitigation option, although it is likely to be location-dependent. However, significant energy demand reduction is likely to be critical to facilitate universal electrification (Eyre, 2011), and therefore transition pathways with limited efficiency improvement and high electrification are implausible. Electricity infrastructure in buildings will need increasingly to use information technology in 'smart grids' to provide consumer information and enable demand response to assist load balancing (see Chapter 7.12.3).

9.4.1.3 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 ice or 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 (UTES)with ground source heat pumps (GSHP)(Sanner et al., 2003) are being studied for seasonal energy storage in buildings or district heating and cooling networks, although UTES and GSHP are already used for short term storage (Paksoy et al., 2009).

9.4.2 Path Dependencies and lock-in

Buildings and their energy supply infrastructure are some of the longest lived components of the economy. Buildings constructed and retrofitted in the next few years/decades will determine emissions for many decades, without major opportunities for further change. Therefore the sector is particularly prone to lock-in, due to favouring incremental change (Bergman et al., 2008), traditionally low levels of innovation (Rohracher, 2001) and high inertia (Brown and Vergragt, 2008).

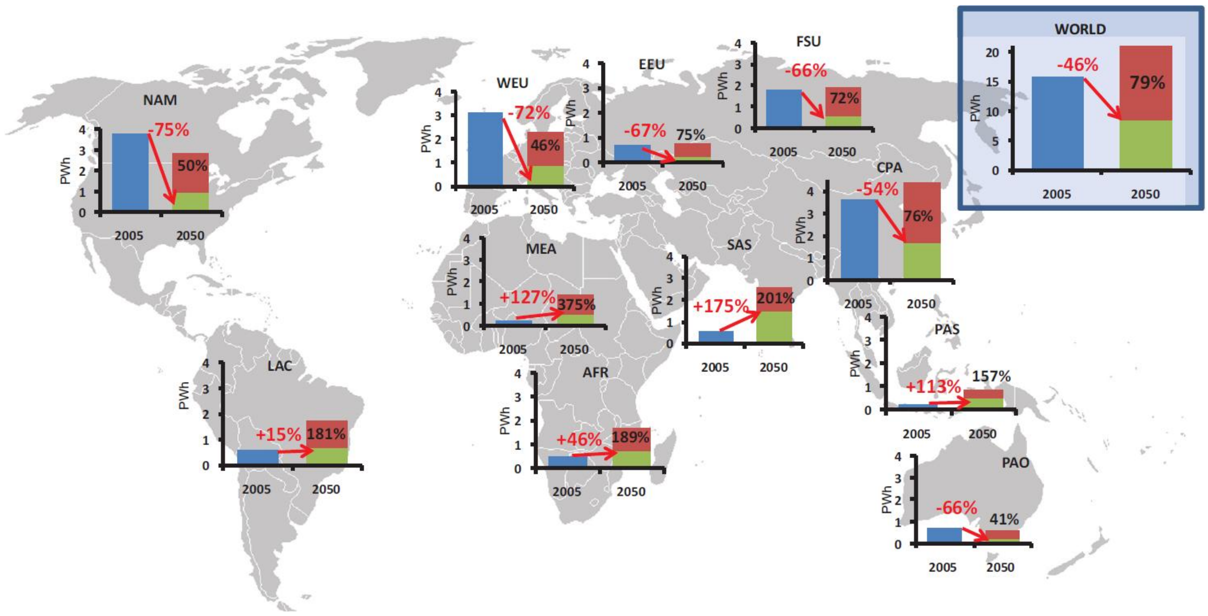

Figure 9.12. Final building heating and cooling energy use scenarios from 2005 to 2050 in the Global Energy Assessment by IEA region (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012). Notes: Green bars, indicated by red arrows and numbers; represent the opportunities through the GEA state-of-the-art 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 (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 Section 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 9.12). This is 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 changed only to today's best policy ambitions. This alerts us that while there are good developments in building energy efficiency policies, significantly more advances can and need to be made if ambitious climate goals are to be reached, otherwise significant emissions can be "locked in" that will not be possible to mitigate for decades. 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 can reach -6% by 2050 and + 5% by 2100; with 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). Emissions implications of this shift are related to the fuels and technologies locally used for heat and power generation: a global reference scenario from Isaac and Van Vuuren (2009b) shows a net increase in residential CO_2 emissions of 0.3+Gt C by 2100.

There is 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 by development and urbanisation level, climate conditions and building infrastructure. 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 heat island reduction, air quality improvement, and *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) and Akbari et al., (2012) 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 to 2.5 tonne CO_2 per 10 m^2 of roof area through enhanced reflection. Global CO_2 *one-time* 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).

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, together with other constraints (Wada et al., 2012). Figure 9.13 and the corresponding Table 9.6 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 identities identified at the beginning of the chapter, translating into the four key mitigation strategies that apply to this sector – i.e. carbon efficiency, technological efficiency, systemic efficiency and energy service demand reduction. However, as pointed out earlier, it is often not possible to precisely distinguish one category from the other, especially given the different categorisations in the studies, 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 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 four key mitigation strategies relevant to buildings can bring very large reductions, although systemic efficiency seems to bring higher results than other strategies, and energy service 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.

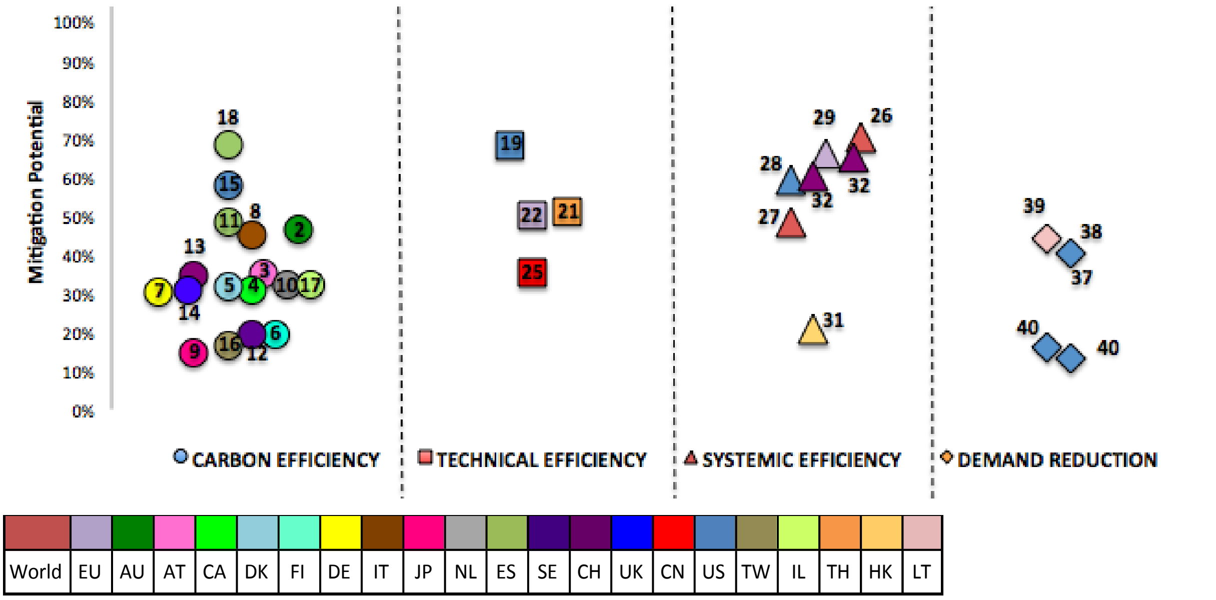

Figure 9.13. Regional studies on aggregated mitigation potentials grouped by key identity (i.e. main mitigation strategy). *Note: Numbers correspond to the percentage reduction as compared to baseline, if available, otherwise to base year, for the cases as numbered in Table 9.6.*

The efficiency and cost studies presented here represent a single snapshot in time potentially implying that as this potential is being captured by policies or measures, the remaining potential dwindles. This has not been reinforced by experience and research. Analyses have shown that technological improvement keeps replenishing the potential for efficiency improvement, so that the potential for cost-effective energy efficiency improvement has not been diminishing in spite of continuously improving standards (NAS, 2010). The National Academy of Science study (NAS, 2010) of the energy savings potentials of energy efficiency technologies and programs across all sectors in the United States state, "Studies of technical and economic energy-savings potential generally capture energy efficiency potential at a single point in time based on technologies that are available at the time a study is conducted. But new efficiency measures continue to be developed and to add to the long-term efficiency potential." These new efficiency opportunities continue to offer substantial cost-effective additional energy savings potentials after previous potentials have been captured so that the overall technical potential has been found to remain at the same order of magnitude for decades (NAS, 2010).

1 **Table 9.6.** 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 HW 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	L	T	CS	2011	-50%		23

Reg	Description of mitigation measures/package (year)	End-uses	Type	Sector	Base-end yrs	% change to baseline	% change to base yr	No*
	illuminance levels, switch-on time, manual dimming, switch-off occupancy sensors, daylighting							
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 (including 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, 2010, 2015 and 2020; renovated RS are upgraded to the energy requirements applicable for the 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
ENERGY SERVICE 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

Reg	Description of mitigation measures/package (year)	End-uses	Type	Sector	Base-end yrs	% change to baseline	% change to base yr	No*
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 lifestyle 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; approximately – 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, Fridley, 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 in more depth. This section focuses on whole-building approaches for new and retrofitted buildings, while the next section analyses a selection of important technologies systematically. Finally, we discuss the sensitivity of these findings to various assumptions and inputs.

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 (Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012; Harvey, 2013 and Section 9.3).There are various methodologies 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 found by these methods in meeting standards as high as the Passive House standard (see 9.3 , and (Lang Consulting, 2013), 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 9.4 in Section 9.3.3 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 ZNEBs 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 construction cost can be reduced to the point that the time required to pay-back the initial investment through operating cost savings is quite attractive.

Figure 9.14 shows the resulting cost-effectiveness from a set of documented best practices from different regions measured in cost of conserved energy (CCE). The figure demonstrates well that, despite the very broad typical variation in construction costs due to different designs and non-energy related extra investments, high-performance new construction can be highly cost-effective; several examples confirming the point established in Section 9.3 that even negative CCEs (Cost of Conserved Energy) can be achieved for commercial buildings - i.e. that the project is profitable already at the investment stage, or that the high-performance building costs less than the conventional one. Cost-effectiveness requires that the investments are optimised with regard to the additional vs. reduced (e.g. simplified or no heating system, ductwork, etc.) investment requirements and no non-energy related “luxury” construction investments are included (see 9.3 for further discussion of ensuring cost-effectiveness at the individual building level). It is also important to note that very high-performance construction is still at the demonstration/early deployment level in many jurisdictions, and further cost reductions are likely to occur (see, e.g. GEA, 2012). The figure also shows that higher savings compared to the baseline come at a typically lower cost per unit energy saving - i.e. deeper reductions from the baseline tend to increase the cost-efficiency.

Although converting energy saving costs to mitigation costs introduces many problems especially due to the challenges of emission factors, Figure 9.15 displays the associated mitigation cost estimates of selected points from Figure 9.14 to illustrate potential trends in cost of conserved carbon (CCC). The result is a huge range of CCC: ranging from three-digit negative costs to triple digit positive costs per ton of CO2 emissions avoided.

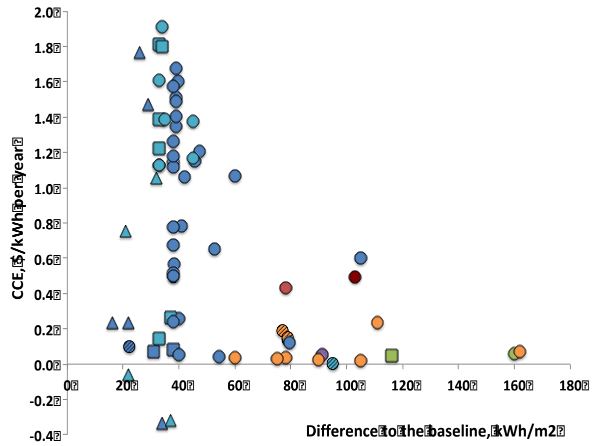

Figure 9.14. Cost of conserved energy as a function of energy performance improvement (kWh/m2yr difference to baseline) to reach "Passive House" or more stringent performance levels, for new construction by different building types and climate zones in Europe[1]

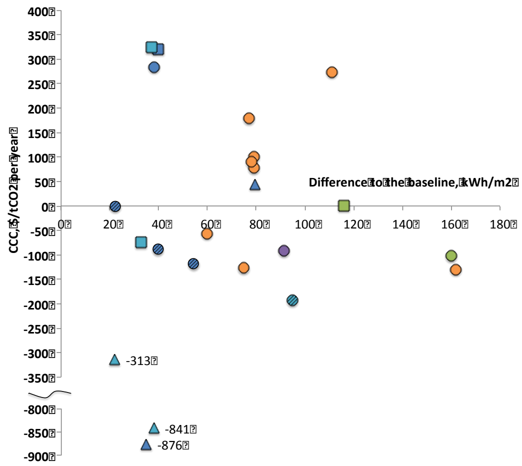

Figure 9.15. Cost of conserved carbon as a function of specific energy consumption for selected best-practices shown in Figure 9.14.

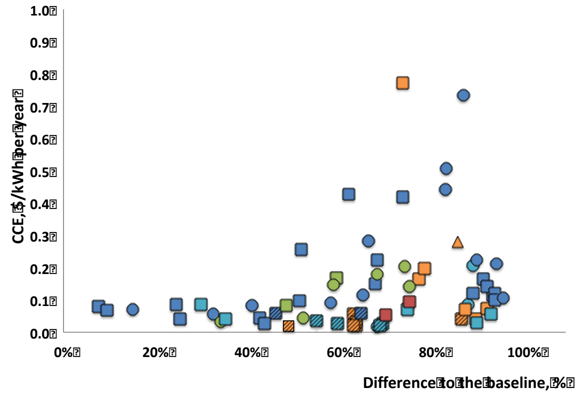

Figure 9.16. Cost of conserved energy as a function of energy saving in % for European retrofitted buildings by building type and climate zones.

[1]The data for the case studies presented in Figure 9.14-Figure 9.16 are coming from various sources (Hermelink, 2006; Galvin, 2010; ETK, 2011; Gardiner and Theobald, 2011; Nieminen, 2011; Energy Institute Vorarlberg, 2013; PHI, 2013; Harvey, 2013). A discount rate of 3% and the lifetime of 30 years for retrofit and 40 years for new buildings have been assumed.

9.6.2.2 Costs of deep retrofits

Studies have repeatedly indicated the important distinction between conventional “shallow” retrofits, often reducing energy use by only 10-30%, and aggressive “deep” retrofits (i.e., 50% or more relative to baseline conditions, especially when considering the lock-in effect.(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 9.16 presents the costs of conserved energy related to a selection of documented retrofit best practices (esp. at the higher end of the savings axis). The figure shows that 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 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 – i.e. their cost-effectiveness can remain at the equally attractive levels for best practices. Retrofits getting closer to 100% savings start to get more expensive, mainly due to the introduction of presently more expensive PV and other building-integrated renewable energy generation technologies.

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 9.16 and Figure 9.17 all vary the baseline for the respective measure.

CCE figures and thus 'profitability" fundamentally depend, furthermore, on the discount rate and assumed lifetime of the measure, and CCC (Cost of Conserved Carbon) depends further on the background emission factor and energy price. Figure 9.17 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.

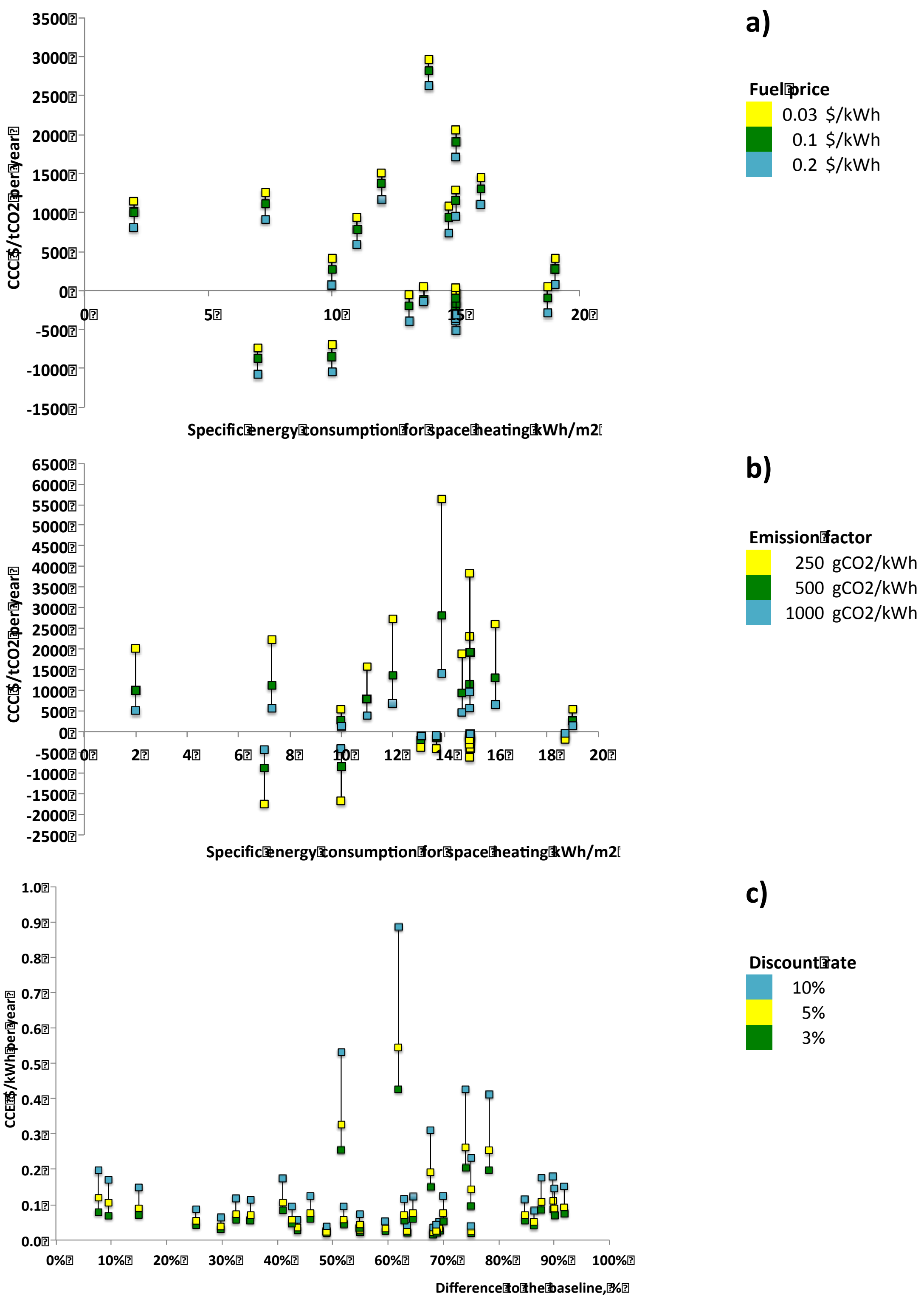

Figure 9.17. Sensitivity analysis of the key parameters: a) CCC for new buildings in response to the variation in fuel price; b) CCC for new buildings in response to the variation in emission factor; c) CCE for retrofit buildings in response to the variation in discount rate for selected data points shown in Figure 9.14, Figure 9.15 and Figure 9.16.

9.7 Co-benefits, risks and spillovers

9.7.1 Overview

Mitigation measures depend on and interact with a variety of factors that relate to broader economic, social and/or environmental objectives that drive policy choices. Positive side-effects are deemed 'co-benefits'; if adverse and uncertain they imply risks.[2] Potential co-benefits and adverse side-effects of alternative mitigation measures (Sections 9.7.1 - 9.7.3), associated technical risks and uncertainties, as well as their public perception (see the relative discussion in Sections 9.3.10 and 9.8), can significantly affect investment decisions, individual behaviour and policymaking priority settings. Table 9.7 provides an overview of the potential co-benefits and adverse side-effects of the mitigation measures assessed in accordance with sustainable development pillars (Chapter 4). The extent to which co-benefits and adverse side-effects will materialize in practice as well as their net effect on social welfare differ greatly across regions. It is strongly dependent on local circumstances, implementation practices, scale and pace of measures deployment (see Section 6.6). (Ürge-Vorsatz et al., 2009; GEA, 2012), synthesizing previous research efforts (e.g.(Mills and Rosenfeld, 1996),recognize the following major categories of co-benefits attributed to mitigation actions in buildings: (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. reduction 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 and the reduction of outdoor noise, increased safety). Taken together, the GEA (2012) found that only the monetizable co-benefits associated with energy efficiency in buildings are at least twice the resulting operating cost savings.

On the other hand, some risks are also associated with the implementation of mitigation actions in buildings emanating mostly from limited energy access and fuel poverty issues due to higher investment and (sometimes) operating costs, health risks in sub-optimally designed airtight buildings and the use of sub-standard energy efficiency technologies including risks of premature failure. The IPCC AR4 (Levine et al., 2007) and other major recent studies (UNEP, 2011b; GEA, 2012) provide a detailed presentation and a comprehensive analysis of such effects. Here, a review of recent advances focus on selected co-benefits/risks, with a view to providing methods, quantitative information and examples that can be utilised in the decision-making process.

[2] Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters (particularly 2.4, 3.6.3, and 4.8) as well as to the glossary in Annex I for concepts and definitions.

Table 9.7. Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) associated with mitigation actions in buildings. Please refer to Sections 7.9, 11.7 and 11.13 for possible upstream effects of low-carbon electricity and biomass supply on additional objectives. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace and scale (see section 6.6). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2.

Co-benefits / Adverse side-effects	**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										
↑ Employment impact	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)
↑ 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)
↑ Disaster resilience	X	X	X	X	X	X				(Berdahl, 1995; Mills, 2003; Coaffee, 2008)
Social										
↑ Fuel poverty alleviation (reduced demand for energy)	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)
↓ Fuel poverty alleviation (in cases of increases in the cost of energy)	X		X	X				X		(GEA, 2012; Rao, 2013)
↓ Energy access (in cases of increases in the cost of energy, high investment costs needed, etc.)	X		X	X	X		X	X		(GEA, 2012); for a more in-depth discussion please see Section 7.9.1
↑ Quality of life (noise impact, thermal comfort)	X	X	X	X	X	X				(Jakob, 2006; Stoecklein and Skumatz, 2007)
↑ Increased productive time for women and children (for replaced traditional cookstoves)	X			X			X	X		(Reddy et al., 2000; Lambrou and Piana, 2006; Hutton et al., 2007; Anenberg et al., 2013) (Wodon and Blackden, 2006)
↓ Rebound effect	X	X	X	X	X	X	X	X		(Greening et al., 2000; Sorrell, 2007; Hens et al., 2009; Sorrell et al., 2009; Druckman et al., 2011; Ürge-Vorsatz, Eyre, Graham, Harvey, et al., 2012)
Health/Environmental										
Health impact 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; Milner et al., 2012); see Section 7.9.2
↑ *reduced indoor pollution*	X			X			X	X		(Bruce et al., 2006; Zhang and Smith, 2007; Duflo et al., 2008; WHO, 2009; Wilkinson et al., 2009; Howden-Chapman and Chapman, 2012; Milner et al., 2012); WGII Section 11.9.
↑ *improved indoor environmental conditions*	X	X	X	X	X	X			X	(Fisk, 2002; Singh, Syal, et al., 2010; Howden-Chapman and Chapman, 2012; Milner et al., 2012)
↑ *fuel poverty alleviation*	X		X	X	X		X	X		(Healy, 2004; Liddell and Morris, 2010; Ürge-Vorsatz and Tirado Herrero, 2012a; Hills, 2012a;

Co-benefits / Adverse side-effects	**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**
										Howden-Chapman and Chapman, 2012; Milner et al., 2012; Tirado Herrero and Urge-Vorsatz, 2012)
↓ *insufficient ventilation (sick building syndrome), sub-standard energy efficiency technologies, etc.*	X	X	X	X	X		X			(Fisk, 2002; GEA, 2012; Milner et al., 2012)
↑ Ecosystem impact	X	X	X	X	X	X	X	X	X	(Aunan et al., 2004; Mirasgedis et al., 2004; Ürge-Vorsatz et al., 2009; Cam, 2012)
↑ Reduced water consumption and sewage production	X	X	X	X	X	X	X			(Kats et al., 2005; Bansal et al., 2011)
↑ Urban heat island effect	X		X	X	X	X		X		(Cam, 2012; Xu, Sathaye, et al., 2012); see Sections 9.5 and 12.8

9.7.2 Socio-economic effects

9.7.2.1 Impacts on employment

Studies (Scott et al., 2008; Pollin et al., 2009; Kuckshinrichs et al., 2010; Köppl et al., 2011; ILO, 2012) have found 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. 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). A review of the literature on quantification of employment effects of energy efficiency and GHG mitigation measures in the building sector is summarized in Figure 9.18 . The bulk of the studies reviewed, which concern mainly developed economies, point out that the implementation of GHG mitigation interventions in buildings generates on average 13 (range of 0.7 to 35.5) job-years per $2010 million spent. This range does not change if only studies 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). However, to what extent investing on clean energy creates more employment compared to conventional activities depends also on the structure of the economy in question, level of wages and if the production of equipment and services to develop these investments occurs inside or not the economy under consideration. 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. Investing in clean technologies may create new job activities (e.g. in solar industry, in the sector of new building materials etc.), but the vast majority of jobs can be in traditional areas (Pollin et al., 2009) albeit with different skills required (ILO, 2012).

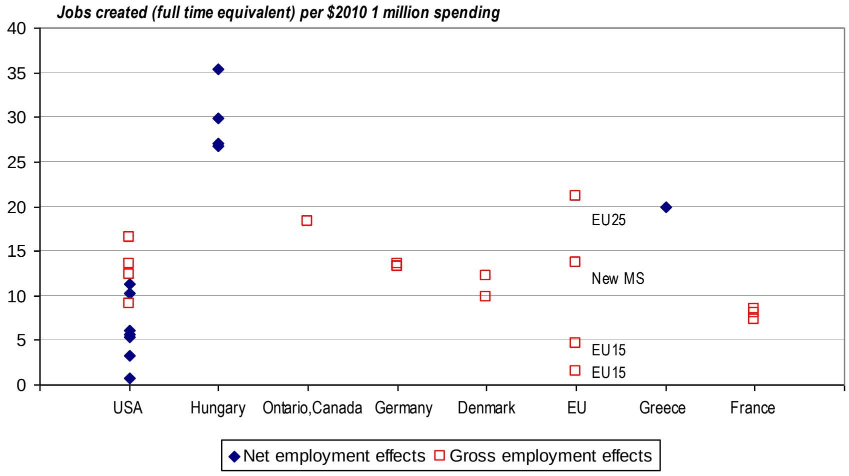

Figure 9.18. Employment effects attributed to GHG mitigation initiatives in the building sector.

Sources used: USA: (Scott et al., 2008; Bezdek, 2009; Hendricks et al., 2009; Pollin et al., 2009; Garrett-Peltier, 2011; Gold et al., 2011). Hungary: (Ürge-Vorsatz et al., 2010). Ontario, Canada: (Pollin and Garrett-Peltier, 2009). Germany: (Kuckshinrichs et al., 2010). Denmark: (Ege et al., 2009). EU: (ETUC, 2008). Greece: (Markaki et al., 2013) France: (ADEME, 2008). All studies from the US, Hungary, Ontario Canada and Greece include the direct, indirect and induced employment effects. In (ADEME, 2008) and (ETUC, 2008) only the direct effects are taken into account. (Ege et al., 2009) includes the direct and indirect effects while this information is not provided in (Kuckshinrichs et al., 2010)

9.7.2.2 Energy security

Implementation of GHG mitigation measures in the buildings sector can play an important role in increasing the sufficiency of resources to meet national energy demand at competitive and stable prices and improving the resilience of the energy supply system. Specifically, mitigation actions result in: (i) strengthening power grid reliability, through the enhancement of properly managed on-site generation and the reduction of the overall demand, which result in 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 (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). A more general discussion on energy security is provided in Section 6.6.

9.7.2.3 Benefits related to workplace productivity

Investment in low-carbon technologies related to air conditioning and wall thermal properties during construction or renovation improves 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 can be attributed to: (i) reduced working days lost to asthma and respiratory allergies; (ii) fewer work hours affected by flue, respiratory illnesses, depression and stress; and (iii) improved worker performance from changes in thermal comfort and lighting. Productivity gains can rank among the highest value co-benefits when these are monetised, especially in countries with high labor costs (GEA, 2012).

9.7.2.4 Rebound effects

Improvements in energy efficiency can be offset by increases in demand for energy services due to the rebound effect. The general issues relating to the effect are set out in Sections 3.9.5 and 5.6.. It is of particular importance in buildings because of the high proportion of energy efficiency potential in this sector. Studies related to buildings form a major part of the two major reviews of rebound (Greening et al., 2000; Sorrell, 2007). Direct rebound effects 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) in developed countries. For energy services where energy is a smaller fraction of total costs, e.g. electrical appliances, there is less evidence, but values are lower and less than 20% (Sorrell, 2007). Somewhat higher rebound levels have been found for lower income groups (Roy, 2000; Hens et al., 2009), implying that efficiency contributes positively to energy service affordability and development goals - which are often the purposes of efficiency policies in these countries. However there is limited evidence outside OECD countries (Roy, 2000; Ouyang et al., 2010) and further research is required here. Studies of indirect rebound effects for buildings tend to show low values, e.g. 7% for thermostat changes (Druckman et al., 2011). 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), but there is no evidence to support large rebound effects for energy efficiency in buildings. Declining energy use in developed countries with strong policies for energy efficiency in buildings indicates rebound effects are low (see Section 9.2). Rebound effects should be taken into account in building energy efficiency policies, but do not alter conclusions about their importance and cost effectiveness in climate mitigation (Sorrell, 2007).

9.7.2.5 Fuel poverty alleviation

Fuel 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 TiradoHerrero, 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 . Despite the fact that some mitigation measures (e.g. renewables) may result in higher consumer energy prices aggravating energy poverty, substantially improving the thermal performance of buildings (such as Passive house) and educating residents on appropriate energy management can largely alleviate fuel poverty. Several studies have shown that fuel poverty-related monetized co-benefits 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; TiradoHerrero 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 resulting in significant co-benefits for public health, through: (i) reduction of indoor air pollution, (ii) improvement of indoor environmental conditions and (iii) fuel poverty alleviation particularly in cold regions. In developing countries inefficient combustion of traditional solid fuels in households produces significant gaseous and particulate 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). 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 (WHO, 2009), with recent estimates (Lim et al., 2012) reaching as high as 3.5 million premature deaths in 2010. Another half a million premature deaths are attributed to household cookfuel's contribution to outdoor air pollution, making a total of about 4 million (see WGII 11.9.1.3). Several climate mitigation options such as improved cookstoves, switching to cleaner fuels, behavioural changes, switching to more efficient and less dangerous lighting technologies, etc. address not only climate change but also these health issues (Anenberg et al., 2012; Smith et al., 2013; Rao et al., 2013). 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 and the costs associated with the implementation of selected interventions aiming at reducing indoor air pollution from the use of solid fuels for cooking/space heating in various world regions (Table 9.8)

Table 9.8. 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	1300-1790	660-1190	~1210	700-760	1700-2970	550-9300
Access to cleaner fuels: Kerosene	11090-15390	1460-8770	~9730	5070-5560	14820-25790	4110-79500
Improved stoves	36710-45860	840-980	2030-2520	n.a.	62360-70670	1580-3110

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). On the other hand, insufficient ventilation in airtight buildings, is found to affect negatively their occupants' health as has the installation of sub-standard energy efficiency technologies due to in-situ toxic chemicals (Fisk, 2002; GEA, 2012; Milner et al., 2012). Of particular importance is the alleviation of fuel poverty in buildings, which is associated with excess mortality and morbidity effects, depression and anxiety (Green and Gilbertson, 2008). 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; TiradoHerrero 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 and school. A study in the UK found that investing $ 1 for warming homes reduces the healthcare costs by $ 0.48 (Liddell, 2008). Such findings suggest addressing fuel poverty issues and the resulting health impacts in developing nations are even more important, as a greater share of the population is affected (WHO, 2011).

9.7.3.2 Health and environmental co-benefits due to 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(Smith et al., 2010; Harlan and Ruddell, 2011)(see Section 12.8); and (ii) less stresses on natural and anthropogenic ecosystems (see Section 7.9.1). Quantification and valuation of these benefits is possible allowing them to be integrated into cost-benefit analysis. 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 of 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 higher in developing nations (see Chapter 6.6). (Markandya et al., 2009), estimated that the health benefits expressed in $2010 per ton of CO_2 not emitted from power plants (through for example the implementation of electricity conservation interventions) are in the range of 2 $/t CO_2 in EU7 $/t CO_2 in China and 46 $/t CO_2 in India, accounting for only the mortality impacts associated with $PM_{2.5}$ emissions. Please refer to Section 5.7 for higher estimates in the assessed literature.

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., 2011). More generally, a number of studies show that green design in buildings is associated with lower demand for water, resulting in reduced costs and emissions from the utilities sector. 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 CO_2 emissions, etc.(Cam, 2012; Xu, Sathaye, et al., 2012)(see Gill et al., 2007 and Section 12.5.2.2).

9.8 Barriers and opportunities

Strong barriers – many to particular to the buildings sector - hinder the market uptake of largely cost-effective opportunities to achieve energy efficiency improvements shown in earlier sections. Large potentials will remain untapped without adequate policies that induce the needed changes in private decisions and professional practices. 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, cultural aspects, cognitive and behavioural patterns, as well as difficulties concerning patent protection and technology transfer. In less developed areas, lack of awareness, of financing, of qualified personnel, economic informality and insufficient service levels lead to suboptimal policies and measures causing lock-in effects in terms of emissions. The pace of 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 (Williams et al., 2012). 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 as well as sectoral bottom-up modeling literature from the perspective of what main trends are projected for the future building emissions and energy use developments, and the role of major mitigation strategies outlined in Section 9.1 . The section complements the analysis in Section 6.8 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 scenarios from integrated models (665 scenarios in total) grouped by their long-term CO_2-equivalent concentration level by 2100, complemented by the analysis of sectoral models (grouped by baseline and advanced scenario, since often these do not relate to concentration goals); and (b) a more detailed analysis of a small selection of integrated and end-use/sectoral models. The source of the IAMs is the AR5 Scenario Database (see Section 6.2.2 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

Figure 9.19, together with Figure 9.20 and Figure 9.21, indicate that without action, global building final energy use could double or even close to triple by mid-century. While the median of integrated model scenarios forecast an app. 75% increase as compared to 2010 (Figure 9.19), several key scenarios that model this sector in greater detail foresee a larger growth: such as AIM, Message and GCAM all projecting an over 150% baseline growth (Figure 9.20). The sectoral/bottom-up literature, however, indicates that this growing trend can be reversed and the sector's energy use can stagnate, or even decline, by mid-Century, under advanced scenarios.

Hence, the projected development in building final energy use is rather different in the sectoral (bottom-up) and integrated modelling literature, as illustrated in Figure 9.19**.**, Figure 9.20 and Figure 9.21. For instance, the integrated model literature foresees an increase in building energy consumption in most scenarios with almost none foreseeing stabilisation; whereas the vast majority of ambitious scenarios from the bottom-up/sectoral literature stabilise or even decline, despite the increases in wealth, floorspace, service levels and amenities (see Section 9.2). Several stringent mitigation scenarios from integrated models are above baseline scenarios from the sectoral literature (Figure 9.20). In general, the sectoral literature sees deeper opportunities for energy use reductions in the building sector than integrated models.

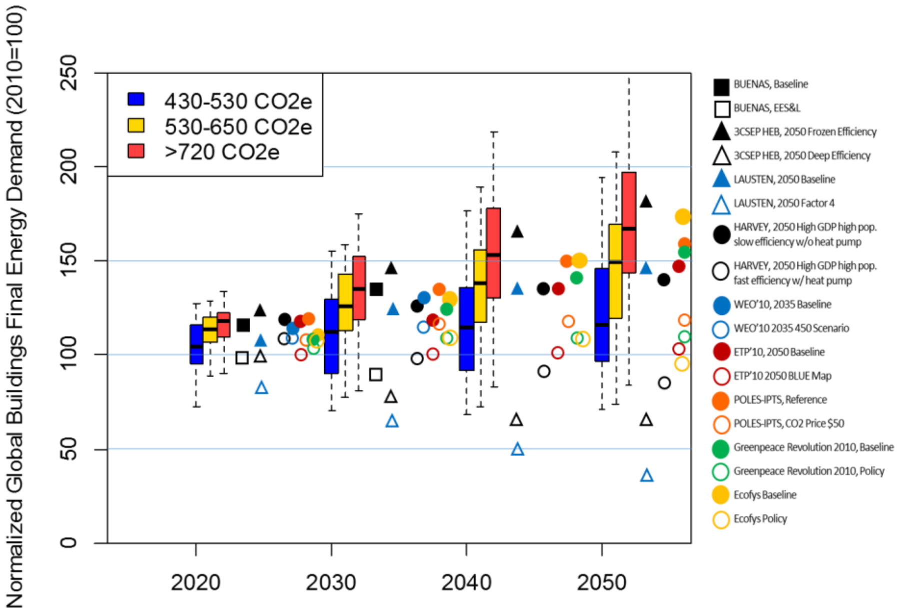

Figure 9.19. Development of normalized annual global building final energy demand (2010=100) until 2050 in the integrated modeling literature, grouped by the three levels of long-term $CO_{2\text{-e}}$ concentration level by 2100[3] (245 scenarios with 430-530 ppm $CO_{2\text{-e}}$, 156 scenarios with 530-650ppm $CO_{2\text{-e}}$, and 177 scenarios exceeding 720ppm $CO_{2\text{-e}}$—for category descriptions see Chapter 6.3.3) and sectoral/bottom-up literature (9baselinescenarios and 9 advanced scenarios). Scenarios with full service coverage are denoted as squares, scenarios covering heating/cooling/water heating as triangles, scenarios covering heating/cooling/water heating/lighting/appliances as circles. Filled symbols are for baseline scenario, whereas empty symbols are for advanced scenarios.

As the focus on selected scenarios in Figure 9.21. 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. Figure 9.21 shows that deep reductions are foreseen only in the thermal energy uses by bottom-up/sectoral scenarios; but appliances can be reduced only moderately even in sectoral studies. This indicates that mitigation is more challenging for non-thermal end-uses and becoming increasingly important for ambitious mitigation over 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

[3]This section builds upon emissions scenarios, which were collated by Chapter 6 in the AR5 scenario database (Section 6.2.2), and compares them to detailed building sector studies. The scenarios were grouped into baseline and mitigation scenarios. As described in more detail in Section 6.3.2, the scenarios are further categorized into bins based on 2100 concentrations: between 430- 480 ppm CO_2eq, 480-530 ppm CO_2eq, 530-580 ppm CO_2eq, 580-650 ppm CO_2eq, 650-720 ppm CO_2eq, and >720 ppm CO_2eq by 2100. An assessment of geo-physical climate uncertainties consistent with the dynamics of Earth System Models assessed in WGI found that the most stringent of these scenarios – leading to 2100 concentrations between 430 and 480 ppmv CO_2e – would lead to an end-of-century median temperature change between 1.6 to 1.8°C compared to pre-industrial times, although uncertainties in understanding of the climate system mean that the possible temperature range is much wider than this range. They were found to maintain temperature change below 2°C over the course of the century with a likely chance. Scenarios in the concentration category of 650-720 ppm CO_2eq correspond to comparatively modest mitigation efforts, and were found to lead to median temperature rise of approximately 2.6-2.9°C in 2100 (see Section 6.3.2 for details)..

a 46% reduction in heating and cooling energy demand as compared to 2005 – even under baseline assumptions on wealth and amenities increases. In contrast, the selected integrated models that focus on detailed building sector modelling project very little reduction in heating and cooling.

Another general finding is that studies show significantly larger reduction potentials by 2050 than by 2030, pointing to the need for a longer-term, strategic policy planning, due to long lead times of building infrastructure modernization (see Section 9.4). In fact, most of these studies and scenarios show energy growth through 2020, 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.

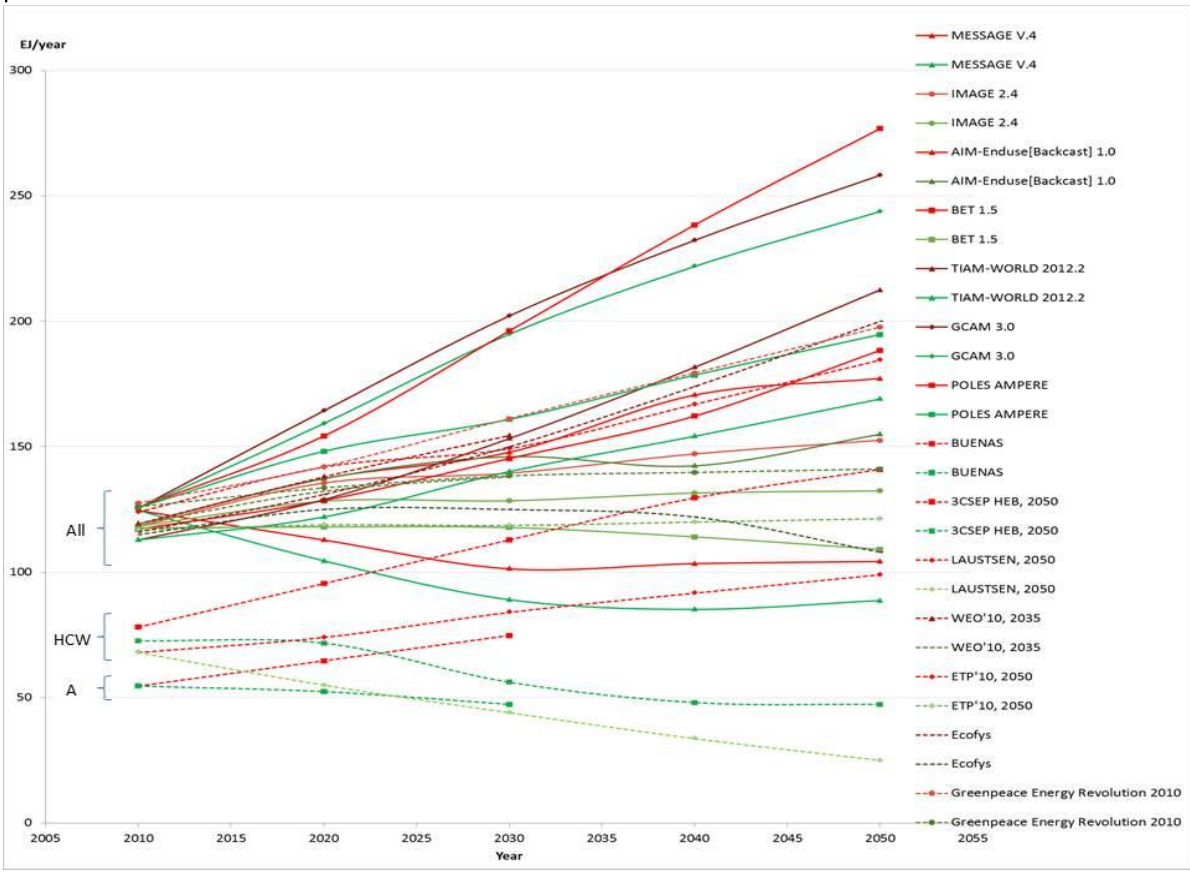

Figure 9.20. Annual global final energy demand development in the building sector by 2050 in selected sectoral models, baseline and advanced scenarios, for total energy in EJ/yr (HCWLA, top),thermal energy (HCW, incl. heating/cooling/hot water), and appliances (A); compared to selected IAMs. Red shades are reference scenarios, green shades are advanced ones. Solid lines show IAM models, dashed lines show other sectoral/bottom-up models. Sources as indicated in Section 9.9.1.[4].

[4] For the analysis to follow, we have chosen seven illustrative integrated models with two scenarios each, covering the full range of year-2050 final energy use in all no-policy scenarios in the AR5 scenario database and their 450ppmv scenario counterparts. These no-policy scenarios are MESSAGE V.4_EMF27-Base-EERE, IMAGE 2.4_AMPERE2-Base-LowEI-OPT, AIM-Enduse[Backcast] 1.0_LIMITS-StrPol, BET 1.5_EMF27-Base-FullTech, TIAM-WORLD 2012.2_EMF27-Base-FullTech, GCAM 3.0_AMPERE3-Base, and POLES AMPERE_AMPERE3-Base. The mitigation scenario counterparts are MESSAGE V.4_EMF27-450-EERE, IMAGE 2.4_AMPERE2-450-LowEI-OPT, AIM-Enduse[Backcast] 1.0_LIMITS-StrPol-450, BET 1.5_EMF27-450-FullTech, TIAM-WORLD 2012.2_EMF27-450-FullTech, GCAM 3.0_AMPERE3-CF450, and POLES AMPERE_AMPERE3-CF450. In addition, sectoral/bottom-up models and scenarios were also included. The no policy/baseline scenarios are BUENAS Baseline, 3CSEP HEB Frozen efficiency, LAUSTSEN Baseline, WEO'10Current Policies, ETP'10 Baseline, Ecofys Baseline, and Greenpeace Energy Revolution 2010 Baseline. The advanced scenarios are BUENAS EES&L, 3CSEP HEB Deep efficiency, LAUSTSEN Factor 4, WEO'10 450 Scenario, ETP'10 BLUE Map, Ecofys TER, and Greenpeace Energy Revolution 2010 Revolution.

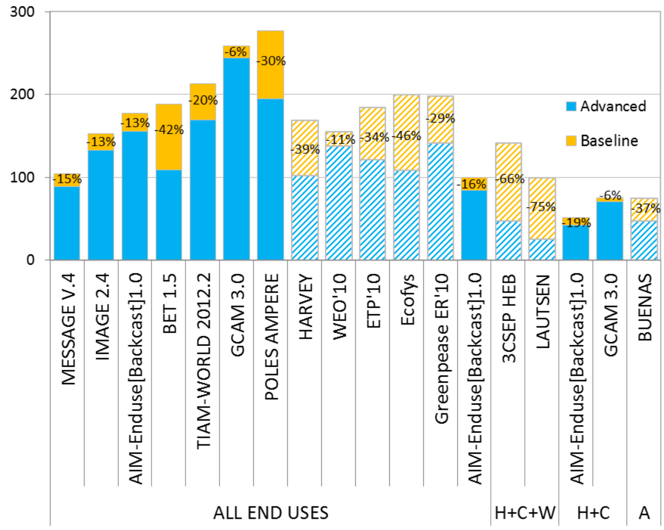

Figure 9.21. Building final energy use in EJ/yr (total or heating/cooling, as indicated) in 2050 (2030 for the Buenas model) in advanced scenarios as compared to reference ones. Solid bars show scenarios from integrated models meeting 480-580 ppm CO_2eq concentration in 2100, striped ones from sectoral models. Sources as indicated in Section 9.9.1

However, these trends are very different in the different world regions. As Figure 9.22 demonstrates, both per capita and total final building energy use is expected to decline or close to stabilise even in baseline scenarios in OECD countries. In contrast, the Latin-American and Asian regions will experience major growth both for per capita and total levels, even in the most stringent mitigation scenarios. MAF will experience major growth for total levels, but growth is not projected for per capita levels even in baseline scenarios. This is likely due mainly to the fact that fuel switching from traditional biomass to modern energy carriers results in significant conversion efficiency gains, thus allowing substantial increases in energy service levels without increasing final energy use.

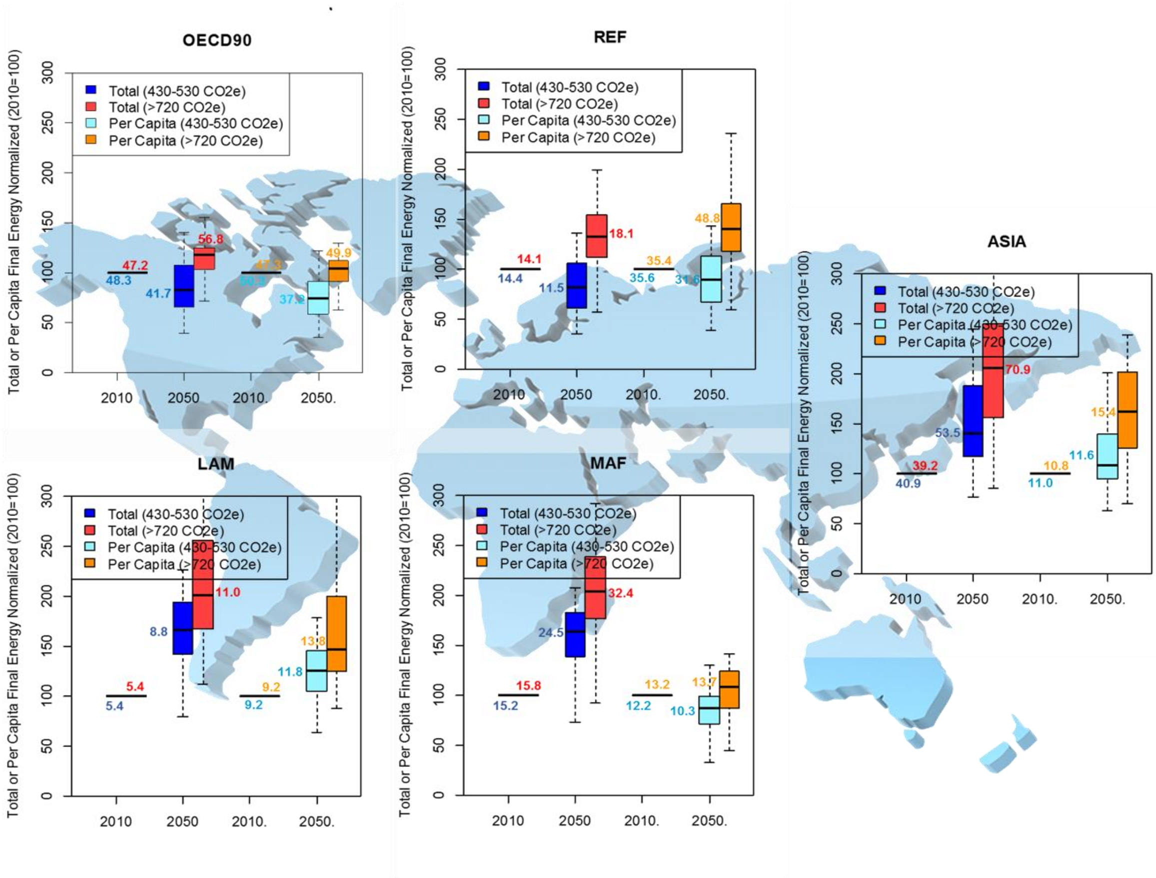

Figure 9.22. Normalized total (for first two sets of boxes) and per capita (for next two sets of boxes) buildings final energy demand in 2010 and 2050 for each of the five RCP regions in scenarios from integrated models (2010=100). The absolute values of the medians are also shown with the unit of EJ for total buildings final energy demand and the unit of GJ for per capita buildings final energy demand (229 scenarios with 430-530 ppm CO2-e and 154 scenarios exceeding 720ppm CO2-e—for category descriptions see Section 6.3.2). Note that the 2010 absolute values are not equal for the two CO2e concentration categories because for most integrated models 2010 is a modeling year implying some variation across models, such as in the treatment of traditional biomass.

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 stringent mitigation scenarios suggest that different models take different foci for their building mitigation strategies. While most mitigation and advanced bottom-up/sectoral scenarios show flat or reducing global final building energy use, a few integrated models achieve stringent mitigation 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 mitigation scenarios. This suggests a focus on energy supply side measures for decarbonisation. In general, Figures Figure 9.19, Figure 9.20, and Figure 9.21 all demonstrate that integrated models generally place a larger focus on supply-side solutions than on final energy reduction opportunities in the building sector (cf. Section 6.8) – except for a small selection of studies.

Fuel switching to electricity that is increasingly being decarbonised is a robust mitigation strategy as shown in Sections 6.3.4 and 6.8. However, as Figure 9.23 indicates, this is not fully the case in the buildings sector. The total share of electricity in this sector is influenced little by mitigation stringency except for the least ambitious scenarios: it exhibits an autonomous increase from about 28% of final energy in 2010 to 50% and more in 2050 in almost all scenarios, i.e. “electrification” is an important baseline trend in the sector. Compared to this robust baseline trend, the additional electrification in mitigation scenarios is rather modest (see also Section 6.8.4).

Figure 9.23b indicates that the higher rates of energy growth (x-axis) in the models involve generally higher rates of electricity growth (y-axis). The two increases are nearly proportional, so that the rates of electricity demand share growth, of which level is indicated by 45° lines, remain mostly below 2% per year even in the presence of climate policy.

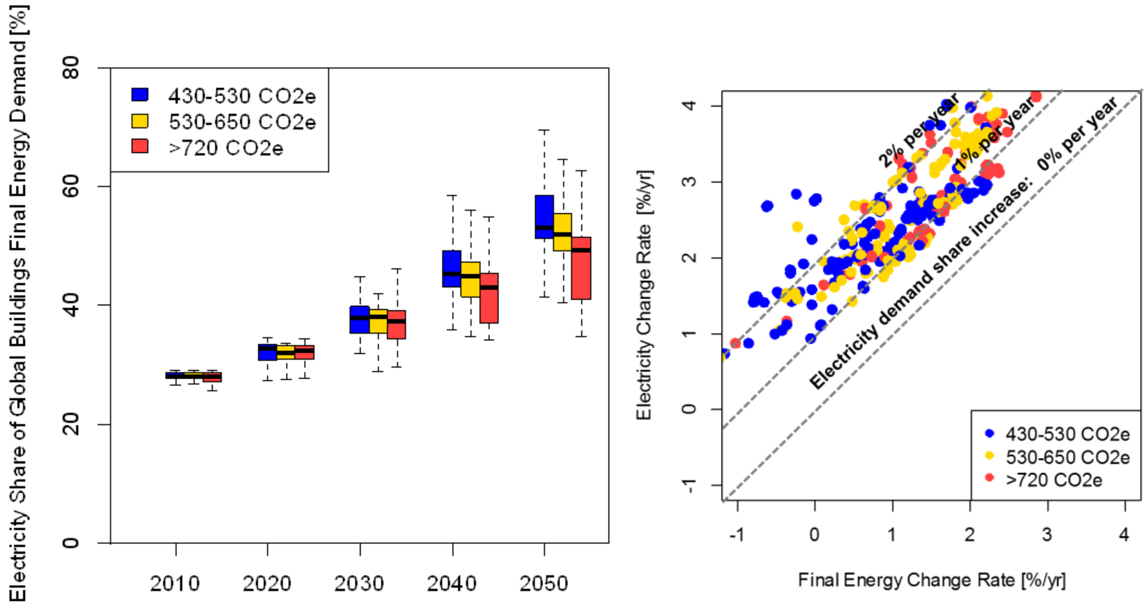

Figure 9.23. **(a)** The development in the share of electricity in global final energy demand until 2050 in integrated model scenarios (167scenarios with 430-530 ppm CO_{2-e}, 138 scenarios with ppm 530-650 CO_{2-e}, and 149 scenarios exceeding 720ppm CO_{2-e}—for category descriptions see Chapter 6.3.3), and **(b)** decomposition of the annual change in electricity demand share into 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.

The seven selected integrated models see a very different development in the fuel mix (Figure 9.24). In the baseline scenarios, interestingly, most scenarios show a fairly similar amount of power use; and the difference in total building final energy use largely stems from the differences in the use of other fuels. Particularly large differences are foreseen in the use of natural gas and oil, and, to a lesser extent, biomass. Mitigation scenarios are somewhat more uniform: mostly a bit over half of their fuel mix is comprised of electricity, with the remaining part more evenly distributed among the other fuels except coal that disappears from the portfolio, although some scenarios exclude further individual fuels (such as no biomass in MESSAGE, no oil in BET, no natural gas in Image) by scenarios outcomes.

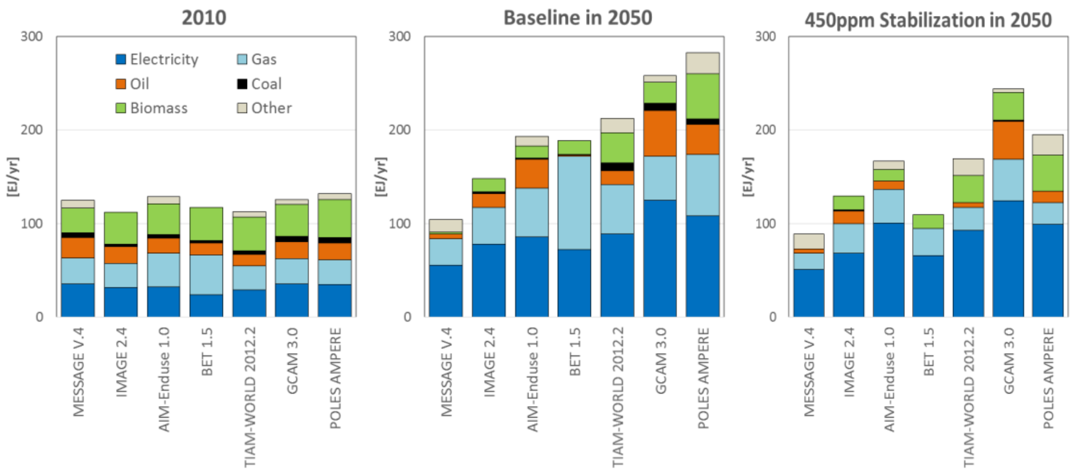

Figure 9.24. Global buildings final energy demands by fuel for the seven baseline scenarios of seven integrated models and their corresponding mitigation scenarios (480-580 ppm CO_2eq concentration in 2100).

9.9.4. Conclusion and general observations

The section has concluded that, without action, global building final energy use may even double or potentially even triple by mid-century, while it can even stabilise or decline as compared to its present levels with ambitious action. However, the integrated and sectoral models do not fully agree with regard to the extent of mitigation potential and the key mitigation strategy, although there is a very wide variation among integrated models with some more agreement across sectoral models' conclusions.

The broad mitigation strategy for buildings implied by sectoral analysis is first to reduce demand for both primary fuels and electricity significantly, by using available technologies for energy efficiency improvement, many of which are cost effective without a carbon price. To the extent this is insufficient, further mitigation is achieved through additional use of low and zero carbon electricity, from a combination of building integrated renewable energy and substitution of fossil fuels with low carbon electricity.

The broad mitigation strategies for buildings implied by integrate models, however, include a greater emphasis on switching to low-carbon energy carriers (predominantly electricity). There is less emphasis on reducing energy demand, possibly because many integrated models do not represent all technical options to reduce building energy consumption cost-effectively which are covered in sectoral studies and because of the implicit assumption of general equilibrium models that all cost-effective opportunities had been taken up already in the baseline which is at odds with empirical data from the buildings sector. Integrated model outputs tend to show energy demand reduction over the coming decades, followed by a more significant role for decarbonization of energy supply (with, in some cases, heavy reliance on bioenergy with CCS to offset remaining direct emissions from buildings and the other end-use sectors).

To summarize, sectoral studies show there is a larger potential for energy efficiency measures to reduce building sector final energy use than is most typically shown by integrated models. This indicates that some options for demand reductions in the buildings sector are not included, or at least not fully deployed, by integrated models because of different model assumptions and/or level of richness in technology/option representation (cf. Section 6.8).

9.10 Sectoral policies

This section first outlines the policy options to promote energy efficiency in buildings, then provides more detail on the emerging policy instruments since AR4, then focuses on the key new instruments for financing and finally considers the policy issues specific to developing countries.

9.10.1 Policies for Energy Efficiency in Buildings

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 to correct market failures and to encourage new business and financial models that overcome the first-investment cost hurdle, which is one of the key barriers. There is a broad portfolio of effective policy instruments available, many of them have been implemented in developed countries and more recently also in developing countries, showing reductions of emissions at low and negative costs. When these policies are implemented in a coordinated manner, they can be effective in reversing the trend of growing energy consumption. For example, building energy use has fallen in several European countries in recent years where strong policies have been implemented. Beside technological 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 behaviour and lifestyle, based on the concept of sufficiency. Particularly in developed countries, the existing building stock is large and renewed only very slowly, and therefore it is important to introduce policies specifically targeting the existing stock, e.g. aiming at accelerating rates of energy refurbishment and avoiding lock-in to suboptimal retrofits – the case of China (Dongyan, 2009). Policies also need to be dynamic, with periodic revision to follow technical and market changes, in particular regulations need regular strengthening, for example for equipment minimum efficiency standards (Siderius and Nakagami, 2013) or building codes (Weiss et al., 2012). Recently there has been more attention to enforcement, which is needed if countries are to achieve the full potential of implemented or planned policies (Ellis et al., 2009; Weiss et al., 2012).

The most common policies for the building sector are summarised in **Table 9.9**, which includes some examples of the results achieved. Policy instruments for energy efficiency in buildings may be 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 (Boza-Kiss et al., 2013) if properly enforced (Weiss et al., 2012). This is also confirmed by other authors (Koeppel and Ürge-Vorsatz, 2007; McCormick and Neij, 2009). Standards need to be set at appropriate levels and periodically strengthened to avoid lock-in to sub-optimal performance. (ii) ***Information instruments*** including equipment energy labels, building labels and certificates and mandatory energy audits can be relatively effective on their own depending on their design, but can also support other instruments, in particular standards(Kelly, 2012; Boza-Kiss et al., 2013). (iii) ***Direct market intervention instruments*** include public procurement, which can have an important role in transforming the market. More recently Governments have supported the development of energy service companies (ESCOs) (see section 9.10.3). (iv) ***Economic Instruments*** include several options, including both tradable permits, taxes and more focussed incentives. Tradable permits (often called market-based instruments) include tradable white certificates (see section 9.10.2), as well as broader carbon markets (see Chapter 13).Taxes include energy and carbon taxes and have increasingly been implemented to accelerate energy efficiency (Orlov 2013). They are discussed in more detail in Chapter 15, and can complement and reinforce other policy instruments in the building sector. Sector specific tax exemptions and reductions, if appropriately structured, can provide a more effective mechanism than energy taxes (UNEP SBCI, 2007). Options include tax deductions building retrofits (Valentini and Pistochini, 2011), value-added tax exemption and various tax reliefs (Dongyan, 2009), as well as exemptions from business taxes for CDM projects (RSA, 2009). More focussed incentives include low interest loans and incentives which can be very effective in enlarging the market for new efficient products and to overcoming first cost barriers for deep retrofits (McGilligan et al., 2010). (v) ***Voluntary agreements*** include programmes such as industry agreements. Their effectiveness depends on the context and on accompanying policy measures (Bertoldi, 2011). (vi) ***Advice and leadership programmes*** include policies such as information campaigns, advice services and public leadership programmes to build public awareness and capacity.

A large number of countries have adopted building sector policies successfully. The most popular instruments in developing countries so far have been appliance standards, public procurement and leadership programs. The table provides more detailed descriptions of the various instruments, a brief identification of some key issues related to their success and a quantitative evaluation of their environmental and cost-effectiveness from the literature. Although there is a significant spread in the results, and the samples are small for conclusive judgments on individual instruments, the available studies indicate that among the most cost-effective instruments have been building codes and labels, appliance standards and labels, supplier obligations, public procurement and leadership programs. Most of these are regulatory instruments. However, most instruments have best practice applications that have achieved CO_2 reductions at low or negative social costs, signalling that a broad portfolio of tools is available to governments to cut building-related emissions cost-effectively. Appliance standards and labels, building codes, promotion of ESCOs, CDM and JI, and financing tools (grants and subsidies) have so far performed as the most environmentally effective tools among the documented cases. However, the environmental effectiveness also varies a lot by case. Based on a detailed analysis of policy evaluations, virtually any of these instruments can perform very effective (environmentally and/or cost-wise) if tailored to local conditions and policy settings, and if implemented and enforced well (Boza-Kiss et al., 2013). Therefore it is likely that the choice of instrument is less crucial than whether it is designed, applied, implemented and enforced well and consistently. Most of these instruments are also effective in developing countries, where it is essential that the co-benefits of energy-efficiency policies (see Section 10.7) 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.

Table 9.9: Policies for energy efficiency in buildings, their environmental effectiveness, i.e. emission reduction impact and societal cost-effectiveness. Source: Based on (Boza-Kisset al., 2013).

Policy title and brief definition	Further information, comments	Environmental effectiveness (selected best practices of annual CO_2 emission reduction)	Cost effectiveness of CO_2 emission reduction (selected best practices, \$2010/tCO_2 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	[1,2,3,4]
Appliance standards (MEPS) are rules or guidelines for a particular product class that set a minimum efficiency level, and usually prohibit the sale of underperforming products.	Most OECD countries have adopted MEPS (in the EU under the Eco-design Directive). 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	[5, 6, 7,8]
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 endorsmentlabelling (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	[9,10,11]
Building labels and certificatesrate 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	[12]
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	[2, 12, 13]
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. In the EU the EED requires Member States to procure only most efficient equipment. In the US this is carried out under FEMP.	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 WieMcGrory et al., 2006; Gov't of Slovakia, 2011; LDA, 2011) [12, 14, 15, 16]
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 similar (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	[2, 17,18]
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 Australia. In all the White Certificates schemes the targets imposed by governments have been so far exceeded (Bertoldi, Rezessy, Oikonomou 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	[19, 20, 21, 22, 23, 24, 25, 26, 27]

Carbon marketslimit 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 CO_2 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	[28, 29, 30]
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 electricity, 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)	[31, 32, 33, 34]
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	[35, 36, 37]
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, Poland and Hungary	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	[35, 37, 38, 39, 40]
Soft loans (including preferential mortgages) are given for carbon-reduction measures with low interest rates.	Governmental a fiscal incentive to banks, which offer preferential interest rates to customers and also incentives based on the performances achieved, e.g. in Germany(CO_2-Rehabilitation Program).	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)	[37, 41]
Voluntary and negotiated agreementsare 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. Some voluntary agreements have a binding character; as the agreed objectives are binding. At city level, an example is the Covenant of Mayors	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	[2, 13, 42, 43]
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	[2, 44, 45, 46, 47]
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	[2, 48]

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. References: [1](EC, 2002);[2] (Koeppel and Ürge-Vorsatz, 2007);[3](DECC, 2011); [4] (Gov't of Latvia, 2011);[5](Kainou, 2007);[6] (AHAM, 2010); [7] (En.lighten, 2010);[8] (US EERE, 2010); [9] (IEA, 2003) [10] (Wiel and McMahon, 2005); [11] (Luttmer, 2006); [12] (Gov't of Slovakia, 2011); [13] (Government of Finland, 2011); [14] (FI, 2005); [15] (Van WieMcGrory et al., 2006);[16] (LDA, 2011); [17] (AEA, 2011); [19] (MNDH, 2011); [20] (Lees, 2006); [21] (Lees, 2008); [22] (Lees, 2011); [23] (Pavan, 2008); [24] (Bertoldi and Rezessy, 2009); [25](Bertoldi, Rezessy, Oikonomou, et al., 2010); [26] (Giraudet et al., 2011); [27] (Langham et al.); [28] (BETMG, 2012); [29] (UNEP Risoe, 2012); [30] (Bertoldi, Rezessy, Steuwer, et al., 2013); [31](Knigge and Görlach, 2005); [32] (Price et al., 2005); [33] (EPC, 2008); [34] (IEA, 2012b); [35] (GMCA, 2009); [36] (APERC, 2010); [37] (BPIE, 2010); [38] (DPMT, 2009); [39] (Missaoui and Mourtada, 2010); [40] (Hayes et al., 2011); [41] (Galvin, 2012); [42] (Rezessy and Bertoldi, 2010); [43] (MIKR, 2011); [44] (Uitdenbogerd et al., 2009); [45] (CPI, 2011); [46] (UK DE, 2011); [47] (CB, 2012); [48] (Government of Ireland, 2011).

9.10.1.1 Policy packages

There is agreement that no single policy is sufficient to achieve the potential energy savings and that combination (packages) of polices can have combined results that are bigger than the sum of the individual policies (Harmelink et al., 2008; Tambach et al., 2010; Weiss et al., 2012; Murphy et al., 2012). The EU's the Energy Efficiency Directive(European Union, 2012) has, since 2008, required Member States to describe co-ordinated packages of policies in their National Energy Efficiency Action Plans. Market transformation of domestic appliances in several developed countries has been achieved through a combination of minimum standards, energy labels, incentives for the most efficient equipment and an effective communication campaign for end-users (Boza-Kiss et al., 2013). The specific policies, regulations, programs and incentives needed are highly dependent on the product, market structure, institutional capacity and the background conditions in each country. Other packages of measures are mandatory audits and financial incentives for the retrofitting of existing buildings, with incentives linked to the implementation of the audit findings and minimum efficiency requirements; voluntary programmes coupled with tax exemptions and other financial incentives (Murphy et al., 2012); and suppliers' obligations and white certificates (and, in France, tax credits)in addition to equipment labelling and standards, in order to promote products beyond the standards' requirements (Bertoldi, Rezessy, Oikonomou et al., 2010).

9.10.1.2 A holistic approach

Energy efficiency in buildings requires action beyond the point of investment in new buildings, retrofit and equipment. A holistic approach considers the whole lifespan of the building, including master planning, life cycle analysis and integrated building design to obtain the broadest impact possible, and therefore needs to begin at the neighbourhood or city level (see Chapter 12). In the holistic approach, building codes, design, operation, maintenance and post occupancy evaluation are coordinated. Continuous monitoring of building energy use and dynamic codes allow policies to close the gap between design goals and actual building energy performance.The use of modern technologies to provide feedback on consumption in real time, allows adjustment of energy performance also as a function of external energy supply. Dynamic information can also be used for energy certificates and databases to disclose building energy performance. Moreover, studies on durability and climate mitigation show that the lifespan of technical solution is as important than the choice of material, signalling to the importance of related policies, such as eco-design directives and mandatory warranties (Mequignon, Adolphe, et al., 2013; Mequignon, Ait Haddou, et al., 2013). Another challenge is the need to develop the skills and training to deliver, maintain and manage 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. Implementation and enforcement of policies are a key component of effective policy. It is the only way to ensure that the expected results of the policy are achieved. Developed countries are now increasing attention to proper implementation and enforcement (Jollands et al., 2010), for example to survey equipment efficiency when minimum standards are in place and to check compliance with building codes. For example, EU Member States are required to develop independent control systems for their building labelling schemes (European Union, 2012). 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 policies. In addition to enforcement, ex-post evaluation of policies is needed to assess their impact and to review policy design and stringency or to complement it with other policies. Implementation and enforcement is still a major challenge for developing countries which lack much of the capacity (e.g. testing laboratories for equipment efficiency) and knowledge to implement policies such as standards, labels and building codes.

9.10.2 Emerging policy instruments in buildings

Since recent reports have reviewed building-related policies comprehensively (IPCC, 2007; GEA, 2012), the remainder of this chapter focuses on recent developments and important emerging instruments.

While technical efficiency improvements are still needed and important to reduce energy demand, (Alcott, 2008), increases in energy use are driven primarily by increasing demand for energy services (e.g. built space per capita and additional equipment). To address this policies need to influence consumer behaviour and lifestyle(Herring, 2006; Sanquist et al., 2012) and the concept of sufficiency has been introduced in the energy efficiency policy debate (Herring, 2006; Oikonomou et al., 2009). Policies to target sufficiency aim at capping or discouraging increasing energy use due to increased floor space, comfort levels and equipment. Policy instruments in this category include: (i) personal carbon trading (i.e. carbon markets with equitable personal allocations) - this has not yet been introduced and its social acceptability (Fawcett, 2010) and implementation (Eyre, 2010) have to be further demonstrated; (ii) property taxation (e.g. related to a building's CO_2 emissions); and (iii) progressive appliance standards and building codes, e.g. with absolute consumption limits (e.g. kWh/person/year) rather than efficiency requirements (kWh/m^2/year) (Harris et al., 2007).

In order to reduce energy demand, policies may include promoting density, high space utilization, and efficient occupant behaviour, as increased floor space entails more energy use. This might be achieved, for example, through incentives for reducing energy consumption - the so-called energy saving feed-in tariff (Bertoldi, Rezessy, Lees, et al., 2010; Bertoldi, Rezessy, and Oikonomou, 2013).

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

A large number of jurisdictions have now set, or are considering, very significant strengthening of the requirements for energy performance in building codes. There are debates about the precise level of ambition that is appropriate, especially with regard to net zero energy building mandates that can be problematic (see 9.3). The EU is requiring its Member States to introduce building codes set at the cost optimal point using a life cycle calculation, both for new buildings and those undergoing major renovation. As a result, by the end of 2020, all new buildings must be nearly zero energy by law. Many Member States (e.g. Denmark, Germany) have announced progressive building codes to gradually reduce the energy consumption of buildings towards nearly net zero levels. There is also action within local jurisdictions, e.g. 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 (MoniteurBelge, 2011; BE, 2012; CSTC.be, 2012). In China, building codes have been adopted that seek saving of 50% from pre-existing levels, with much increased provision for enforcement, leading to high expected savings (Zhou, McNeil, et al., 2011) As demonstrated in sections 9.2 and 9.9, the widespread proliferation of these ambitious building codes, together with other policies to encourage efficiency, have already contributed to total building energy use trends stabilising, or even turning down.

9.10.2.2. *Energy efficiency obligation schemes and 'white' certificates*

Energy efficiency obligation schemes with or without so-called "white certificates" as incentive schemes have been applied in some member states of the European Union (Bertoldi et al., 2009) and Australia (Crossley, 2008), with more recent uses in Brazil and India. White certificates evolved from non-tradable obligations on monopoly energy utilities, also known as suppliers' obligations or energy efficiency resources standards, 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 suppliers 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 are a key part of EU policy for energy efficiency and the Energy Efficiency Directive (European Union, 2012) requires all EU Member States to introduce this policy or alternative schemes. Precise objectives, traded quantity and rules differ across countries. Cost effectiveness is typically very good (Bertoldi, 2012). However, white certificates tend to incentivise low cost, mass market measures rather than deep retrofits, and therefore there are concerns that this policy approach may not be best suited to future policy objectives(Eyre et al., 2009).

9.10.3 Financingopportunities

9.10.3.1. *New financing schemes for deep retrofits*

Energy efficiency in buildings is not a single market: it covers a diverse range of end-use equipment and technologies and requires very large numbers of small, dispersed projects with a diverse range of decision makers. As the chapter has demonstrated, many 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. 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 shortage of relevant finance and of delivery mechanisms that suit the specifics of energy efficiency projects and the lack – in some markets – of pipelines of bankable energy efficiency projects. Creative business models from energy utilities, businesses and financial institutions can overcome first-cost hurdles (Veeraboina and Yesuratnam, 2013). One innovative example is for energy-efficiency investment funds to capitalize on the lower risk of mortgage lending on low-energy housing; the funds to provide such investment can be attractive to socially responsible investment funds. In Germany, through the KfW development bank, energy efficiency loans with low interest rate are offered making it attractive to end-users. The scheme has triggered many building refurbishments (Harmelink et al., 2008). The ***'Green Deal'*** is a new initiative by the UK government designed to facilitate the retrofitting of energy saving measures to all buildings. Such scheme allows for charges on electricity bills in order to recoup costs of buildings energy efficiency improvements by private firms to consumers (Bichard and Thurairajah, 2013). The finance is tied to the energy meter rather than the building owner. The Green Deal was expected primarily to finance short payback measures previously covered by the suppliers' obligation, rather than deep retrofits. However, the UK government does not subsidise the loan interest rate, and commercial interest rates are not generally attractive to end-users. Take-up of energy efficiency in the Green Deal is therefore expected to be much lower than in a supplier obligation (Rosenow and Eyre, 2013). In areas of the US with ***PACE*** (Property Assessed Clean Energy) legislation in place, municipality governments offer a specific bond to investors and then use 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. Legal concerns about the effect of PACE lending on mortgages for residential buildings (Van Nostrand, 2011) have resulted in the approach being mainly directed to non-domestic buildings. ***ESCOs*** provide solutions for improving energy efficiency in buildings 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. 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 by the Chinese government and World Bank in 1998, a market-based energy performance contract mechanism and ESCO industry has developed in China (Da-li, 2009) with Chinese government support. Policies for the support of ESCOs in developing countries include the creation of a Super ESCOs (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 EPCs, in which an ESCO invests in a comprehensive refurbishment and repays itself through the generated savings. Social housing operators and ESCOs have established the legal, financial and technical framework to do this (Milin and Bullier, 2011).

9.10.1.3 Opportunities in Financing for Green Buildings

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). A survey on responsible property investing (RPI) (UNEP FI, 2009), covering key markets around the world, has shown 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 energy-saving devices had significantly higher occupancy rates than the average for other properties in the neighbourhood, and investment return rates were also higher (MLIT, 2010a; b).A survey comparing rent and vacancy rates of buildings (Watson, 2010) showed rents for LEED certified buildings were consistently higher than for uncertified buildings. 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 (Murakami et al., 2004). 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, 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, both newly constructed and existing buildings. This program has contributed to the promotion of green buildings, with 160,000 (approximately 20% of the total market) applications for subsidies for newly constructed buildings in 2010. In existing buildings, the number of window replacements has increased, and has attracted much attention (MLIT, 2012).

9.10.4 Policies in developing countries

Economic instruments and incentives are very important means to encourage stakeholders and investors in the building sector to adopt more energy efficient approaches in the 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. However, it until recently has bypassed the sector entirely, due to some methodological obstacles to energy efficiency projects (Michaelowa et al., 2009). However, a "whole building" baseline and monitoring methodology approved in 2011 may pave the way for more building projects (Michaelowa and Hayashi, 2011). Since 2009, the share of CDM project in the buildings sector has increased, particularly with regard to efficient lighting schemes (UNEP Risoe, 2012) . The voluntary market has complemented the CDM as a financing mechanism, for example for solar home systems projects (Michaelowa et al., 2009; Michaelowa and Hayashi, 2011). ***Public benefits charges*** are financing mechanisms meant to raise funds for energy efficiency measures and to accelerate market transformation in both developed and developing countries (UNEP SBCI, 2007). In 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 a developing country context, it is common practice to house DSM programmes within the local utilities due to their healthy financial means and strong 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, the 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 that have been installed in households (Winkler and Van Es, 2007). ***Capital subsidies, grants and subsidized loans*** are among the most frequently used instruments for implementation of increased energy efficiency projects in buildings. Financial subsidy is used as the primary supporting fund in the implementation of retrofit projects in China (Dongyan, 2009). In recent years, the World Bank Group has steadily increased energy efficiency lending to the highest lending ever in the fiscal year of 2009 of US$3.3 billion, of which 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).

9.11 Gaps in knowledge and data

Addressing these main gaps and problems would improve the understanding of mitigation in buildings:

- adequate bottom-up data – their lack leading to a dominance of top down and supply-focused decisions about energy systems
- misinformation and simplified techniques – these risks to the understanding of integrated and regionally adequate building systems, leading to fragmented actions and poorer results
- poor information about opportunities and costs – these affect optimal decisions and appropriate allocation of financial resources
- energy indicators – which relate to efficiency, but rarely to sufficiency
- improved and more comprehensive databases on real, measured building energy use, and capturing behaviour and lifestyles – these are necessary to develop exemplary practices from niches to standard
- continuous monitoring and constant modification of performance and dynamics of codes – these would allow implementation to catch up with the potential for efficiency improvements and co-benefits, as well as providing better feedback to the policymaking process, to education, to capacity building and to training
- quantification and monetization of (positive and negative) externalities over the building life cycle, well integrated into decision-making processes.

9.12 Frequently asked questions

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?

Recent advances in information technology, design, construction and know-how have opened new opportunities for a transformative change in building-sector related emissions that can contribute to meeting ambitious climate targets at socially acceptable costs, or often at net benefits. Main advances do not lie in major technological developments, but rather in their extended systemic application, partially as a result of advanced policies; as well as in improvements in the performance and reductions in the cost of several technologies. For instance, there are over 57,000 buildings meeting Passive House standard and "nearly zero energy" new construction has become the law in the 27 member states of the European Union. Even higher energy performance levels are being successfully applied to new and existing buildings, including non-residential ones. The costs have been gradually declining; for residential buildings at the level of Passive house standard they account for 5-8% of conventional building costs, and some net zero or nearly zero energy commercial buildings having been built at equal or even lower costs than conventional ones (see 9.3 and 9.7).

FAQ 9.1.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, GEA (2012)projects an approximately EUR 18 billion in cumulative additional investment needs for realizing these advanced scenarios, but estimates an over EUR 50 billion in cumulative energy cost savings until 2050.

FAQ 9.2.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. Among the most cost-effective instruments have been building codes and labels, appliance standards and labels, supplier obligations, public procurement and leadership programs. Most of these are regulatory instruments. However, most instruments have best practice applications that have achieved CO2 reductions at low or negative social costs, signalling that a broad portfolio of tools is available to governments to cut building-related emissions cost-effectively. Appliance standards and labels, building codes, promotion of ESCOs, CDM and JI, and financing tools (grants and subsidies) have so far performed as the most environmentally effective tools among the documented cases. However, the environmental effectiveness also varies a lot by case. Based on a detailed analysis of policy evaluations, virtually any of these instruments can perform very effective (environmentally and/or cost-wise) if tailored to local conditions and policy settings, and if implemented and enforced well (Boza-Kiss et al., 2013). Therefore it is likely that the choice of instrument is less crucial than whether it is designed, applied, implemented and enforced well and consistently.

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